AISC Live Webinars

Structural Stability –
Letting the Fundamentals Guide Your Judgement
April 16, 2020

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Course Description

Structural Stability – Letting the Fundamentals Guide Your Judgement
April 16, 2020

One of the great things about working with structural steel is that most design provisions are based on first principles and fairly predictable experimental test results. This is especially true when assessing structural stability. The primary objective of this lecture is to show how most stability problems can be understood by focusing on the big picture rather than on the details of the seemingly complex mathematics. The presentation will begin by identifying those factors that primarily impact the buckling strength of a system, member, or cross section. Drawing on several example applications, the proper use of today's computational analysis tools will be demonstrated as a means for enhancing engineering judgement.
A case will be made for how a fundamental understanding of structural stability is often sufficient for today's steel designers, whether applying the direct analysis method to assess system strength or a column curve to evaluate the strength of a compression member. The lecture will also include an overview of the author's paper "Formulation and Validation of Minimum Brace Stiffness for Systems of Compression Members."

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Learning Objectives

- List the five factors that influence frame stability, the effects of which are required to be considered by AISC *Specification* Section C1.
- Identify indicators for assessing whether a structure is a stability-sensitive system.
- Explain the modeling considerations for direct analysis by advanced elastic analysis and inelastic analysis methods, and the repercussions for determining member capacity.
- Describe how the configuration of a system of stability braces in series affects the required stiffness of the individual brace.

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Structural Stability –
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April 16, 2020

Ronald D. Ziemian, PhD, PE
Professor
Bucknell University
Lewisburg, PA

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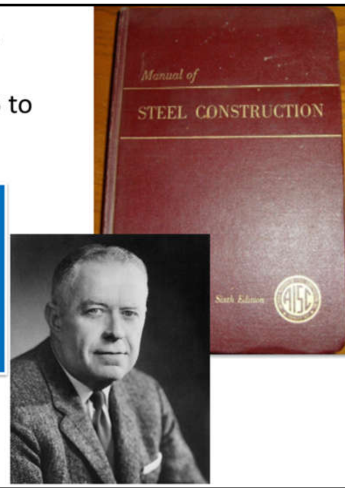
Structural Stability –
Letting the Fundamentals Guide Your Judgement

Ron Ziemian

2019 TR Higgins Award Lecture

T.R. HIGGINS was AISC's director of Engineering and Research from 1945 to 1968…

New to the 6th edition
- Effective length concept
- M-amplification factors
- Plastic design
- Semi-tension field theory
- etc.



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Structural Stability –
Letting the Fundamentals Guide Your Judgement

Some thoughts on…

FUNDAMENTALS AND JUDGEMENT

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The fundamentals…stabilty

- Force follows stiffness (wet spaghetti test!)
- Basis for every structural analysis

Yes, I know the room is full of brilliant engineers, but please allow me to start here…

- Behavior of steel structures
  - Material level
  - Cross-section, Member, System level

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The fundamentals…stabilty

- Force follows stiffness (wet spaghetti test!)
- Basis for every structural analysis
  - Equilibrium ("forces" must be in agreement!)
  - Compatibility ("displacements" must be in agreement)
  - Constitutive Relationship ("forces" -to- "displacements")
- Superposition – always so tempting!
  - Linear response (geometric and material)
  - Serviceability (yeah!) vs. ultimate strength (instability?!)
- Behavior of steel structures
  - Material level
  - Cross-section, Member, System level

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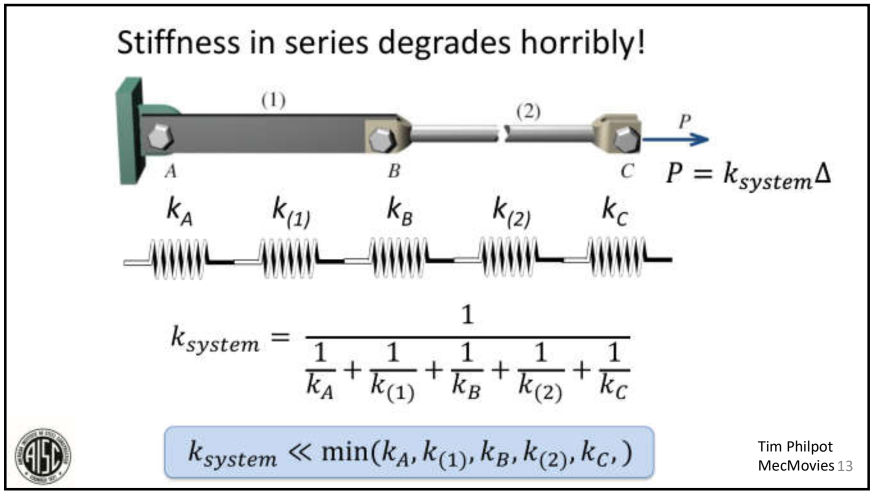
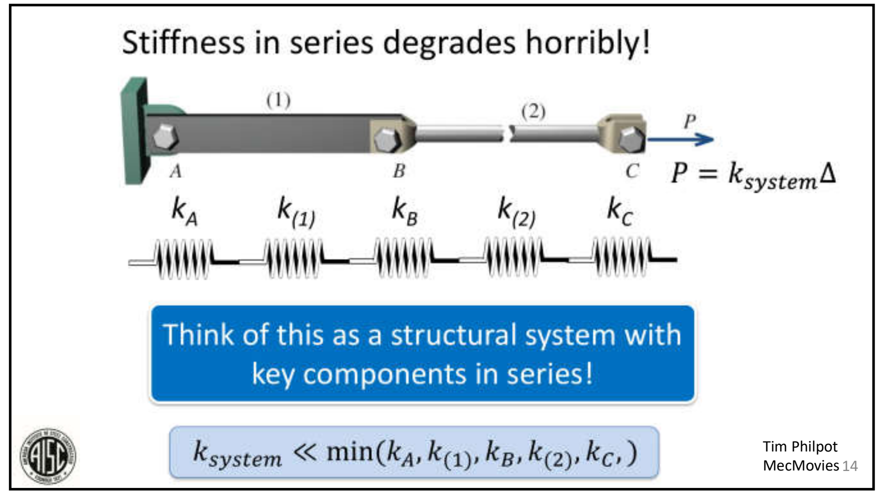
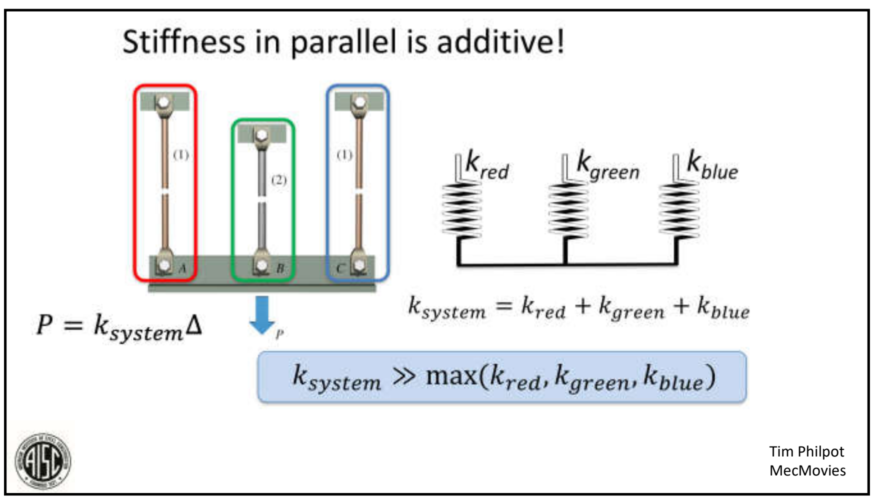
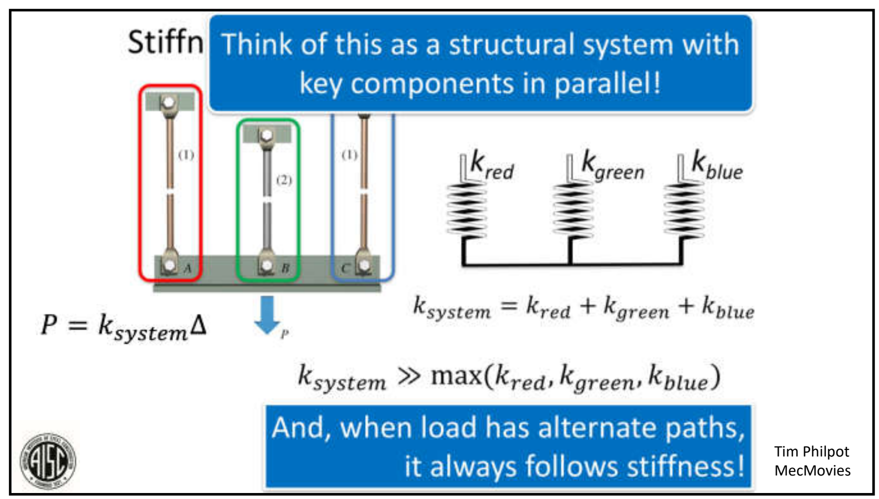

