AISC
Night School

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We will begin shortly. Please standby.

Modern Methods for Learning the Basics of Structural Stability: From Behavior to Practice
Session 7: Behavior of Structural Systems – The Fundamentals
December 1, 2020

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AISC Live Webinars

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Course Description

Behavior of Structural Systems – The Fundamentals
December 1, 2020

This lecture will begin with a review of basic concepts related to the stability of structural systems. With an eye toward design, the difference between a bifurcation or critical load analysis and the loss in stiffness due to second-order effects and material yielding, as the maximum resistance of physical structures is approached, will be emphasized. The lecture will then provide an overview of the direct analysis and effective length methods. The speakers will conclude by introducing the fourth learning module.

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Learning Objectives

- Describe how the story lateral stiffness is related to P-Δ effects.
- Identify indicators for assessing whether a structure is a stability-sensitive system.
- Compare and contrast the direct analysis method and the effective length method.
- Explain the modeling considerations for direct analysis by advanced elastic analysis and inelastic methods, and the repercussions for determining member capacity.

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

Session 7: Behavior of Systems – The Fundamentals
December 1, 2020

Ronald D. Ziemian, PE, PhD
Professor
Bucknell University

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

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Course Overview

- Topics
  - Compression Members (Weeks 1 & 2)
  - Flexural Members (Weeks 3 & 4)
  - Beam-Columns (Weeks 5 & 6)
  - Systems (Weeks 7 & 8)
- "Active" learning! Weekly virtual lab experiences…
- Case studies from the real world…

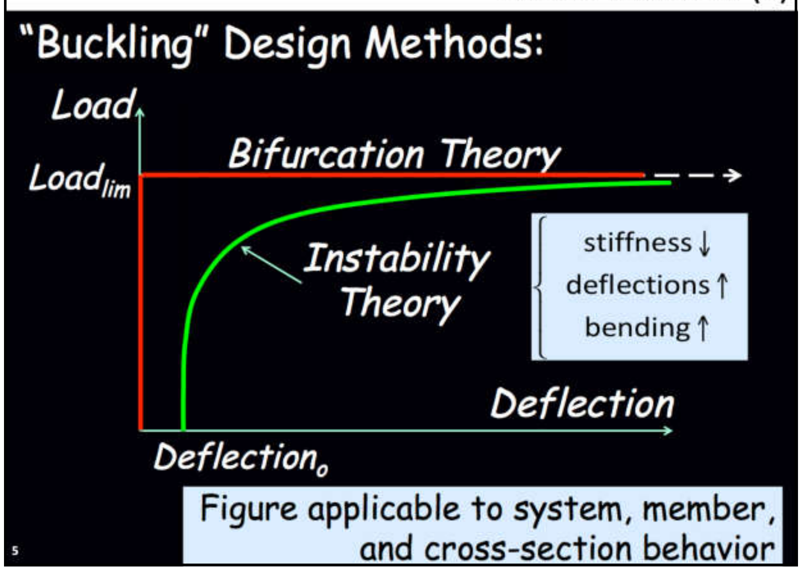
2

Course Overview (2)

Course Overview (3)

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

Course Overview (4)



Course Overview (5)

Analysis acronyms:

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

LA: linear analysis; 1st-order elastic analysis; assumes equilibrium on the undeformed shape and linear elastic material, with no initial imperfections

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

GNIA: same as GNA, but includes initial imperfections

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

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

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

- Course Introduction
- Compression Members
- Flexural Members
- Beam-Columns
- Systems

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7

"Buckling" Design Methods:

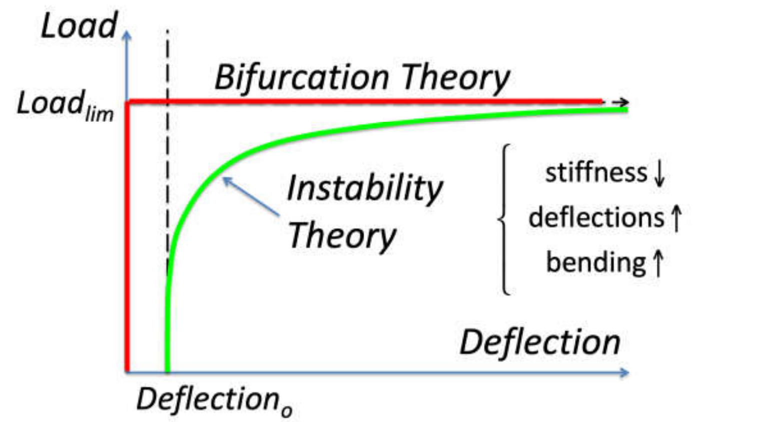
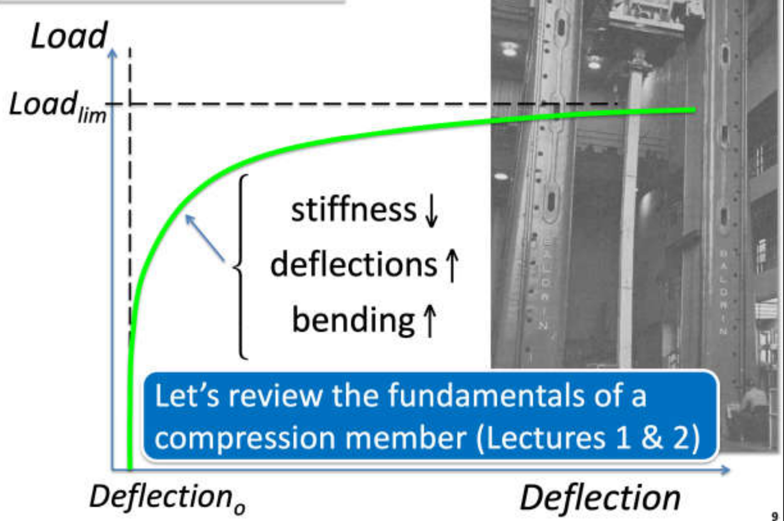


Figure applicable to system, member, and cross-section behavior

8

Instability Theory:



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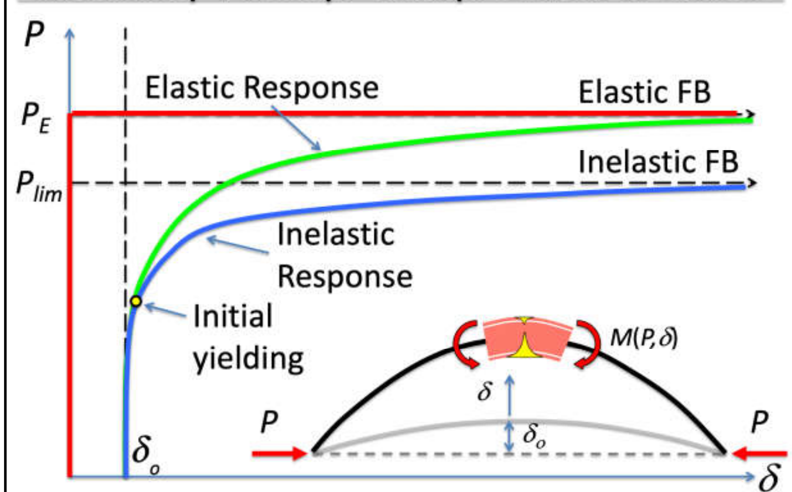
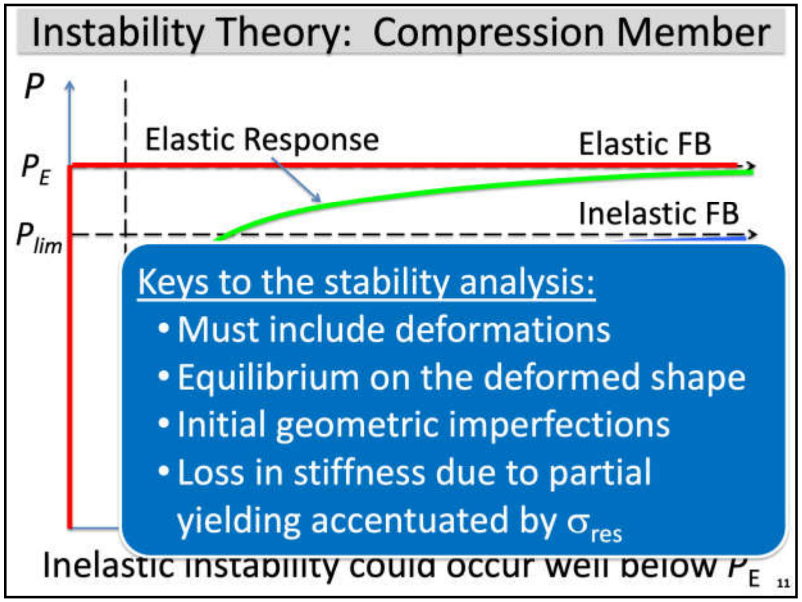
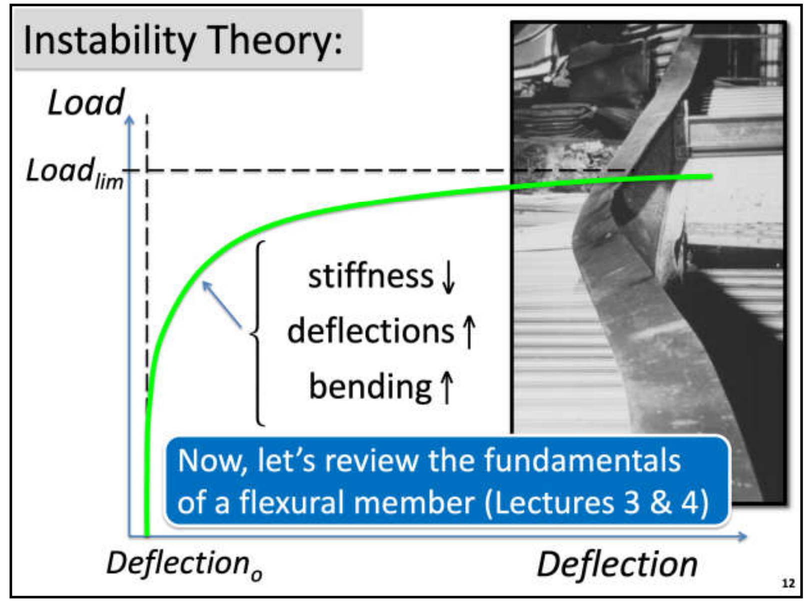
Instability Theory: Compression Member

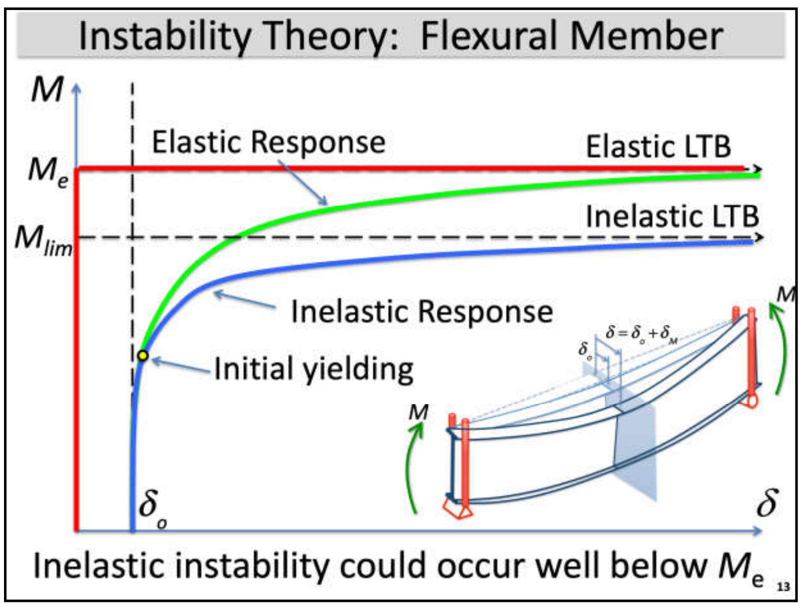


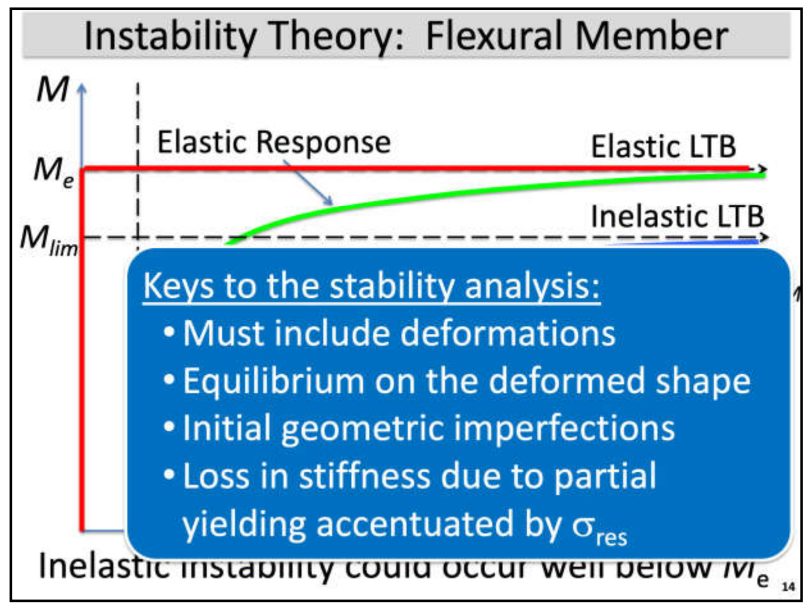
Inelastic instability could occur well below P_E

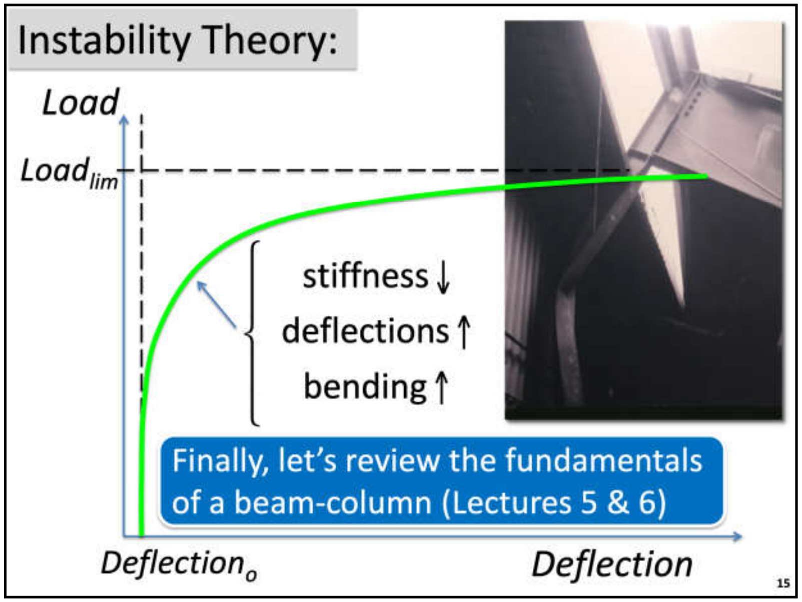
10

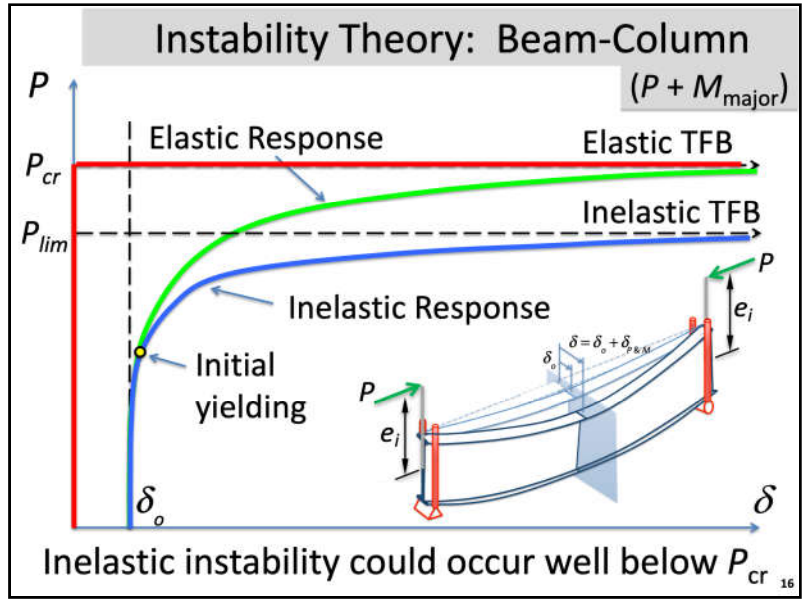

Instability Theory: Compression Member
P
P_E
P_{lim}
Elastic Response
Elastic FB
Inelastic FB
Keys to the stability analysis:
• Must include deformations
• Equilibrium on the deformed shape
• Initial geometric imperfections
• Loss in stiffness due to partial yielding accentuated by σ_{res}
Inelastic instability could occur well below P_E
11

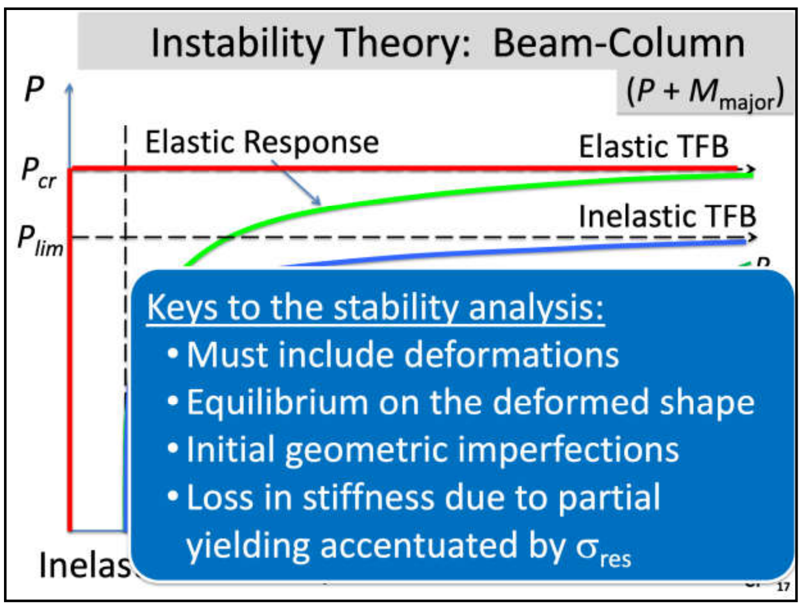

Instability Theory:
Load
$Load_{lim}$
stiffness ↓
deflections ↑
bending ↑
Now, let's review the fundamentals of a flexural member (Lectures 3 & 4)
$Deflection_o$
Deflection
12

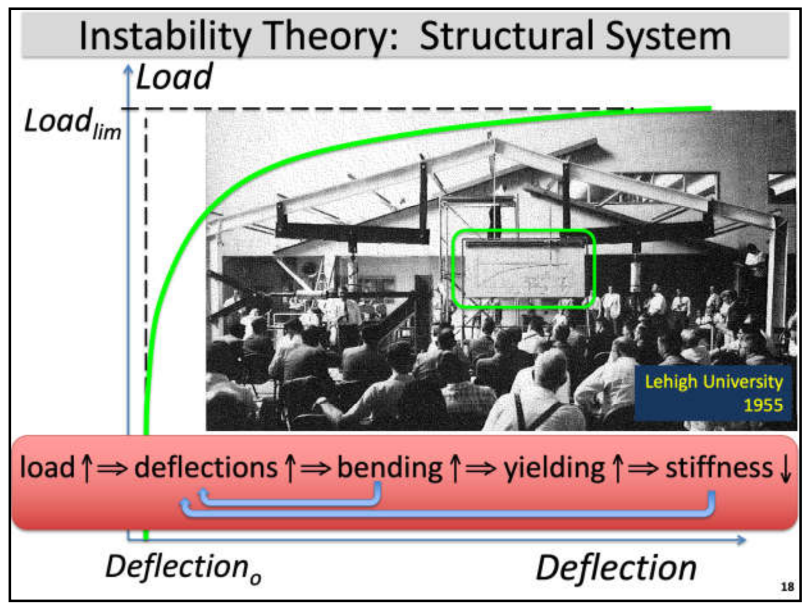

Instability Theory: Flexural Member
M
M_e
M_{lim}
Elastic Response
Elastic LTB
Inelastic LTB
Inelastic Response
Initial yielding
δ_o
δ
$\delta = \delta_o + \delta_M$
M
Inelastic instability could occur well below M_e
13


Instability Theory: Flexural Member
M
M_e
M_{lim}
Elastic Response
Elastic LTB
Inelastic LTB
Keys to the stability analysis:
• Must include deformations
• Equilibrium on the deformed shape
• Initial geometric imperfections
• Loss in stiffness due to partial yielding accentuated by σ_{res}
Inelastic instability could occur well below M_e
14


Instability Theory:
Load
Load$_{lim}$
stiffness ↓
deflections ↑
bending ↑
Finally, let's review the fundamentals of a beam-column (Lectures 5 & 6)
Deflection$_o$
Deflection
15


Instability Theory: Beam-Column
($P + M_{major}$)
P
P_{cr}
P_{lim}
Elastic Response
Elastic TFB
Inelastic TFB
Inelastic Response
Initial yielding
P
e_i
δ_o
δ
Inelastic instability could occur well below P_{cr}
16


Instability Theory: Beam-Column
($P + M_{major}$)
P
P_{cr}
P_{lim}
Elastic Response
Elastic TFB
Inelastic TFB
Keys to the stability analysis:
• Must include deformations
• Equilibrium on the deformed shape
• Initial geometric imperfections
• Loss in stiffness due to partial yielding accentuated by σ_{res}
17


Instability Theory: Structural System
Load
Load$_{lim}$
Lehigh University 1955
load ↑ ⇒ deflections ↑ ⇒ bending ↑ ⇒ yielding ↑ ⇒ stiffness ↓
Deflection$_o$
Deflection
18