Stiffness in series degrades horribly!
(1)
(2)
P
A
B
C
$P = k_{system}\Delta$
k_A
$k_{(1)}$
k_B
$k_{(2)}$
k_C
$k_{system} = \frac{1}{\frac{1}{k_A} + \frac{1}{k_{(1)}} + \frac{1}{k_B} + \frac{1}{k_{(2)}} + \frac{1}{k_C}}$
$k_{system} \ll \min(k_A, k_{(1)}, k_B, k_{(2)}, k_C,)$
Tim Philpot
MecMovies 13


Stiffness in series degrades horribly!
(1)
(2)
P
A
B
C
$P = k_{system}\Delta$
k_A
$k_{(1)}$
k_B
$k_{(2)}$
k_C
Think of this as a structural system with key components in series!
$k_{system} \ll \min(k_A, k_{(1)}, k_B, k_{(2)}, k_C,)$
Tim Philpot
MecMovies 14


Stiffness in parallel is additive!
(1)
(2)
(1)
A
B
C
P
k_{red}
k_{green}
k_{blue}
$P = k_{system}\Delta$
$k_{system} = k_{red} + k_{green} + k_{blue}$
$k_{system} \gg \max(k_{red}, k_{green}, k_{blue})$
Tim Philpot
MecMovies


Stiffn
Think of this as a structural system with key components in parallel!
(1)
(2)
(1)
A
B
C
P
k_{red}
k_{green}
k_{blue}
$P = k_{system}\Delta$
$k_{system} = k_{red} + k_{green} + k_{blue}$
$k_{system} \gg \max(k_{red}, k_{green}, k_{blue})$
And, when load has alternate paths, it always follows stiffness!
Tim Philpot
MecMovies

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  - Material level
  - Cross-section, Member, System level

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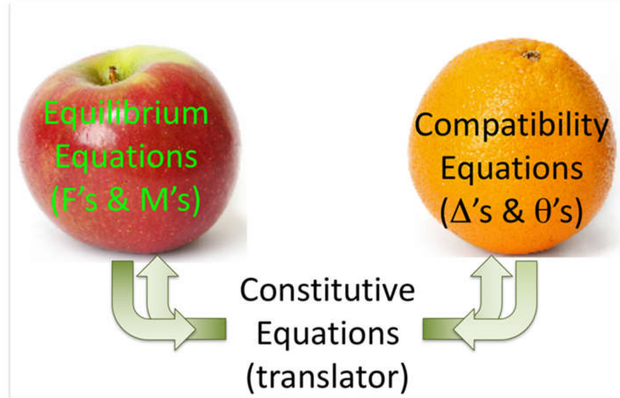
The fundamentals…



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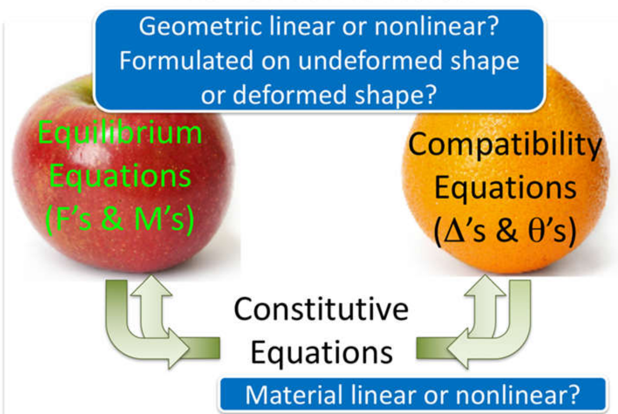
The fundamentals…



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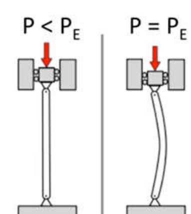
First stability analysis…

- Leonhard Euler, 1744 and 1757
- Assumptions!
  - prismatic member (I = constant)
  - small deflections after buckling
  - no bending prior to bifurcation
    - perfectly straight
    - concentrically loaded
  - linear elastic behavior (E = constant)
  - pinned-roller supports (frictionless)



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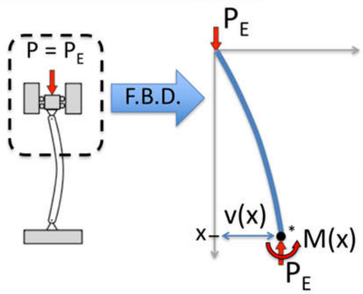
Euler Buckling (2)



Equilibrium:

$$\Sigma M_* = 0$$

$$M(x) + P_E v(x) = 0$$

Moment-curvature: (constitutive rel.)

$$M(x) = EI\frac{d^2 v(x)}{dx^2}$$

Solution:

$$EI\frac{d^2 v}{dx^2} + P_E v = 0 \Rightarrow v(x) = C_1 \cos\left(\sqrt{\frac{P_E}{EI}}x\right) + C_2 \sin\left(\sqrt{\frac{P_E}{EI}}x\right)$$

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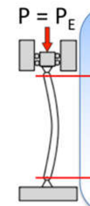
Euler Buckling (3)

$$v(x) = C_1 \cos\left(\sqrt{\frac{P_E}{EI}}x\right) + C_2 \sin\left(\sqrt{\frac{P_E}{EI}}x\right)$$



Compatibility:

$$v(x=0) = 0 \Rightarrow C_1 = 0 \Rightarrow v(x) = C_2 \sin\left(\sqrt{\frac{P_E}{EI}}x\right)$$

Boundary Conditions!

$$v(x=L) = 0 \Rightarrow v(x=L) = 0 = C_2 \sin\left(\sqrt{\frac{P_E}{EI}}L\right)$$

1) $C_2 = 0$ "trivial solution"

2) $\sin\left(\sqrt{\frac{P_E}{EI}}L\right) = 0 \Rightarrow \sqrt{\frac{P_E}{EI}}L = n\pi \Rightarrow P_E = \frac{n^2 \pi^2 EI}{L^2}$, $n = 1, 2, 3, \ldots$

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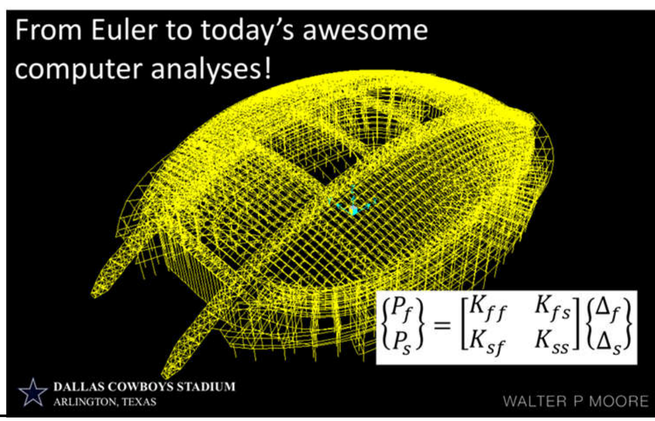
Equilibrium, Compatibility, Constitutive…