Instability Theory: Structural System

Beams	
Levels	
1	W21x48
2	W21x55
3	W21x55
4	W21x55
5	W21x55
6	W24x62
7	W24x62
8	W24x68
9	W24x68
10	W24x68
11	W24x76
12	W24x76
13	W24x84
14	W24x84
15	W24x84
16	W24x84
17	W27x84
18	W27x84
19	W27x84
20	W27x94
21	W27x94
22	W27x94
23	W27x94
24	W27x94
25	W27x94
26	W27x94

Columns		
Levels	Exterior Columns	Interior Columns
1-3	W8x67	W8x35
3-5	W12x87	W12x79
5-7	W14x109	W14x109
7-9	W14x132	W14x132
9-11	W14x145	W14x159
11-13	W14x176	W14x211
13-15	W14x211	W14x233
15-17	W14x233	W14x283
17-19	W14x257	W14x311
19-21	W14x283	W14x342
21-23	W14x311	W14x370
23-25	W14x342	W14x398
25-27	W14x370	W14x426

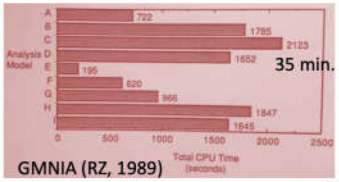
Nominal Loads
Roof Load: Live @ 30 psf
Dead @ 40 psf
Floor Load: Live @ 75 psf
Dead @ 50 psf
Wall Load: 18 kips/story
Wind Load: 20 psf

Frame Spacing = 30 ft

Load Combination Investigated:
1.2 Dead + 0.5 Live + 1.3 Wind

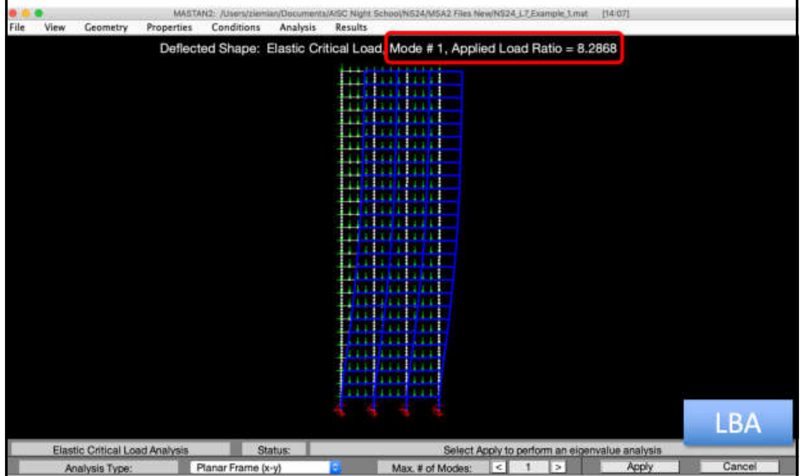
Fy = 36 ksi
E = 29000 ksi

Lu, L. W.; Ozer, Erkan; Daniels, J. H.; and Okten, Omer S., "Frame stability and design of columns in unbraced multistory steel frames, July 8, 1975 (77-27)" (1975). Fritz Laboratory Reports. 2036.



19

Instability Theory: Structural System

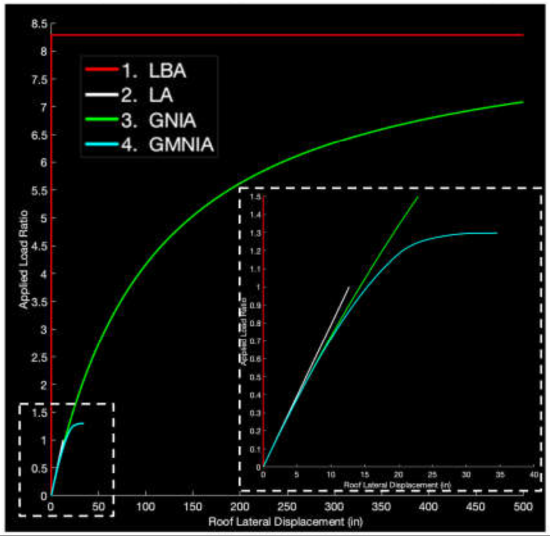


NS24_L7_Example_1.mat

20

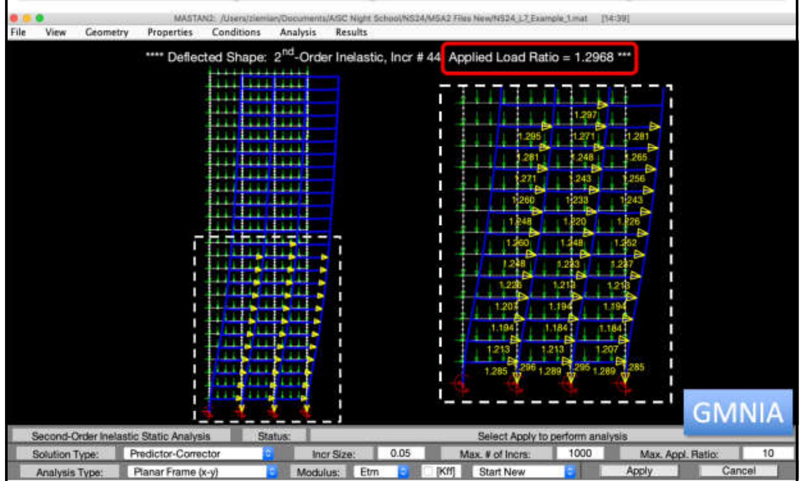
Instability Theory: Structural System

NS24_L7_Example_2.mat



21

Instability Theory: Structural System



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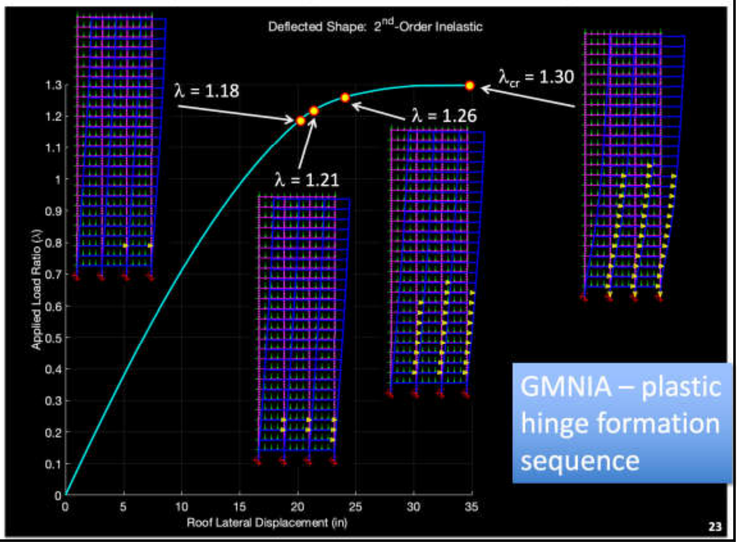
(30 seconds!) 22

Instability Theory: Structural System

NS24_L7_Example_2.mat



Instability Theory: Structural System

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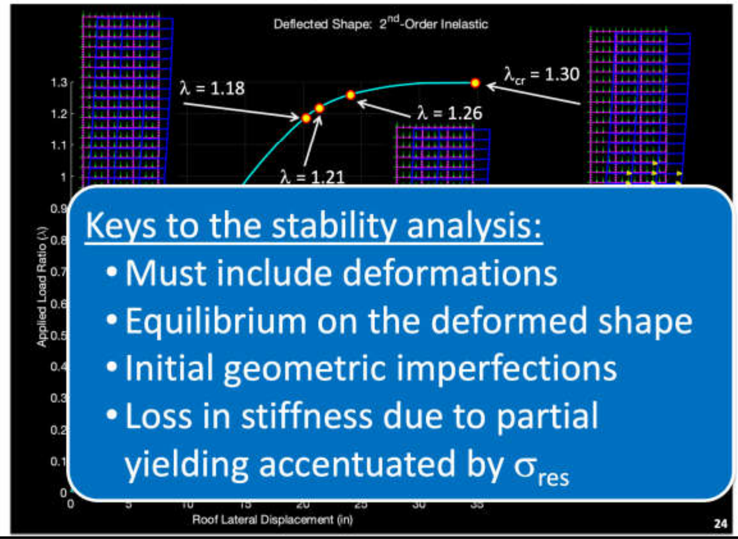


Keys to the stability analysis:

- Must include deformations
- Equilibrium on the deformed shape
- Initial geometric imperfections
- Loss in stiffness due to partial yielding accentuated by σ_{res}

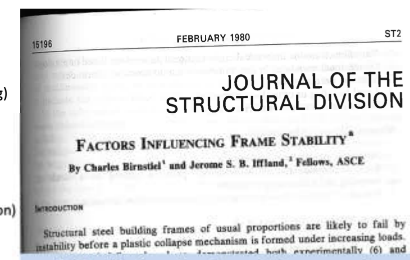
Systems…

DESIGNING FOR STRUCTURAL STABILITY

Factors influencing frame stability

- Geometric effects
  - Axial force on bending stiffness
  - Relative joint displacement
  - Length changes due to axial strain & bowing
  - Initial crookedness of members (manufacturing)
  - Initial out-of-plumb of systems (erection)
  - Finite joint size and panel zone deformations
- Material effects
  - Nonlinear stress-strain relationship
  - Residual stresses (manufacturing and fabrication)
  - Spread of yielding as member forces increase
  - Variations in cross section dimensions
  - Shearing deformations
  - Local buckling
  - Out-of-plane movement of frames and members
  - Connection flexibility
  - Strain Hardening
  - Contributions of slab to strength and stiffness
- Load effects
  - Proportional vs. Non-proportional loading
  - Variable repeated loading
  - Dynamic effects

Birnstiel and Iffland, 1980


15196 FEBRUARY 1980 ST2

JOURNAL OF THE STRUCTURAL DIVISION

FACTORS INFLUENCING FRAME STABILITY*

By Charles Birnstiel[1] and Jerome S. B. Iffland,[2] Fellows, ASCE

INTRODUCTION

Structural steel building frames of usual proportions are likely to fail by instability before a plastic collapse mechanism is formed under increasing loads.

Bridge Engineering Association recognizes Dr. Charles Birnstiel with a Lifetime Achievement Award (2018)

John Fisher

Factors influencing frame stability

Birnstiel and Iffland, 1980

- Geometric effects
- Mat
  - Strain Hardening
  - Contributions of slab to strength and stiffness
- Load effects
  - Proportional vs. Non-proportional loading
  - Variable repeated loading
  - Dynamic effects

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27

Factors influencing frame stability

Birnstiel and Iffland, 1980

- Geometric effe
  - Axial force on
  - Relative joint
  - Length chang
  - Initial crooke
  - Initial out-of-
  - Finite joint si
- Material effect
  - Nonlinear str
  - Residual stres
  - Spread of yiel
  - Variations in
  - Shearing defo
  - Local bucklin
  - Out-of-plane
  - Connection fl
  - Strain Harder
  - Contributions
- Load effects
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  - Nonlinear stress-strain relationship
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  - Contributions of slab to strength and stiffness

28

Factors influencing frame stability

Birnstiel and Iffland, 1980

- Geometric effects
  - Axial force on bending stiffness
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- Load effects
  - Proportional vs. Non-proportional loading
  - Variable repeated loading
  - Dynamic effects

In the spirit of transparency... AISC 2005-2016

CHAPTER C

DESIGN FOR STABILITY

This chapter addresses requirements for the design of structures for *stability*. The *direct analysis method* is presented herein; alternative methods are presented in Appendix 7.