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The fundamentals…stabilty

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The fundamentals…stabilty

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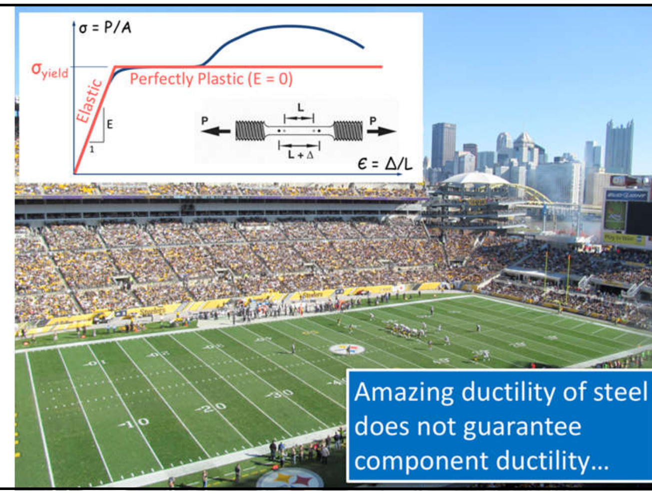

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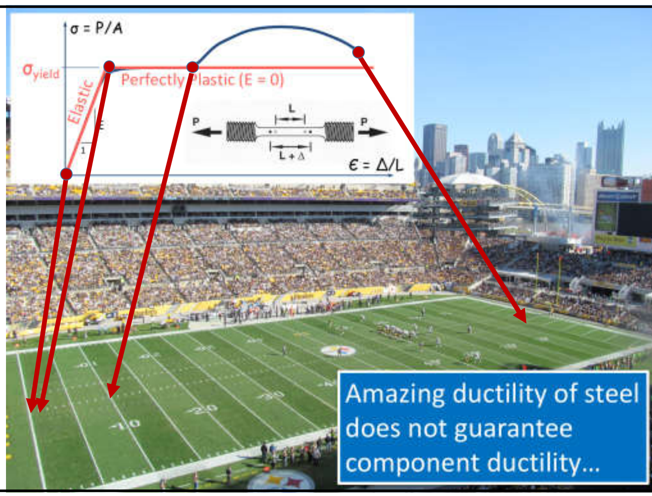

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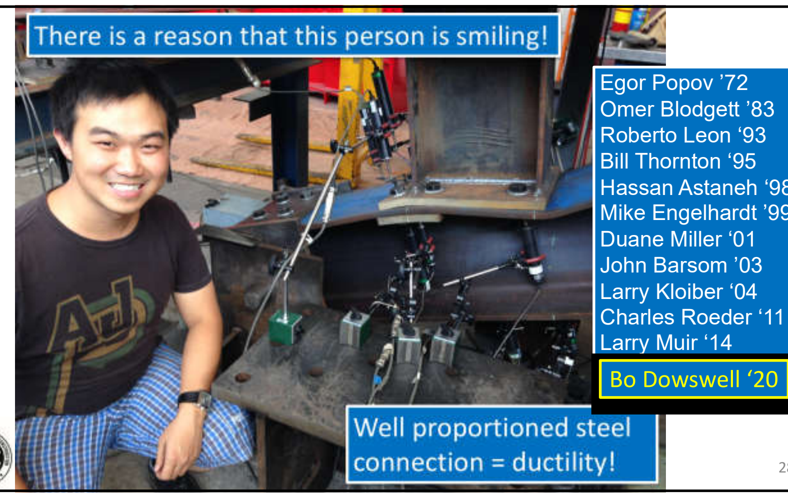

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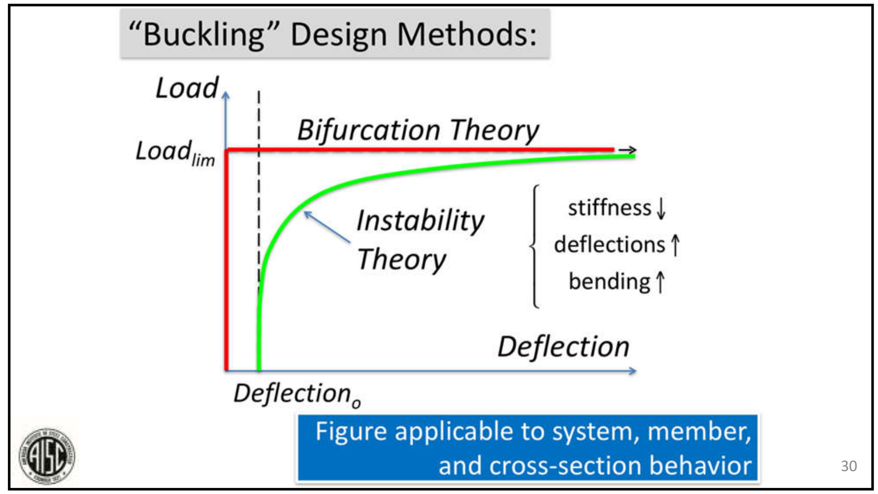
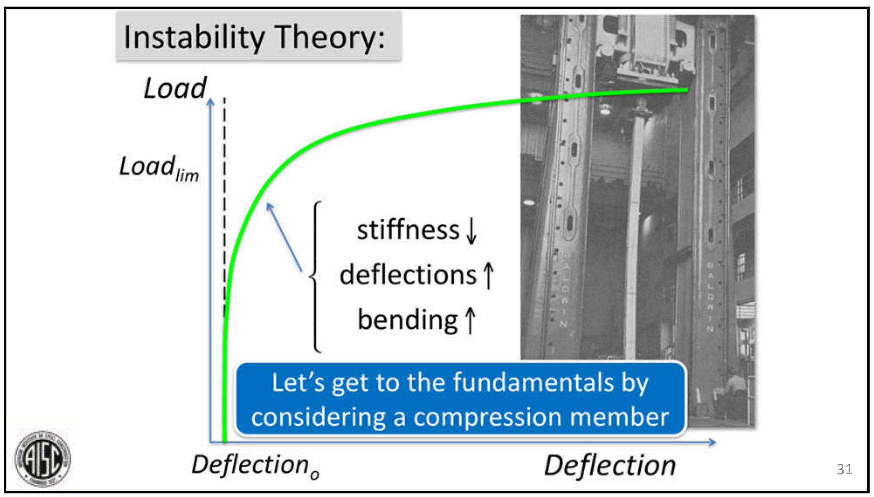
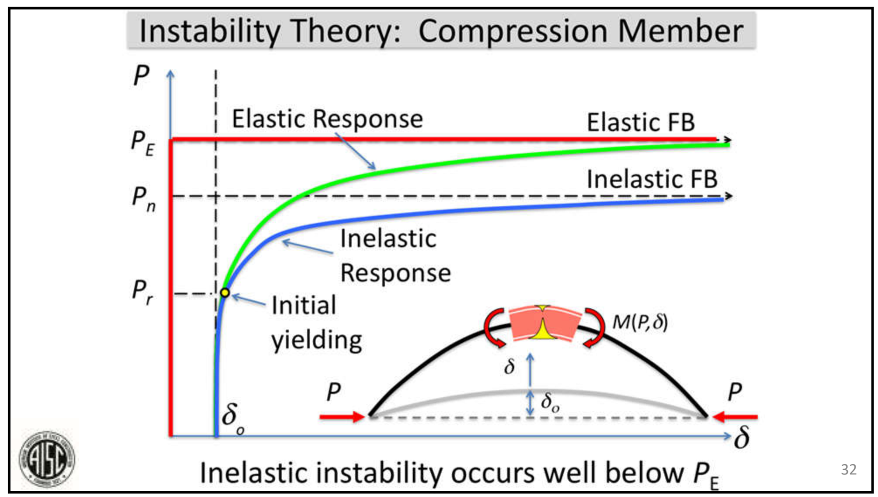
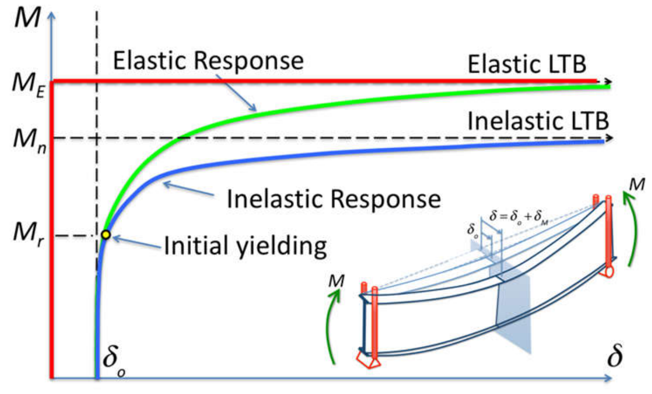
More fun of designing with steel:
Strength/ Weight
Stiffness/ Weight
Competitive $
Slender Systems, Members, and Cross-sections
Design for Stability!
29


"Buckling" Design Methods:
Load
Load$_{lim}$
Bifurcation Theory
Instability Theory
stiffness ↓
deflections ↑
bending ↑
Deflection
Deflection$_o$
Figure applicable to system, member, and cross-section behavior
30


Instability Theory:
Load
Load$_{lim}$
stiffness ↓
deflections ↑
bending ↑
Let's get to the fundamentals by considering a compression member
Deflection$_o$
Deflection
31


Instability Theory: Compression Member
P
P_E
P_n
P_r
Elastic Response
Elastic FB
Inelastic FB
Inelastic Response
Initial yielding
M(P,δ)
δ
δ_o
P
P
δ
Inelastic instability occurs well below P_E
32

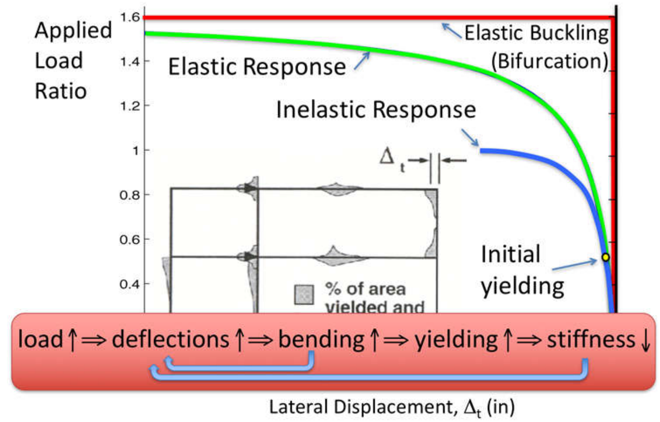
Instability Theory: Flexural Member



Inelastic instability occurs well below M_E

33

Instability Theory: Structural System



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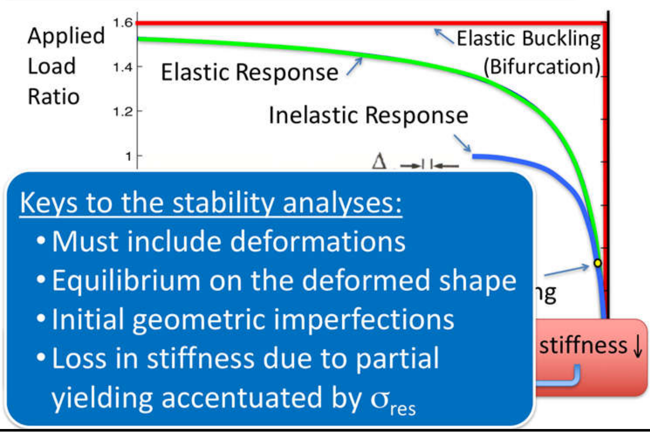
Instability Theory: Structural System



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

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Factors influencing frame stability

Birnstiel and Iffland, 1980

- 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

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.

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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

...bility. The *direct* ... Appendix 7.

C1. GENERAL STABILITY REQUIREMENTS

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The fundamentals…stabilty

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- ✓ Behavior of steel structures
  - ✓ Material level
  - ✓ Cross-section, Member, System level

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Structural Stability – Letting the Fundamentals Guide Your Judgement

- Embrace every opportunity!
- Must be constantly developed!
- Must be constantly questioned!
  - Assumptions made?
  - Satisfy equilibrium and compatibility
- Have conversations about your designs
  - Load paths
  - Ultimate strength failure modes
  - Plot deformed shapes and moment diagrams!
  - What-if scenarios?
- Comes with years of experience…
  - Be the mentor and the mentee

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Structural Stability – Letting the Fundamentals Guide Your Judgement

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  - Ultimate strength failure modes
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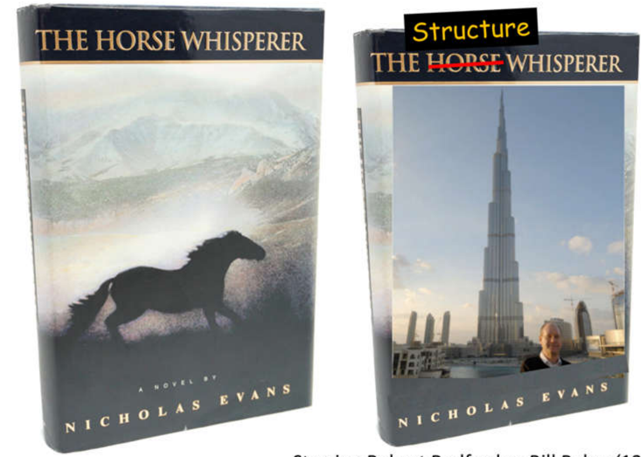

Starring Robert Redford as Bill Baker '13

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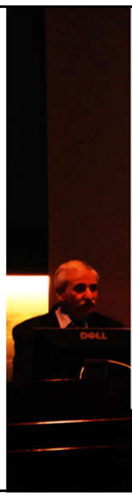

The structural engineer of the future?

- Increasing
  - building code prescription
  - computing and artificial intelligence capability

  threatens the very existence of structural engineering as a profession
- Performance-based design provides the opportunity for engineers to re-emerge as thinking professionals bringing value to the creation of structures

Performance-based Design, the profession's new hope?
Ronald O. Hamburger '06, Simpson Gumpertz & Heger Inc.
2016 Fazlur Kahn Lecture, Lehigh University

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What this means

You can design or build anything, whether it is in the code or not, or even prohibited by the code, providing that:

- You demonstrate the design is capable of achieving equivalent protection of the public with regard to:
  - Safety
  - Health
  - Fire spread
  - Structural Stability
  - Sanitation
- The burden is on the designer to demonstrate equivalence

Bah'ai Temple, Chile

Performance-based Design, the profession's new hope?
Ronald O. Hamburger '06, Simpson Gumpertz & Heger Inc.
2016 Fazlur Kahn Lecture, Lehigh University

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What this means

Ron Z's takeaway of Ron H's lecture…
In general, when judgement is no longer required and/or exercised, then so goes the need for the structural engineer…

- Structural Stability
- Sanitation
- The burden is on the designer to demonstrate equivalence

Bah'ai Temple, Chile

Performance-based Design, the profession's new hope?
Ronald O. Hamburger '06, Simpson Gumpertz & Heger Inc.
2016 Fazlur Kahn Lecture, Lehigh University

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Some thoughts on…

DESIGNING FOR STRUCTURAL STABILITY

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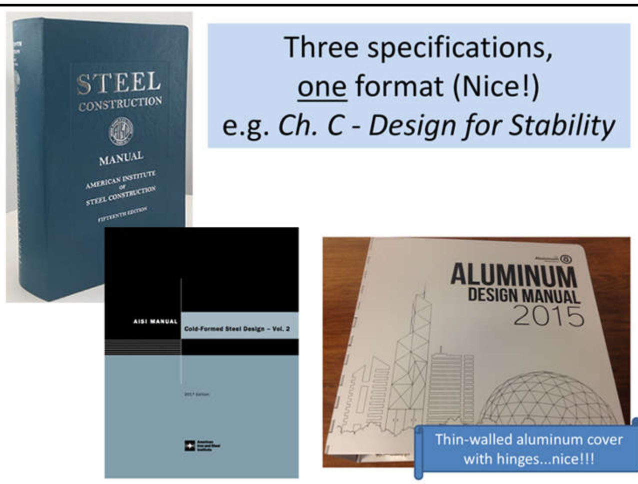
Three specifications,
one format (Nice!)
e.g. *Ch. C - Design for Stability*



Thin-walled aluminum cover with hinges…nice!!!