The chapter is organized as follows:

C1. General Stability Requirements
C2. Calculation of Required Strengths
C3. Calculation of Available Strengths

C1. GENERAL STABILITY REQUIREMENTS

Stability shall be provided for the structure as a whole and for each of its elements. The effects of all of the following on the stability of the structure and its elements shall be considered: (1) flexural, shear and axial member deformations, and all other deformations that contribute to displacements of the structure; (2) *second-order effects* (both P-Δ and P-δ *effects*); (3) geometric imperfections; (4) *stiffness* reductions due to inelasticity; and (5) uncertainty in stiffness and strength. All *load-dependent* effects shall be calculated at a level of loading corresponding to *LRFD load combinations* or 1.6 times *ASD load combinations*.

Any rational method of design for stability that considers all of the listed effects is permitted; this includes the methods identified in Sections C1.1 and C1.2.

29

Factors influencing frame stability

AISC Chapter C's "Big 5":

- ✓ Must include pertinent deformations
- ✓ Equilibrium on the deformed shape
- ✓ Initial geometric imperfections
- ✓ Loss in stiffness due to partial yielding accentuated by σ_{res}
- ✓ Potential for variation

- Out-of-plane movement of f…es and members
  - Connection flexibility
  - Strain Hardening
  - Contributions of slab to streng…
- Load effects
  - Proportional vs. Non-proportional loading
  - Variable repeated loading
  - Dynamic effects

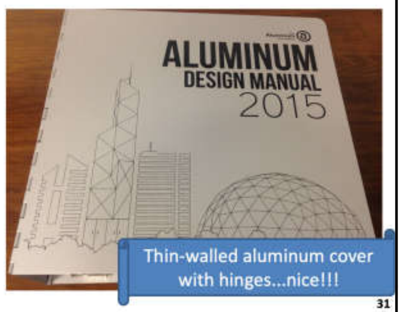
C1. GENERAL STABILITY REQUIREMENTS

Stability shall be provided for the structure as a whole and for each of its elements. The effects of all of the following on the stability of the structure and its elements shall be considered: (1) flexural, shear and axial member deformations, and all other deformations that contribute to displacements of the structure; (2) *second-order effects* (both P-Δ and P-δ *effects*); (3) geometric imperfections; (4) *stiffness* reductions due to inelasticity; and (5) uncertainty in stiffness and strength. All *load-dependent* effects shall be calculated at a level of loading corresponding to *LRFD load combinations* or 1.6 times *ASD load combinations*.

Any rational method of design for stability that considers all of the listed effects is permitted; this includes the methods identified in Sections C1.1 and C1.2.

30

Three specifications,
one format (Nice!)
e.g. *Ch. C - Design for Stability*



31

Basis for Design of Systems

- Elastic Analysis (AISC Spec., Chs. A-K, Apps. 6-8)
  - Allows for no force redistribution due to yielding
  - Strength (stability) of system is indirectly assessed by assessing strength of its components
  - In other words, strength of system is assured by ensuring adequate strength of its components
- Inelastic Analysis (AISC Spec., Appendix 1)
  - Force redistribution due to yielding is accounted for in the analysis
  - System strength (stability) can be assessed directly by the analysis

32

Basis for Design of Systems

- Elastic Analysis (AISC Spec., Chs. A-K, Apps. 6-8)
  - Allows for no force redistribution due to yielding
  - Strength (stability) of system is indirectly assessed by assessing strength of its components
  - In other words, strength of system is assured by ensuring adequate strength of its components

Elastic Analysis → Required Strength ≤ Design Strength ← Stability

Stability
- Column
- Beams
- Beam-columns

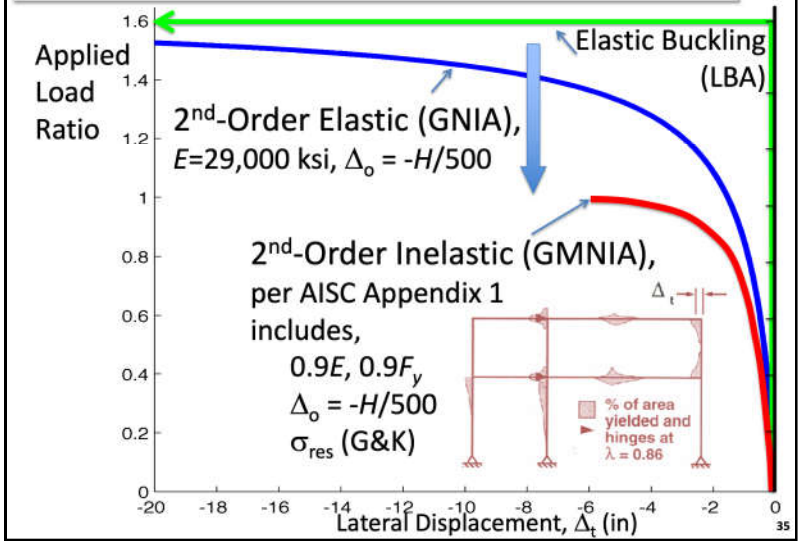
33

Basis for Design of Systems

- Elastic Analysis (AISC Spec., Chs. A-K, Apps. 1,6-8)
  - Allows for no force redistribution due to yielding
  - Strength (stability) of system is indirectly assessed by assessing strength of its components
  - In other words, strength of system is assured by ensuring adequate strength of its components
- Inelastic Analysis (AISC Spec., Appendix 1.3)
  - Force redistribution due to yielding is accounted for in the analysis
  - System strength (stability) can be assessed directly by the analysis – GMNIA!

34

Predicting "actual" behavior with elastic analysis:



General Stability Design Methods:

Analysis for load effects:

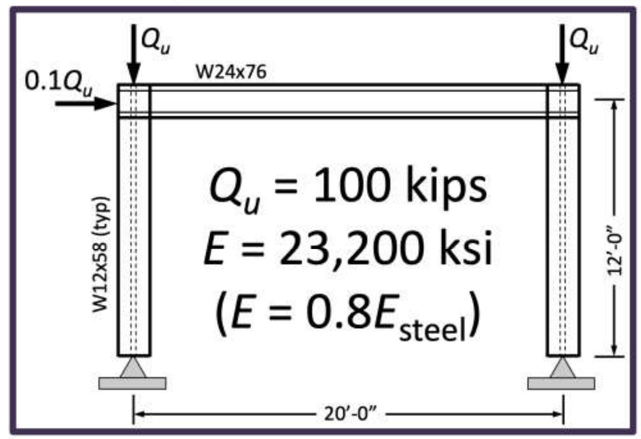
- Reality: Equilibrium on deformed shape

$$R_u \leq \phi R_n$$

- Effective length method
- Direct analysis method

NOTE! Both methods require consideration of 2nd-order effects

1st-Order Analysis (LA)
vs.
2nd-Order Analysis (GNA)



Q_u = 100 kips
E = 23,200 ksi
($E = 0.8E_{steel}$)

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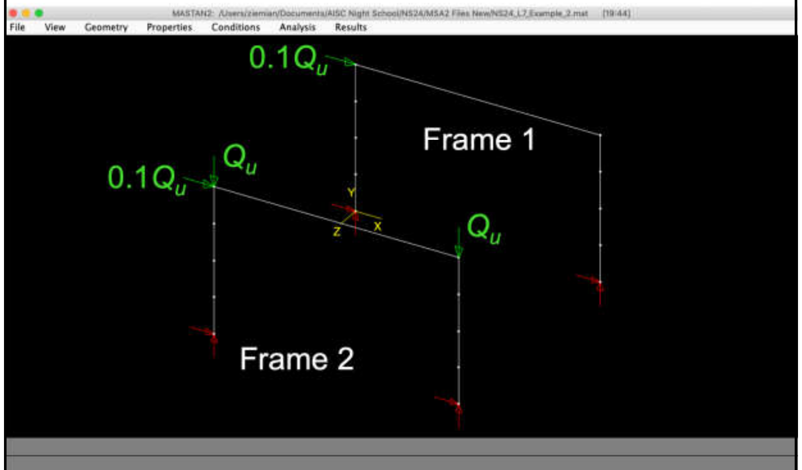

39

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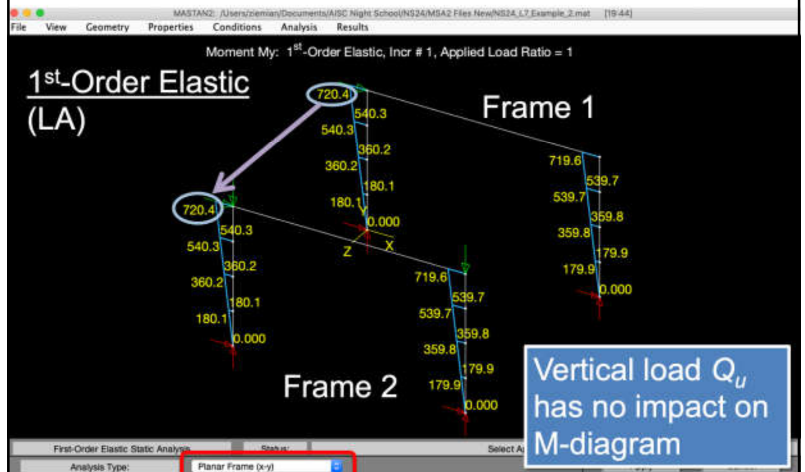