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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)

- 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
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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.

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"Buckling" Design Methods:

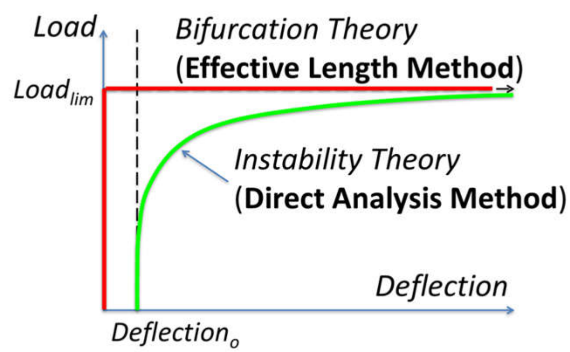

Figure applicable to system and member behavior

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General Stability Design Methods:

Analysis for load effects:

- Reality: Equilibrium on deformed shape

$$R_u \leq \phi R_n$$

Effective length method
- bifurcation theory

Direct analysis method
- instability theory

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

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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
    - $M = B_1M_{nt} + B_2M_{lt}$
- Approximate indicators of their significance
  - $P\delta$ provided by B_1
  - $P\Delta$ provided by B_2

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Stability Sensitive Structural Systems

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

- Indicators include:
  - B_1 and B_2 factors
  - Elastic/Inelastic critical buckling load factors λ_{cr} and mode shapes
  - Natural periods and mode shapes
- Eurocode uses ratio λ_{cr} between the the critical buckling loading and applied loading :
  - $\lambda_{cr} \geq 10$, no need to take into P-Δ effects ($B_2 < 1.1$).
  - $3 \leq \lambda_{cr} < 10$, approximate methods acceptable
  - $\lambda_{cr} < 3$, must employ rigorous 2nd-order analysis ($B_2 > 1.5$)

53

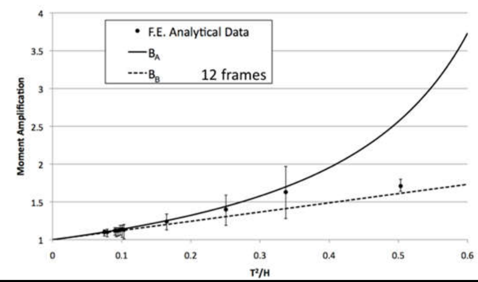
$$B_A = \frac{1}{1 - \frac{3gT^2}{8\pi^2 H}}$$

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

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

54

Stability Sensitive Structural Systems

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

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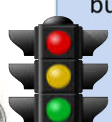

  - $\lambda_{cr} < 3$, must employ rigorous 2nd-order analysis ($B_2 > 1.5$)
  - $3 \leq \lambda_{cr} < 10$, approximate methods acceptable
  - $\lambda_{cr} \geq 10$, no need to take into P-Δ effects ($B_2 < 1.1$)

55

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!)

56

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

57

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???

58

Effective Length Method

- Does the K-factor really account for those system stability effects?
  - Indirectly, through its conservatism...
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Lou Geschwindner '00

59

Effective Length Method

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  - 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???

60

Effective Length Method

- Resources for improving odds of computing accurate *K*'s

Jerry Hajjar '07

  - 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.
  - 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 → ꟼ$_n$ = ??

61

"General" Direct Analysis Method

Shankar Nair '07

Analysis for load effects:

- Equilibrium on deformed shape

$$R_u \le \phi R_n$$

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

62

General Direct Analysis Method

Primary effects:

- All pertinent deformations
- Applied load and relative stiffness distribution
- 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

63

AISC's Direct Analysis Method

Analysis for load effects:

- Equilibrium on deformed shape

$$R_u \le \phi R_n$$

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

64

AISC's Direct Analysis Method (2005-16)

Elastic Analysis for load effects:

Effects modeled:
- All pertinent deformations
- Applied load and stiffness distribution
- 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 ($KL=L$)

DM

65

AISC's Direct Analysis Method (2016)

Elastic Analysis for load effects:

Effects modeled:
- All pertinent deformations
- Applied load and stiffness distribution
- Initial system imperfections (out-of-plumb)
- Initial member imperfections (out-of-straight)
- Yielding accentuated by residual stresses (0.8τ)

- By system, member, ~~and cross-s~~ simplifications are granted in resistance
- Design process will not ~~cross-section~~ instabilities

Simplification granted:
- Compressive strength P_n taken as cross-section axial strength P_y

DM-Adv. Elastic

66

AISC Interaction Equation

The big tradeoff!

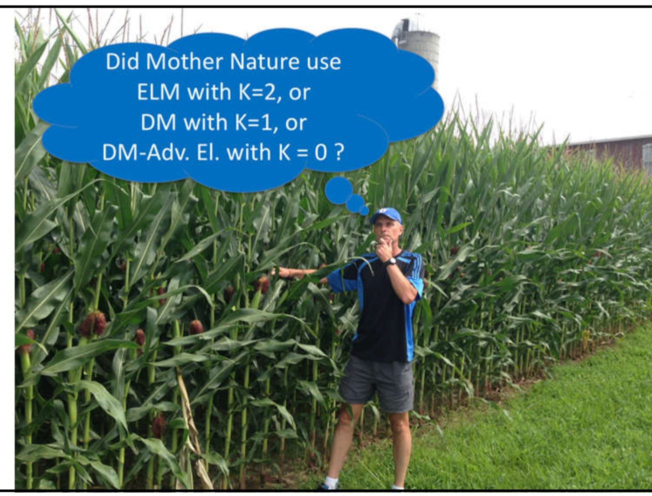
M_u increasing ↓
ELM
DM (Δ_o,0.8τ)
DM-Adv. El. (Δ_o,0.8τ,δ_o)

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

P_n increasing ↓
ELM (KL>L)
DM (KL=L)
Adv. El. ($P_n=A_eF_y$)

Methods often give very similar designs

67



68

Additional thoughts…

- Automated modeling and analysis is <u>not</u> the objective, <u>more opportunities</u> 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

69

Additional thoughts…

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- Goal is to improve design process by providing a more detailed, and hopefully more "realistic" understanding of structural behavior…
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More — Prescriptive specification equations — Less
Given Design Situation
Less — Directly modeling effects impacting stability — More

70

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- 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

71

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

72

More — Prescriptive specification equations — Less

Given Design Situation

Less — Directly modeling effects impacting stability — More

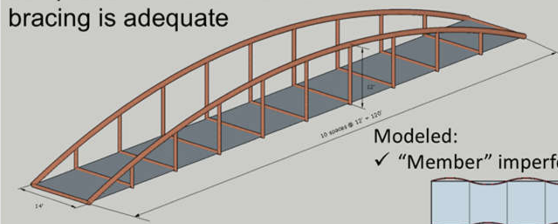
DM-Adv. Elastic

73

Pedestrian Bridges

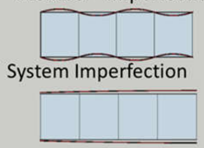
Walter P. Moore and Associates, Inc.

Ensure adequate strength of top compression chord and that bracing is adequate



Modeled:

✓ "Member" imperfections



✓ System Imperfection

Larry Griffis '94

WALTER P MOORE

74

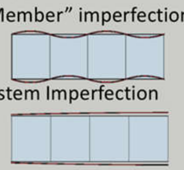
Pedestrian Bridges

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 '94

WALTER P MOORE

75

AISC's Direct Analysis Method (2010-16)

Inelastic Analysis of load effects:

Based on instability

Effects modeled:

- All pertinent deformations
- Applied load and initial stiffness distribution
- Initial system and member imperfections
- Yielding and residual stresses (directly modeled)
- Redistribution of stresses (F/M's) resulting from changes in relative stiffness distributions

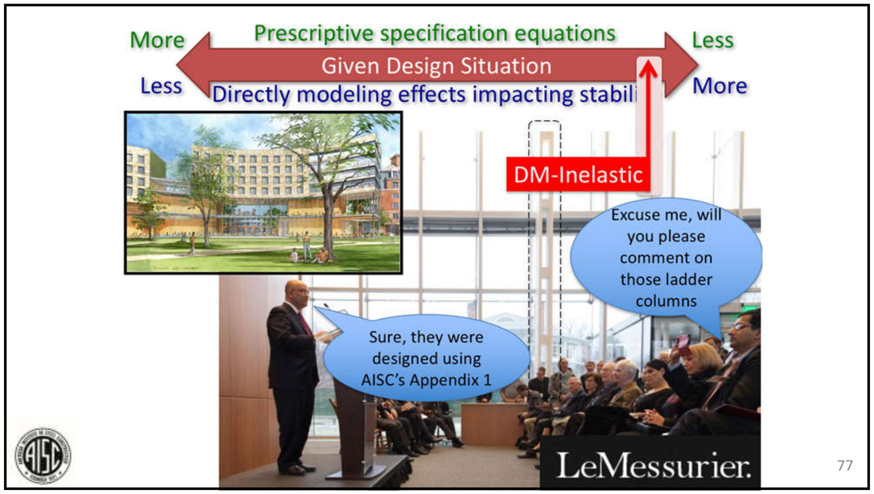
- By directly modeling effects known to impact system, member, ~~and cross-section~~ instability, simplifications are granted in compu...

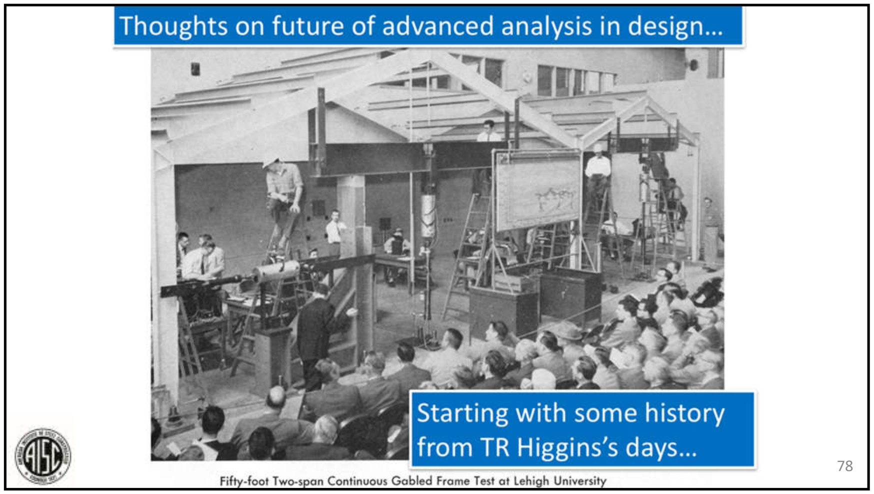
DM-Adv. Inelastic

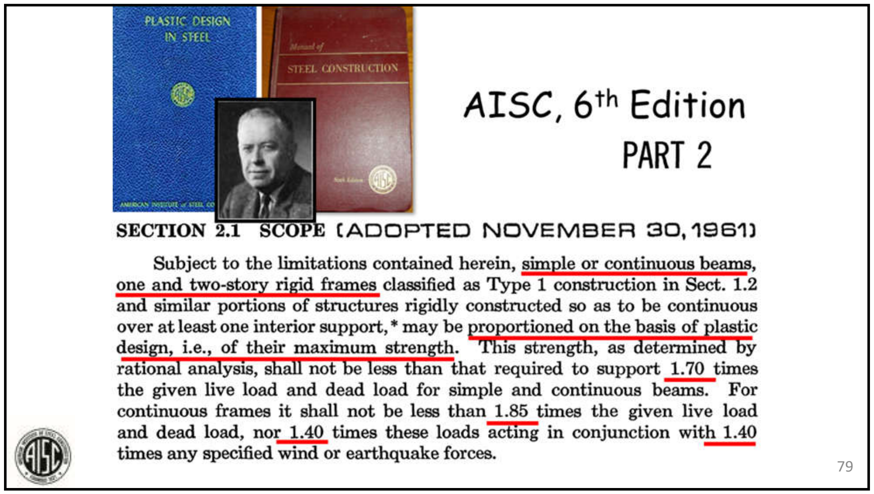
Simplifications granted:

- Specification design equations waived
- Go beyond first-plastic hinge!

76


More
Prescriptive specification equations
Less
Given Design Situation
Less
Directly modeling effects impacting stabili
More
DM-Inelastic
Excuse me, will you please comment on those ladder columns
Sure, they were designed using AISC's Appendix 1
LeMessurier.
77


Thoughts on future of advanced analysis in design…
Starting with some history from TR Higgins's days…
Fifty-foot Two-span Continuous Gabled Frame Test at Lehigh University
78


PLASTIC DESIGN IN STEEL
Manual of STEEL CONSTRUCTION
AISC, 6th Edition
PART 2
SECTION 2.1 SCOPE (ADOPTED NOVEMBER 30, 1961)
Subject to the limitations contained herein, simple or continuous beams, one and two-story rigid frames classified as Type 1 construction in Sect. 1.2 and similar portions of structures rigidly constructed so as to be continuous over at least one interior support,* may be proportioned on the basis of plastic design, i.e., of their maximum strength. This strength, as determined by rational analysis, shall not be less than that required to support 1.70 times the given live load and dead load for simple and continuous beams. For continuous frames it shall not be less than 1.85 times the given live load and dead load, nor 1.40 times these loads acting in conjunction with 1.40 times any specified wind or earthquake forces.
79


PLASTIC DESIGN of MULTI-STORY FRAMES
PLASTIC DESIGN of MULTI-STORY FRAMES
by
George C. Driscoll, Jr.
John W. Fisher '77
Lynn S. Beedle '73
Alexis Ostapenko
Theodore V. Galambos '81
J. Hartley Daniels
Le-Wu Lu
LECTURE NOTES
DESIGN AIDS
Lehigh University
Department of Civil Engineering
Fritz Engineering Laboratory
Lehigh University
Department of Civil Engineering
Fritz Engineering Laboratory
Summer 1965
80

Plastic Design of a 14-Story Apartment Building

WILLIAM A. BENNETT

AISC ENGINEERING JOURNAL
APRIL / 1967

1967

Figure 1

William A. Bennett is Structural Engineer, George E. Yurchison, Architect, Rochester, N. Y.

2018

81

Plastic Design of a 14-Story Apartment Building

WILLIAM A. BENNETT

AISC ENGINEERING JOURNAL
APRIL / 1967

Bennett indicates…Better understanding of stability and strength limit state behavior resulted in a better design

- ✓ More rational method
- ✓ Significant economies gained
- ✓ Included P-Δ effects
- ✓ Track limit state behavior
- ✓ More flexibility in design process

82

"It is expected that further research will produce computer programs which can provide solutions for extremely complex frames and include more secondary effects, as well as proportional and nonproportional loading of frames."