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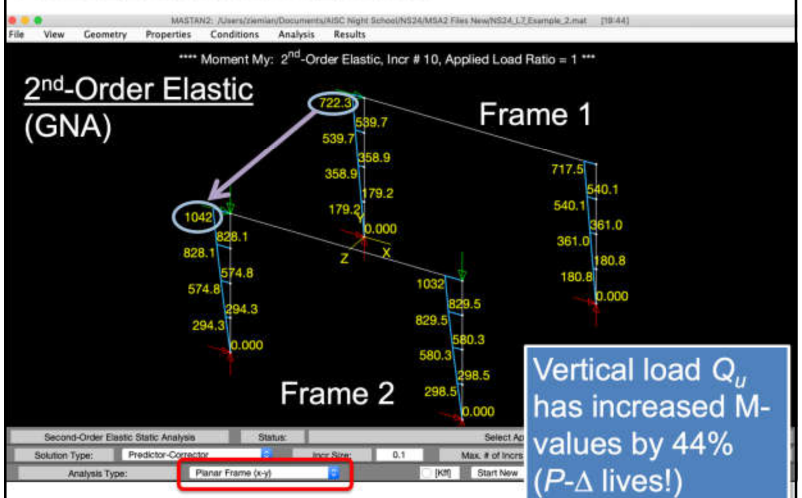
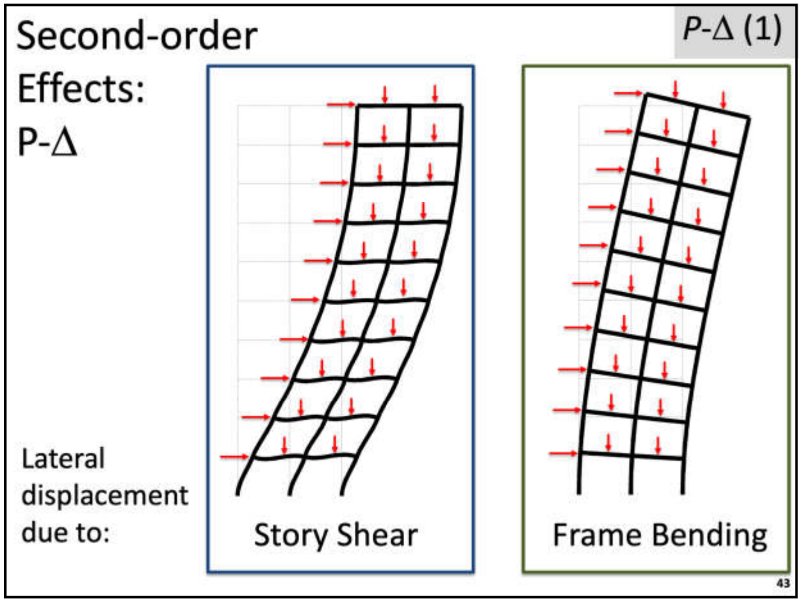


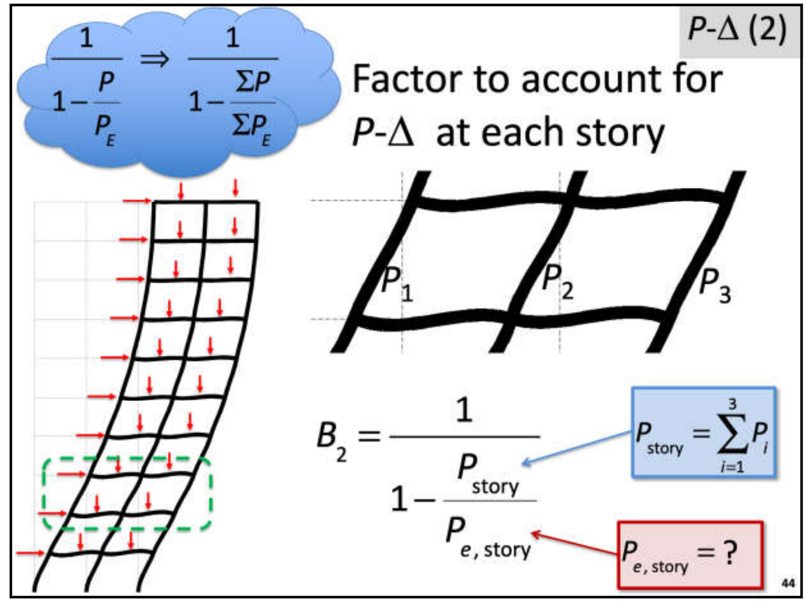
41

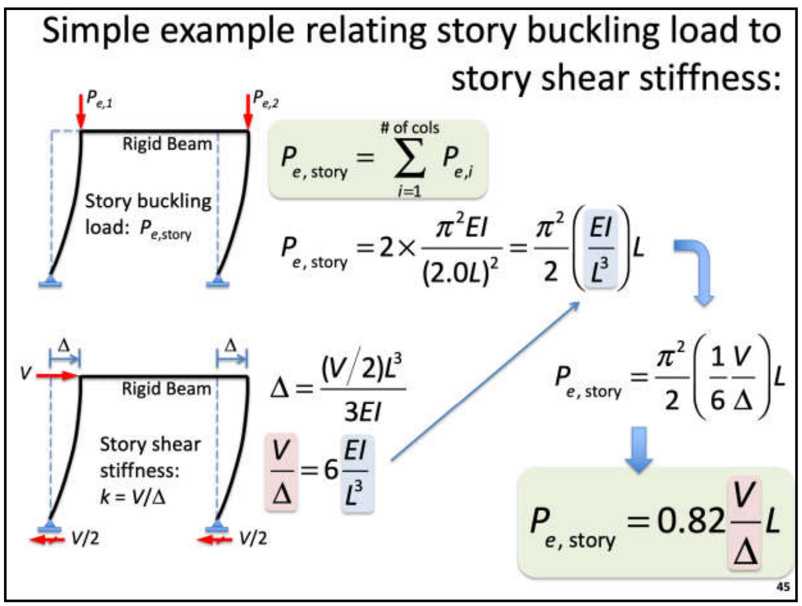
Including Second-Order Effects

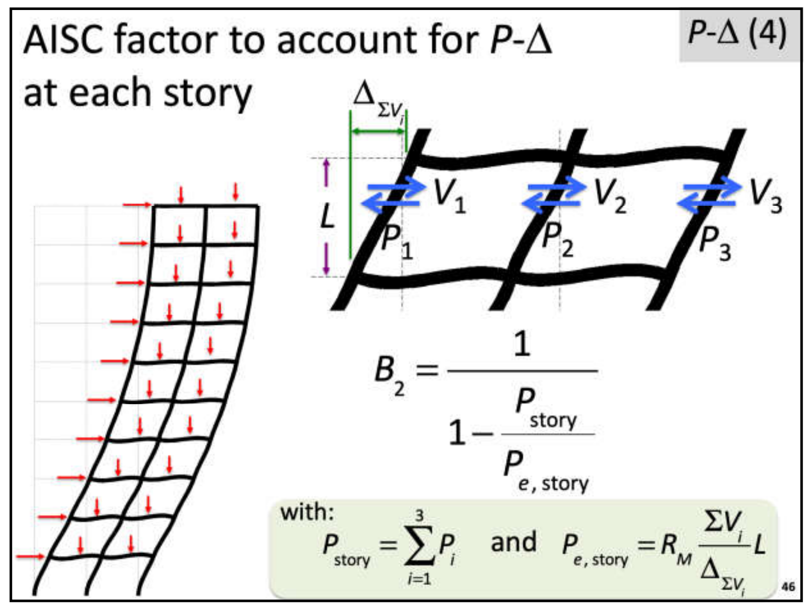
- Analysis options for :
  - Rigorous computational analysis (recommended!)
    - loads applied incrementally/iteratively
    - geometric stiffness matrix
    - updating geometry after each increment of loading
  - B_1 and B_2 amplification factors
    - $M = B_1 M_{nt} + B_2 M_{lt}$
- Approximate indicators of their significance
  - $P\delta$ provided by B_1
  - $P\Delta$ provided by B_2

42


P-Δ (1)
Second-order Effects: P-Δ
Lateral displacement due to:
Story Shear
Frame Bending
43


P-Δ (2)
$\frac{1}{1-\frac{P}{P_E}} \Rightarrow \frac{1}{1-\frac{\Sigma P}{\Sigma P_E}}$
Factor to account for P-Δ at each story
P_1 P_2 P_3
$B_2 = \frac{1}{1-\frac{P_{story}}{P_{e,story}}}$
$P_{story} = \sum_{i=1}^{3} P_i$
$P_{e,story} = ?$
44


Simple example relating story buckling load to story shear stiffness:
$P_{e,1}$ $P_{e,2}$
Rigid Beam
Story buckling load: $P_{e,story}$
$P_{e,story} = \sum_{i=1}^{\#\ of\ cols} P_{e,i}$
$P_{e,story} = 2 \times \frac{\pi^2 EI}{(2.0L)^2} = \frac{\pi^2}{2}\left(\frac{EI}{L^3}\right)L$
V Δ Δ
Rigid Beam
Story shear stiffness: $k = V/\Delta$
V/2 V/2
$\Delta = \frac{(V/2)L^3}{3EI}$
$\frac{V}{\Delta} = 6\frac{EI}{L^3}$
$P_{e,story} = \frac{\pi^2}{2}\left(\frac{1}{6}\frac{V}{\Delta}\right)L$
$P_{e,story} = 0.82\frac{V}{\Delta}L$
45


P-Δ (4)
AISC factor to account for P-Δ at each story
$\Delta_{\Sigma V_i}$
L
V_1 V_2 V_3
P_1 P_2 P_3
$B_2 = \frac{1}{1-\frac{P_{story}}{P_{e,story}}}$
with: $P_{story} = \sum_{i=1}^{3} P_i$ and $P_{e,story} = R_M \frac{\Sigma V_i}{\Delta_{\Sigma V_i}} L$
46

Stability Sensitive Structural Systems

- Indicators include:
  - B_1 and B_2 factors
  - Elastic/Inelastic critical buckling load factors λ_{cr} and mode shapes
  - Natural periods and mode shapes

$$B_2 = \frac{1}{1 - \frac{\alpha P_{story}}{P_{e\ story}}} \qquad P_{e\ story} = R_M \frac{HL}{\Delta_H}$$

- Eurocode uses ratio λ_{cr} (think LBA) between the the critical buckling loading and applied loading :
  - $\lambda_{cr} < 3$, must employ rigorous 2nd-order analysis ($B_2 > 1.5$)
  - $3 \leq \lambda_{cr} < 10$, approximate methods acceptable
  - $\lambda_{cr} \geq 10$, no need to consider P-Δ effects ($B_2 < 1.1$)

47

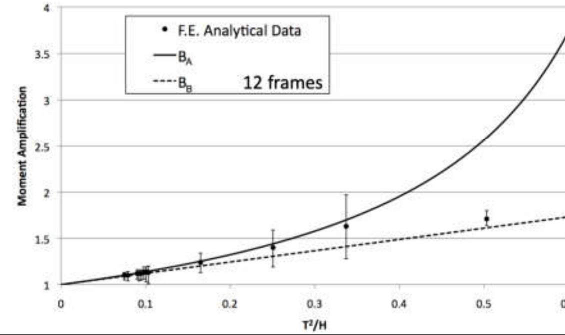
$$B_A = \frac{1}{1 - \frac{3gT^2}{8\pi^2 H}}$$

$$B_B = 1 + \frac{3gT^2}{8\pi^2 H}$$

Proceedings of the Annual Stability Conference
Structural Stability Research Council
Pittsburgh, Pennsylvania, May 10-14, 2011

The Natural Period as an Indicator of Second-Order Effects

D.E. Statler[1], R.D. Ziemian[2], L.E Robertson[3]



Note: Most important to also plot the mode shape

48

Stability Sensitive Structural Systems

- Indicators include:
  - B_1 and B_2 factors
  - Elastic/Inelastic critical buckling load factors λ_{cr} and mode shapes
  - Natural periods and mode shapes

$$B_2 = \frac{1}{1 - \frac{\alpha P_{story}}{P_{e\ story}}} \qquad P_{e\ story} = R_M \frac{HL}{\Delta_H}$$

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  - $3 \leq \lambda_{cr} < 10$, approximate methods acceptable
  - $\lambda_{cr} \geq 10$, no need to consider P-Δ effects ($B_2 < 1.1$)

49

AISC's Stability Provisions!