Plastic Design in Steel - Guide and Commentary
ASCE, 1971

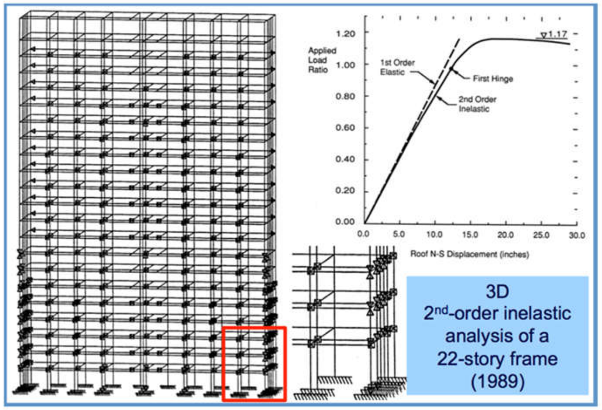
83

Computer programs –
lots of further research…

1970's → 1990's

- Computing hardware
- Graphical user interfaces
- Geometric nonlinear:
  - 2nd-order effects (P-Δ , P-δ)
- Material nonlinear:
  - Plastic hinge vs. zone

84



85

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING
Cornell University
HOLLISTER HALL, ITHACA, NY 14853-3501

November 13, 1990

MEMORANDUM TO: R. Bjorhovde '87
W. F. Chen '85
G. Haaijer
J. S. B. Iffland
J. W. Larson
S. D. Lindsey
H. Pak
J. A. Yura '74

FROM: W. McGuire '92 Bill

SUBJECT: AISC Task Committee 117 on Inelastic Analysis and Design

86

Computer programs –
lots of further research…

1970's

- Computing hardware
- Graphical user interfaces
- Geometric nonlinear:
  - 2nd-order effects (P-Δ , P-δ)
- Material nonlinear:
  - Plastic hinge vs. zone

1990's

U.S. steel design profession slow to adopt limit states design philosophy (LRFD)

87

Building Code of Australia primary referenced Standard

ABCB
Australian Building Codes Board

AS 4100 - 1990

Australian Standard™

Steel structures

Wow!

APPENDIX D
ADVANCED STRUCTURAL ANALYSIS
(Normative)

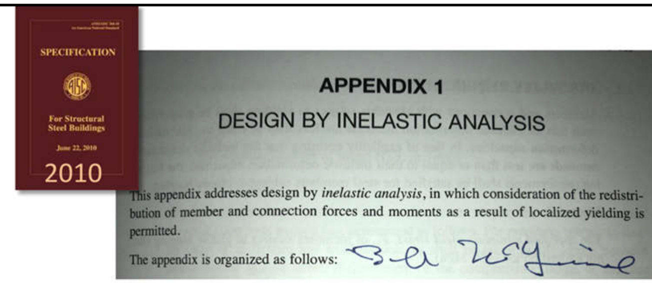
STANDARDS AUSTRALIA

88

Editors: D.W. White '09 and W.F. Chen '85 SSRC, 1993

Editors: A. Surovek ASCE, 2010

89



AISC Sub-Committee on Inelastic Analysis and Design (2007-2010)

Bill Baker '13	Bill McGuire '92
Greg Deierlein	Chia-Ming Uang '15
Subhash Goel '97	Don White '09
Rich Henige	Ron Ziemian, Chair
Dick Kaehler	Brent Leu, AISC

90

Inelastic analysis and seismic design, perfect together…

- Over the years, the use of pushover analyses has become quite common, especially for structures in high seismic areas
- Today, the use of full nonlinear, or at least material nonlinear, time history analyses are now sometimes being employed
- With this in mind, AISC has recently formed an ad hoc TG on Seismic Analysis (Hooper – Chair)
  - Direct Analysis Method dovetail with seismic
  - AISC 341 may include a new Appendix 1 - Design Verification Using Nonlinear Response History Analysis

91

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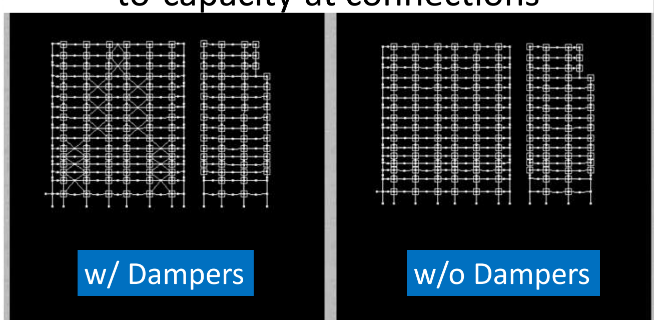
93

Caltrans District 4 Office Building retrofitted with viscous dampers (Oakland, CA)

94

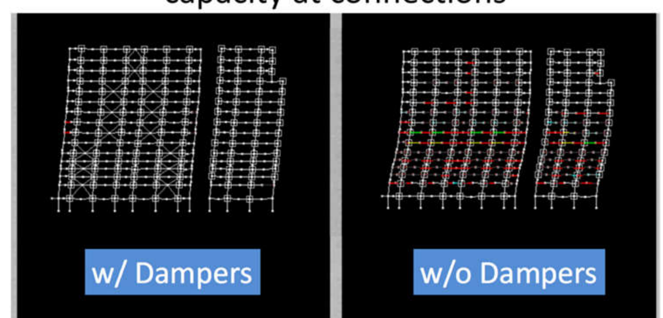
Caltrans District 4 Office Building – assess rotational deformation demand-to-capacity at connections



Nonlinear time history analysis results

95

Caltrans District 4 Office Building – assess rotational deformation demand-to-capacity at connections



Nonlinear time history analysis results

96

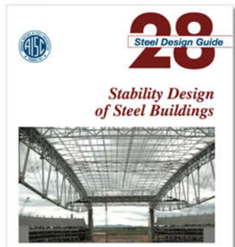
More ← Prescriptive specification equations → Less

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 '94
Don White '09

97

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

ELSEVIER

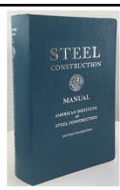
Formulation and validation of minimum brace stiffness for systems of compression members

Ronald D. Ziemian [a,*], Constance W. Ziemian [b]

Quick overview…

Z&Z'S TR HIGGINS AWARD PAPER - SOME FUN WITH STABILITY BRACING!

98



16.1-237

APPENDIX 6

MEMBER STABILITY BRACING

Joe Yura '74
Todd Helwig '17
Don White '09

strength and stiffness!

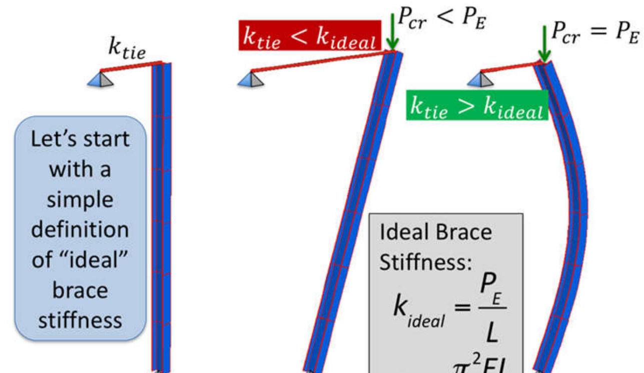
This appendix addresses the minimum strength and stiffness necessary to provide a braced point in a column, beam or beam-column.