"Any rational method of design for stability… is permitted" with AISC code provisions for

- ✓ Effective length K-factor method (staple of profession since 1960)
- ✓ Direct analysis method (now becoming staple of the profession)

– Connection flexibility
– Strain Hardening
– Contributions of slab to streng[th] and stiffness
- Load effects
  – Proportional vs. Non-proportio[nal] loading
  – Variable repeated loading
  – Dynamic effects

C1. GENERAL STABILITY REQUIREMENTS

Stability shall be provided for the structure as a whole and for each of its elements. The effects of all of the following on the stability of the structure and its elements shall be considered: (1) flexural, shear and axial member deformations, and all other deformations that contribute to displacements of the structure; (2) *second-order effects* (both *P*-Δ and *P*-δ *effects*); (3) geometric imperfections; (4) *stiffness* reductions due to inelasticity; and (5) uncertainty in stiffness and strength. All *load*-dependent effects shall be calculated at a level of loading corresponding to *LRFD load combinations* or 1.6 times *ASD load combinations*.

Any rational method of design for stability that considers all of the listed effects is permitted; this includes the methods identified in Sections C1.1 and C1.2.

50

"Buckling" Design Methods:

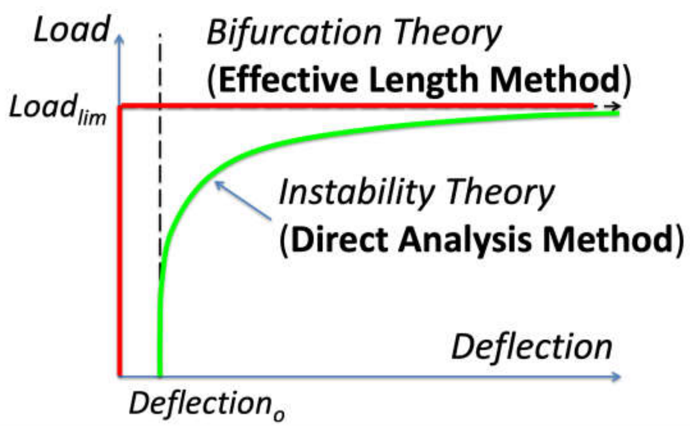


Figure applicable to system and member behavior

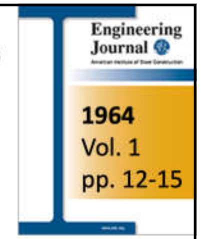
51

Effective Column Length—Tier Buildings

T. R. HIGGINS

SUMMARY

The trend in modern tier building construction away from heavy masonry exterior walls and substantial tight ...



New lighter systems warrant K > 1

...no worries, nomographs to assist...designers will gain experience and develop a feel for the problem as they have for other design rules in the past...

for the problem as they have developed a feel for the design of structural members under the more familiar rules of the past.

K-factors first appearing in 1961 AISC Specification

52

Effective Length Method

Analysis for load effects:

- Equilibrium on deformed shape

$$R_u \leq \phi R_n$$

Based on bifurcation theory (binary buckling)

- Effective lengths account for all effects known to impact system and member instability
- Given the correct effective length of all compression members, this method has been proven acceptable (55+ years of use!)

53

Effective Length Method

2nd-order elastic analysis

For $\dfrac{P}{P_n} \geq 0.2, \quad \dfrac{P}{P_n} + \dfrac{8}{9}\dfrac{M}{M_n} \leq 1.0$

P_n based on effective length $L_c = KL$, with $K \geq 1$:

comparing KL/r to $4.71\sqrt{E/\sigma_y}$

$$\sigma_{cr} = 0.658^{\frac{\sigma_y}{\sigma_e}}\sigma_y$$

or

$$\sigma_{cr} = 0.877\sigma_e$$

$$\sigma_e = \frac{\pi^2 E}{(KL/r)^2}$$

Effects on system stability:

- flexural, shear, axial deformations
- second-order effects
- geometric imperfections
- stiffness reductions due to inelasticity

54

Effective Length Method

- Does the K-factor really account for those system stability effects?
  - Indirectly, through its conservatism…
- Common methods for computing *K*-factors
  - Alignment charts or modifications based on undoing inherent assumptions
    - be very careful!
  - Buckling or critical load analyses (eigenvalue)
    - $KL = \pi\sqrt{EI/P}$
    - be very careful!
- How confident are you in your *K*-factors???

55

Effective Length Method

- Does the K-factor really account for those system stability effects?
  - Indirectly, through its conservatism…
- Common methods for computing *K*-factors
  - Alignment charts or modifications based on undoing inherent assumptions
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  - Buckling or critical load analyses (eigenvalue)
    - $KL = \pi\sqrt{EI/P}$
    - be very careful!
- How confident are you in your *K*-factors???

56

Effective Length Method

- Does the K-factor really account for those system stability effects?
  - Indirectly, through its conservatism…
- Common methods for computing *K*-factors
  - Alignment charts or modifications based on undoing inherent assumptions
    - be very careful!
  - Buckling or critical load analyses (eigenvalue)
    - $KL = \pi\sqrt{EI/P}$
    - be very careful!
- How confident are you in your *K*-factors???

57

Effective Length Method

- Resources for improving odds of computing accurate *K*'s
  - ASCE Task Committee on Effective Length (1997), *Effective Length and Notional Load Approaches for Assessing Frame Stability: Implications for American Steel Design*, American Society of Civil Engineers. [Ed. Jerry Hajjar]
  - Ziemian, R.D. (ed.) (2010), *Guide to Stability Design Criteria for Metal Structures*, 6th Ed., John Wiley & Sons, Inc.

KL/r → P_n = #

ꓘL/r → q_n= ??

58

"General" Direct Analysis Method

Analysis for load effects:

- Equilibrium on deformed shape

$$R_u \leq \phi R_n$$

Based on instability theory
stiffness ↓
deflections ↑
bending moments ↑

- By directly modeling effects known to impact system, member, and cross-section instability, simplifications are granted in computing design resistance
- Design process will not permit system, member, and cross-section instabilities

59

General Direct Analysis Method

Primary effects:

- All pertinent deformations
- Equilibrium on the deformed shape (P-δ and P-Δ)
- Initial imperfections (system and component)
- Yielding accentuated by residual stresses
- F/M redistribution from relative stiffness changes

- By directly modeling effects known to impact system, member, and cross-section instability, simplifications are granted in computing design resistance
- Design process will not permit system, member, and cross-section instabilities

60

AISC's Direct Analysis Method

Analysis for load effects:

- Equilibrium on deformed shape

$$R_u \leq \phi R_n$$

Based on instability theory (approaching buckling)
stiffness ↓
deflections ↑
bending ↑

- By directly modeling effects known to impact system, member, ~~and cross-section~~ instability, simplifications are granted in computing design resistance
- Design process will not permit system, member, ~~and cross-section~~ instabilities

61

AISC's Direct Analysis Method (2005-16)

Elastic Analysis for load effects:

Effects modeled:

- All pertinent deformations
- Equilibrium on deformed shape (P-δ and P-Δ)
- Initial system imperfections (out-of-plumb)
- Yielding accentuated by residual stresses (0.8τ)

- By directly modeling effects known to impact system, member, ~~and cross~~ simplifications are granted resistance
- Design process will not per ~~cross-section~~ instabilities

Simplification granted:

- Flexural compressive strength P_n is based on unbraced length (L_c=L)

DM 62

Direct Analysis Method

2nd-order "elastic" analysis

For $\frac{P}{P_n} \geq 0.2, \quad \frac{P}{P_n} + \frac{8}{9}\frac{M}{M_n} \leq 1.0$

P_n based on effective length L_c, with $\boldsymbol{L_c = L}$

Effects on system stability:
- flexural, shear, axial deformations
- second-order effects
- geometric imperfections
- stiffness reductions due to inelasticity

63

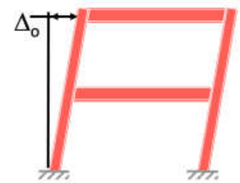
Direct Analysis Method (2)

2nd-order "elastic" analysis

For $\frac{P}{P_n} \geq 0.2, \quad \frac{P}{P_n} + \frac{8}{9}\frac{M}{M_n} \leq 1.0$

Effects on system stability:
- geometric imperfections

1. Member out-of-straightness accounted for in column curve
2. Frame out-of-plumb

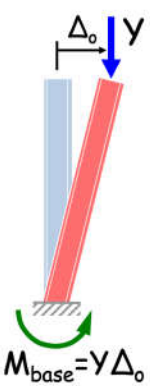


Direct Modeling: distort computational model to include maximum amount considered in design (e.g. AISC *Code of Standard Practice*, $\Delta_o \leq H/500$)

Notional Loads: represent effect of imperfection by equivalent lateral load of $N_i = 0.002Y_i$ for level *i*

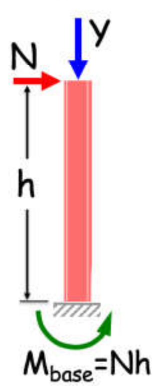
64

Direct Modeling:



Wait! Where did that equivalent notional load come from?

Notional Load:



Require equivalent base moments:

$M_{base} = Y\Delta_o = Nh$

or $N = Y\Delta_o/h$

with $\Delta_o = h/500$

$N = Y(h/500)/h$

$N = 0.002Y$

65

Direct Analysis Method (3)

2nd-order "elastic" analysis

For $\frac{P}{P_n} \geq 0.2, \quad \frac{P}{P_n} + \frac{8}{9}\frac{M}{M_n} \leq 1.0$

Effects on system stability:
- stiffness reductions due to inelasticity

Loss in stiffness due to partial yielding accentuated by presence of residual stresses

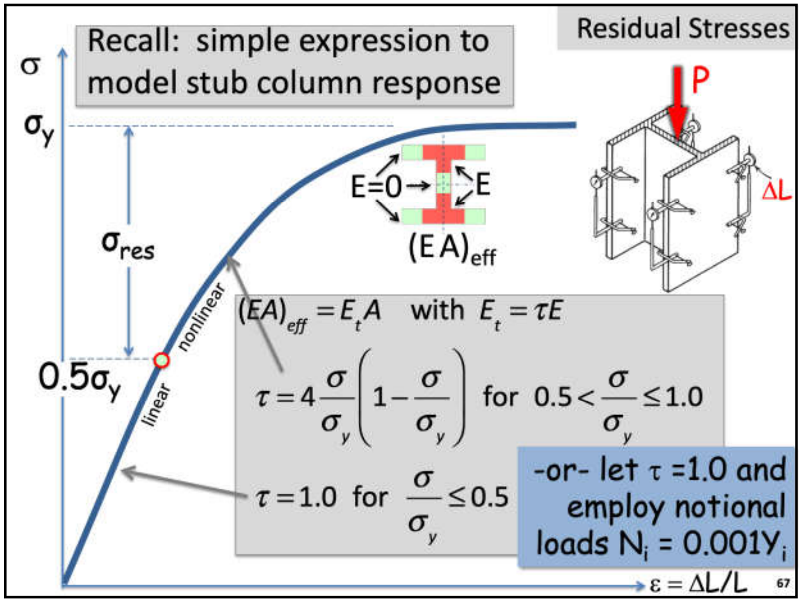
From extensive studies calibrating DM to advanced FEA results

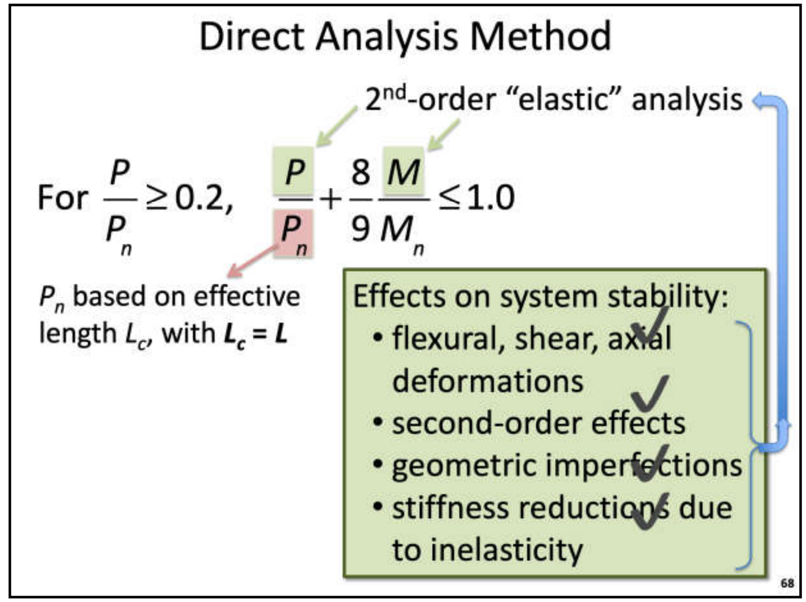
(0.8 is applied to all stiffness contributing to system stability)

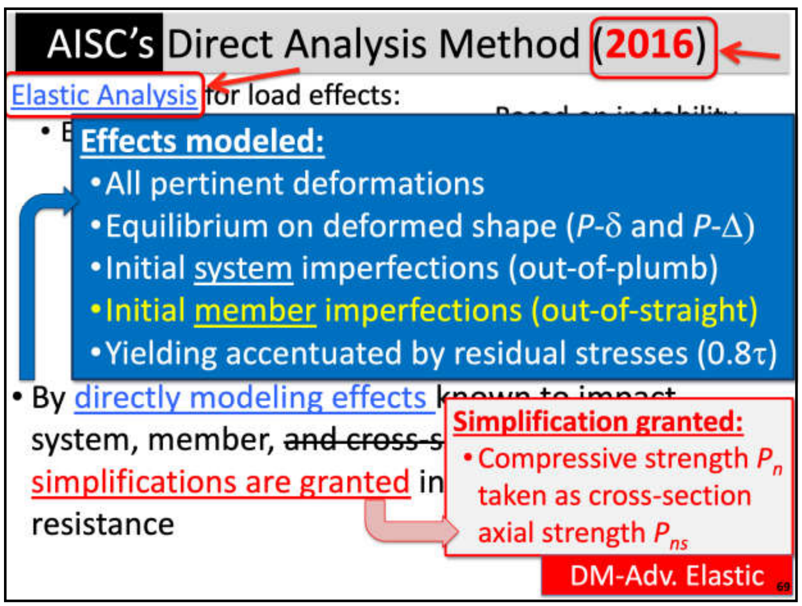
$$(EI)_{analysis} = 0.8\tau(EI)$$

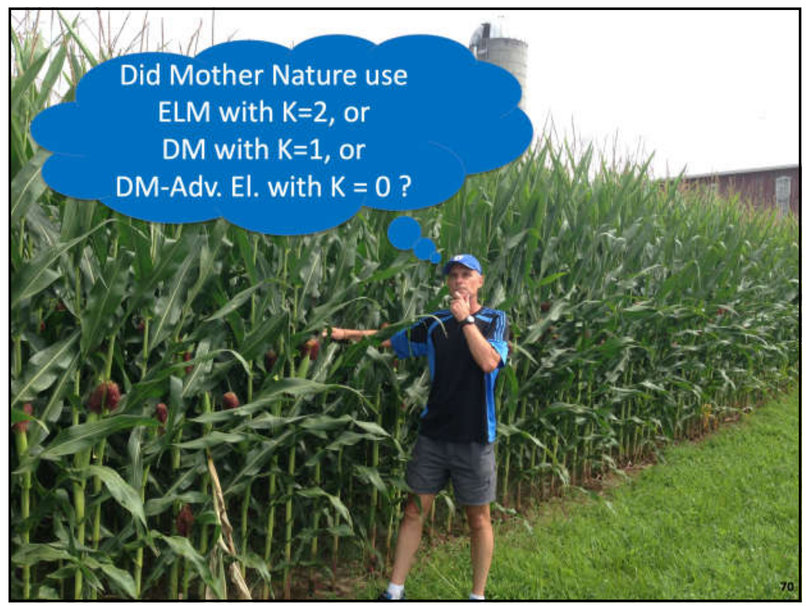
Think back to compression slides...

66


Residual Stresses
Recall: simple expression to model stub column response
σ
σy
σres
0.5σy
linear
nonlinear
E=0
E
(EA)eff
P
ΔL
$(EA)_{eff} = E_t A$ with $E_t = \tau E$
$\tau = 4\frac{\sigma}{\sigma_y}\left(1 - \frac{\sigma}{\sigma_y}\right)$ for $0.5 < \frac{\sigma}{\sigma_y} \le 1.0$
$\tau = 1.0$ for $\frac{\sigma}{\sigma_y} \le 0.5$
-or- let τ =1.0 and employ notional loads $N_i = 0.001Y_i$
ε = ΔL/L
67


Direct Analysis Method
2nd-order "elastic" analysis
For $\frac{P}{P_n} \ge 0.2$, $\frac{P}{P_n} + \frac{8}{9}\frac{M}{M_n} \le 1.0$
P_n based on effective length L_c, with $L_c = L$
Effects on system stability:
• flexural, shear, axial deformations
• second-order effects
• geometric imperfections
• stiffness reductions due to inelasticity
68


AISC's Direct Analysis Method (2016)
Elastic Analysis for load effects:
Effects modeled:
•All pertinent deformations
•Equilibrium on deformed shape (P-δ and P-Δ)
•Initial system imperfections (out-of-plumb)
•Initial member imperfections (out-of-straight)
•Yielding accentuated by residual stresses (0.8τ)
• By directly modeling effects known to impact system, member, and cross-s
simplifications are granted in
resistance
Simplification granted:
•Compressive strength P_n taken as cross-section axial strength P_{ns}
DM-Adv. Elastic
69


Did Mother Nature use
ELM with K=2, or
DM with K=1, or
DM-Adv. El. with K = 0 ?
70

AISC Interaction Equation

The big tradeoff!

M_u increasing ↓
ELM
DM (Δ_o,0.8τ)
DM-Adv. El. (Δ_o,0.8τ,δ_o)

$$\frac{P_u}{\phi P_n} + \frac{8}{9}\frac{M_u}{\phi M_n} \leq 1.0$$

P_n increasing ↓
ELM (L_c=KL,K>1)
DM (L_c=L)
Adv. El. (P_n=$A_e F_y$)

Methods often give very similar designs

71

AISC's Direct Analysis Method (2010-16)

Inelastic Analysis for load effects:

Based on instability

- Eq…

Effects modeled:
- All pertinent deformations
- Equilibrium on deformed shape (*P*-δ and *P*-Δ)
- Initial system and member imperfections
- Yielding and residual stresses (directly modeled)
- Redistribution of stresses (F/M's) resulting from changes in relative stiffness distributions

- By directly modeling effects known to impact system, member, ~~and cross-section~~ instability, simplifications are granted in compu…
- De… se…

DM-Adv. Inelastic

Simplifications granted:
- Specification design equations waived
- Go beyond first-plastic hinge!

72

Additional thoughts…

- Automated modeling and analysis is not the objective, more opportunities for better engineering is the aim
- Goal is to improve design process by providing a more detailed, and hopefully more "realistic" understanding of structural behavior…
- Real question is *where does an engineer have the most knowledge and confidence for a given design situation*?

More — Prescriptive specification equations — Less
Given Design Situation
Less — Directly modeling effects impacting stability — More

73

Additional thoughts…

- Automated modeling and analysis is not the objective, more opportunities for better engineering is the aim
- Goal is to improve design process by providing a more detailed, and hopefully more "realistic" understanding of structural behavior…
- Real question is *where does an engineer have the most knowledge and confidence for a given design situation*?

More — Prescriptive specification equations — Less
Given Design Situation
Less — Directly modeling effects impacting stability — More

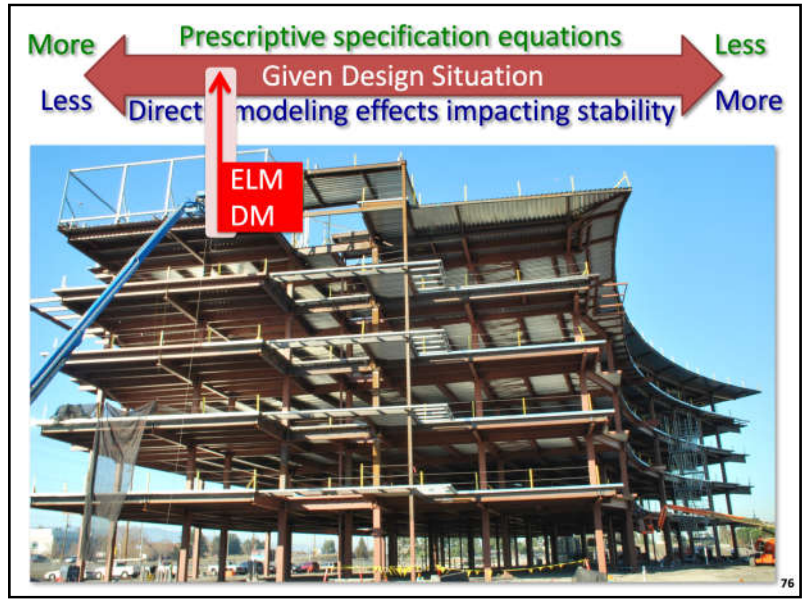
74

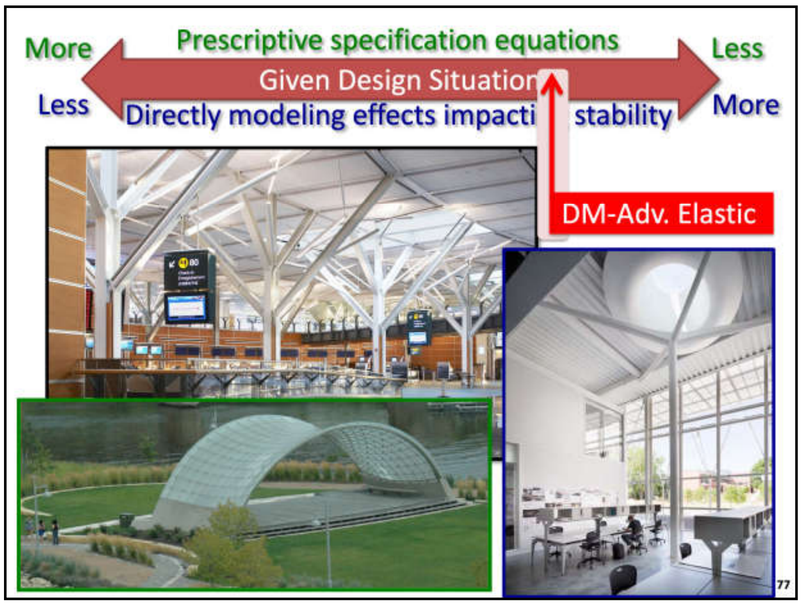
Additional thoughts on DM…

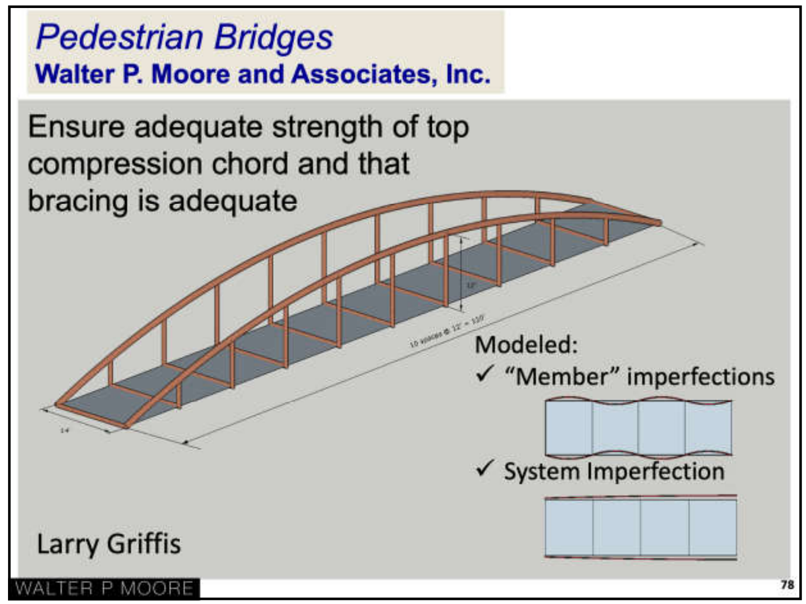
- Automated modeling and analysis is not the objective, more opportunities for better engineering is the aim
- Goal is to improve design process by providing a more detailed, and hopefully more "realistic" understanding of structural behavior…
- Real question is *where does an engineer have the most knowledge and confidence for a given design situation?*

More — Prescriptive specification equations — Less
Given Design Situation
Less — Directly modeling effects impacting stability — More

75



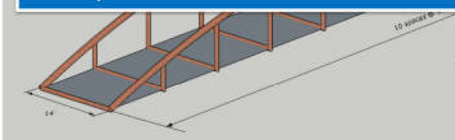




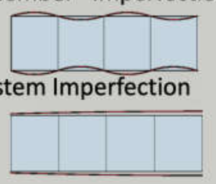
Pedestrian Bridges

Design by Advanced Elastic Analysis (AISC App 1.2):

- Initial system imperfections (out-of-plumb)
- Initial member imperfections (out-of-straightness)
- Yielding accentuated by presence of residual stresses approximated by reducing member stiffness by 0.8τ
- Rigorous 2nd-order elastic analysis (GNIA)
- Only need to confirm cross-section strengths (P_n=P_{ns})



Modeled:
✓ "Member" imperfections
✓ System Imperfection



Larry Griffis

WALTER P MOORE

79

More — Prescriptive specification equations — Less
Given Design Situation
Less — Directly modeling effects impacting stabil — More

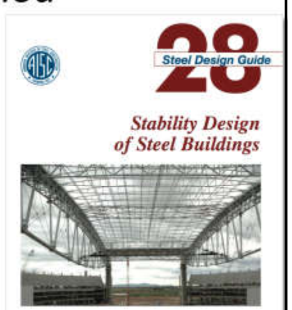
DM-Inelastic

80

More — Prescriptive specification equations — Less
Given Design Situation
Less — Directly modeling effects impacting stability — More

AISC's *Direct Analysis Method* provides a wide range of design opportunities…

✓ Elastic Analysis (Ch. C)
✓ Design by Advanced Elastic Analysis (App. 1.2)
✓ Design by Advanced Inelastic Analysis (App. 1.3)



Larry Griffis
Don White

81

Summary – Systems

- Fundamentals of Stability
  - Compression (Lectures 1 & 2)
  - Flexural (Lectures 3 & 4)
  - Combined compression and flexure (Lectures 5 & 6)
  - Systems (today! and Lecture 8)
- Factors impacting system stability
  - flexural, shear, axial deformations
  - second-order effects (equilibrium on deformed shape!)
    - rigorous analysis vs. amplification factors B_1 and B_2
  - geometric imperfections
  - stiffness reductions due to inelasticity

82

Summary – Systems (cont.)

- Basis for Design of Systems
  - Elastic Analysis (AISC Spec., Chs. A-K, Apps. 1,6-8)
    - strength of system is assured by ensuring adequate strength of its components
  - Inelastic Analysis (AISC Spec., Appendix 1)
    - System strength (stability) can be assessed directly by the analysis
- AISC Methods (lots of options!)
  - Effective Length Method (LBA and GNA)
  - Direct Analysis Method
    - 3 methods based on elastic analysis (GNIA and LA)
    - 1 method on inelastic analysis (GMNIA)

83

Summary – Systems (cont.)

- Finally, if you still do not have confidence that your structural system is stable, then you can always…

Your virtual laboratory assignment…
- Rerun examples presented in this lecture
- Complete a portion of Learning Module 9

84

Thank You!

Hope you enjoyed this lecture!

Smarter. Stronger. Steel.

Single-Session Registrants

CEU / PDH Certificates

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

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Single-Session Registrants

CEU / PDH Certificates

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

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8-Session Registrants

CEU / PDH Certificates

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

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8-Session Registrants

Attendance and PDH Certificates

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

Videos and Quizzes

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

Distribution of Certificates

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

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8-Session Registrants

Course Resources

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

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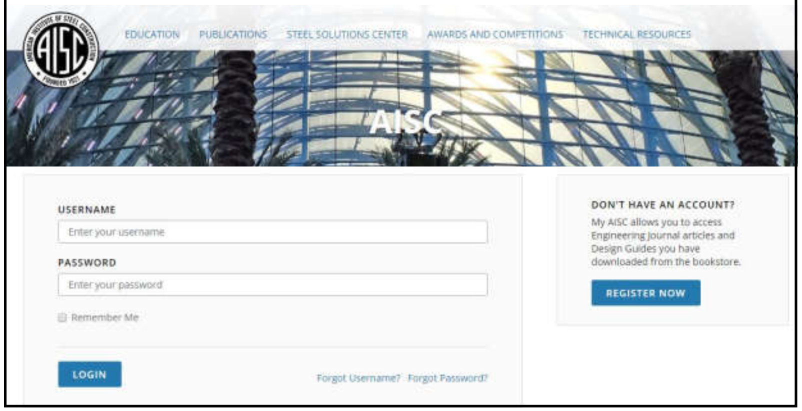
8-Session Registrants

Course Resources

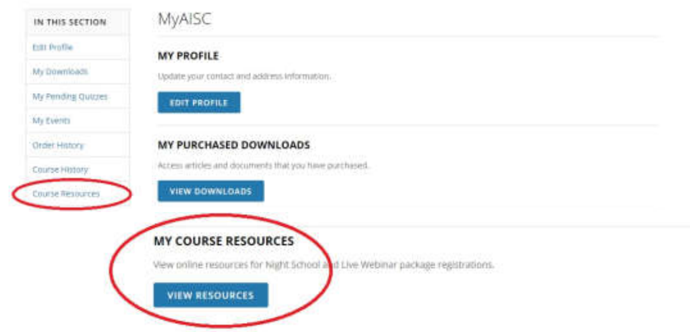
Go to www.aisc.org and sign in.



8-Session Registrants

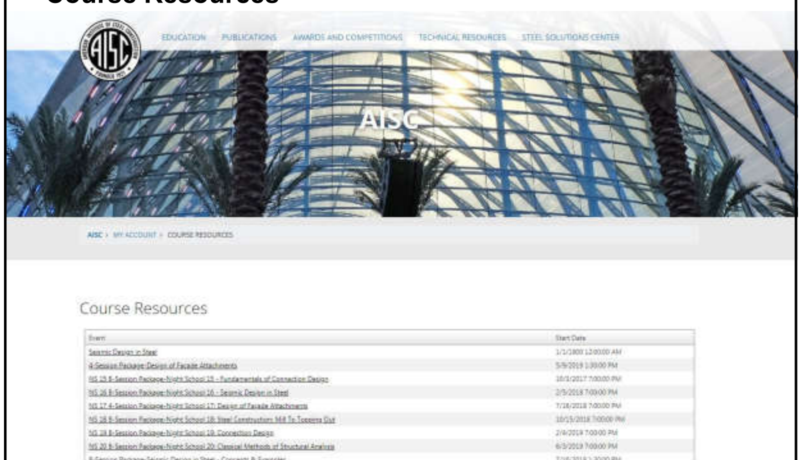
Course Resources

Go to www.aisc.org and sign in.



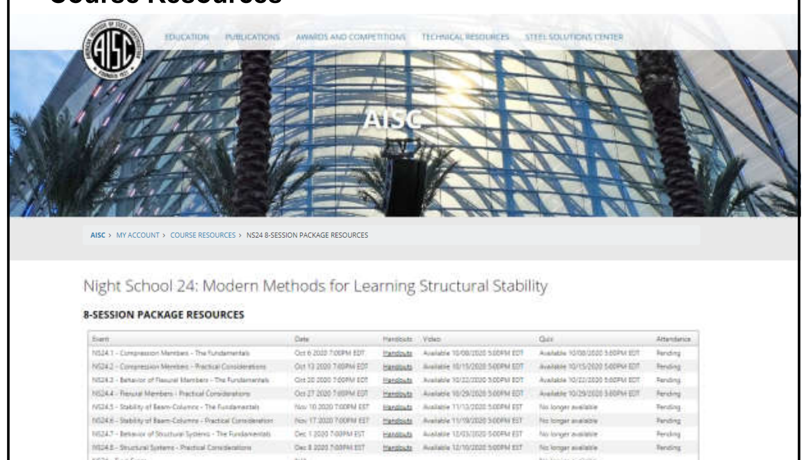
8-Session Registrants

Course Resources



8-Session Registrants

Course Resources




AISC | Thank you.
Smarter.
Stronger.
Steel.