6.1. GENERAL PROVISIONS

Bracing systems shall have the strength and stiffness specified in this Appendix, as applicable. Where such a system braces more than one member, the strength and

Z&Z focused on systems that brace more than one member

99



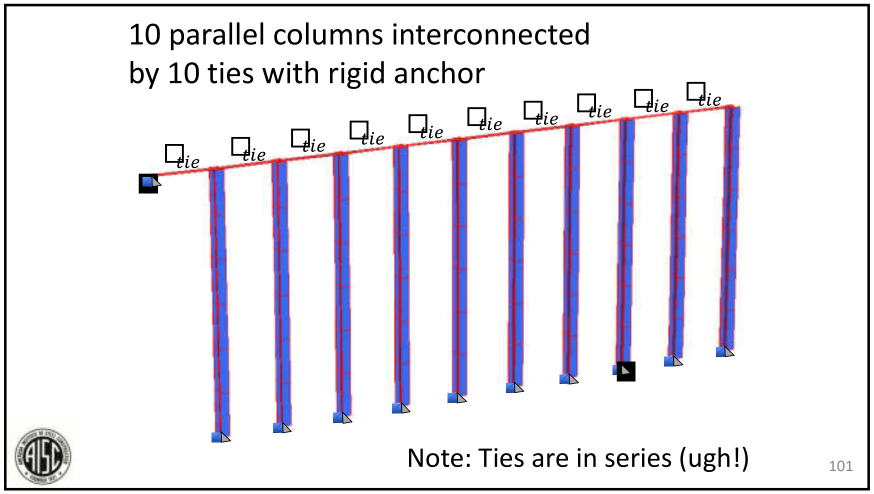
Ideal Brace Stiffness:

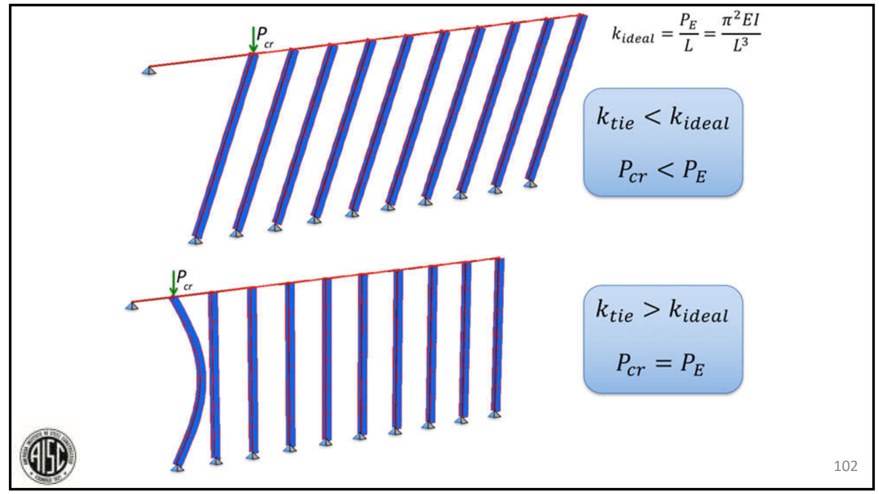
$$k_{ideal} = \frac{P_E}{L}$$

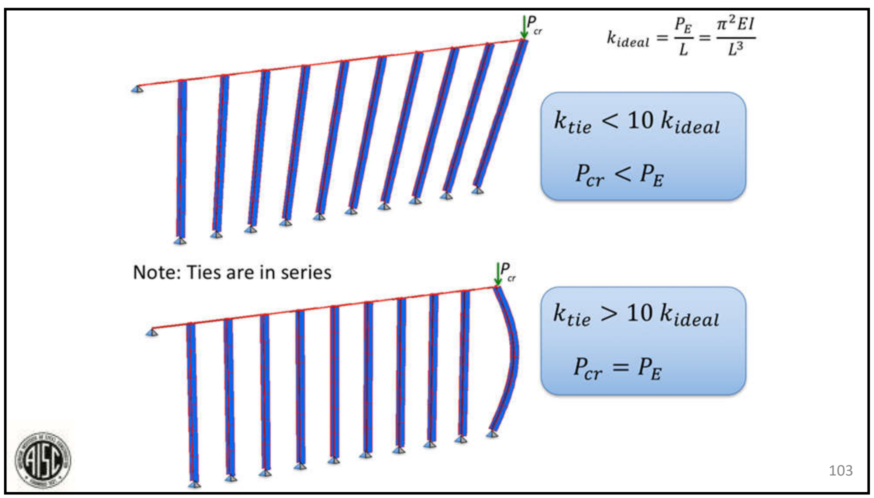
$$P_E = \frac{\pi^2 EI}{L^2}$$

In design, we use 2 or 3 times the ideal brace stiffness

100


10 parallel columns interconnected
by 10 ties with rigid anchor
Note: Ties are in series (ugh!)
101


$k_{ideal} = \frac{P_E}{L} = \frac{\pi^2 EI}{L^3}$
$k_{tie} < k_{ideal}$
$P_{cr} < P_E$
$k_{tie} > k_{ideal}$
$P_{cr} = P_E$
102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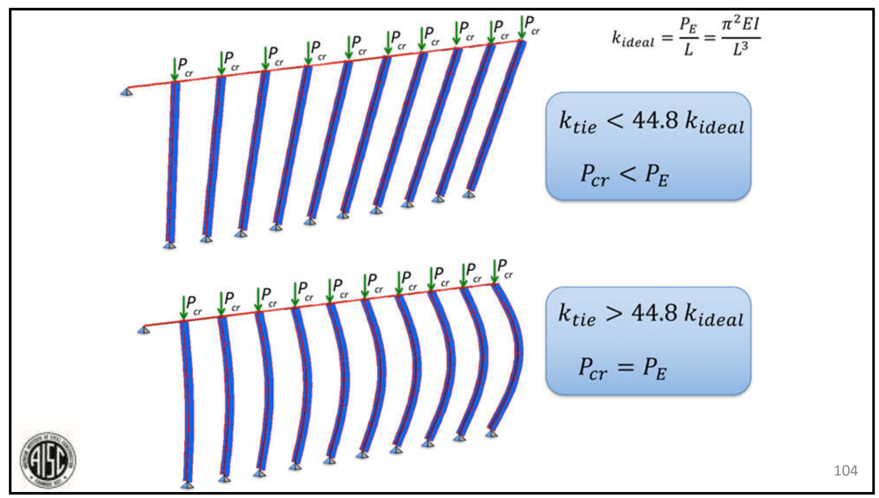
$k_{tie} < 10\ k_{ideal}$
$P_{cr} < P_E$
Note: Ties are in series
$k_{tie} > 10\ k_{ideal}$
$P_{cr} = P_E$
103


$k_{ideal} = \frac{P_E}{L} = \frac{\pi^2 EI}{L^3}$
$k_{tie} < 44.8\ k_{ideal}$
$P_{cr} < P_E$
$k_{tie} > 44.8\ k_{ideal}$
$P_{cr} = P_E$
104

So, where did that threshold of 44.8 come from?

- Advanced analysis – trial and error using elastic critical load (eigenvalue) analyses
- Assuming all ties have the same stiffness
  - Mathematically derived solution (see Z&Z paper…equilibrium and compatbility on the deformed shape!)
  - Curved-fitted parabolic function

$$a_{max} = 0.4n^2 + 0.4n + 0.2$$

105

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$$a_{max} = 0.4n^2 + 0.4n + 0.2$$

106

Multiple Columns: Minimum Brace Stiffness, k_{tie}(n)

n	"Exact" a_{max}	Approximate a_{max}	|% error|
1	1	1	0
2	2.6180	2.6	0.6888
3	5.0489	5	0.9689
4	8.2909	8.2	1.0959
5	12.3435	12.2	1.1629
10	44.7661	44.2	1.2645
15	97.4530	96.2	1.2858
25	263.620	260.2	1.2972
50	1033.66	1020.2	1.3022
100	4093.56	4040.2	1.3035

Approximate Parabola

$a_{max} = 0.4n^2 + 0.4n + 0.2$

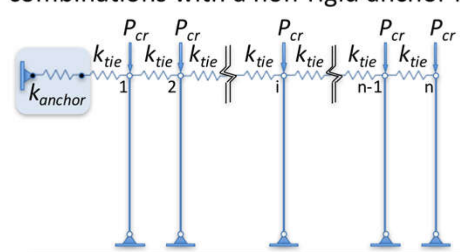
$k_{tie} < a_{max}\, k_{ideal}$
$P_{cr} < P_E$

$k_{tie} > a_{max} k_{ideal}$
$P_{cr} = P_E$

Very Cool!

107

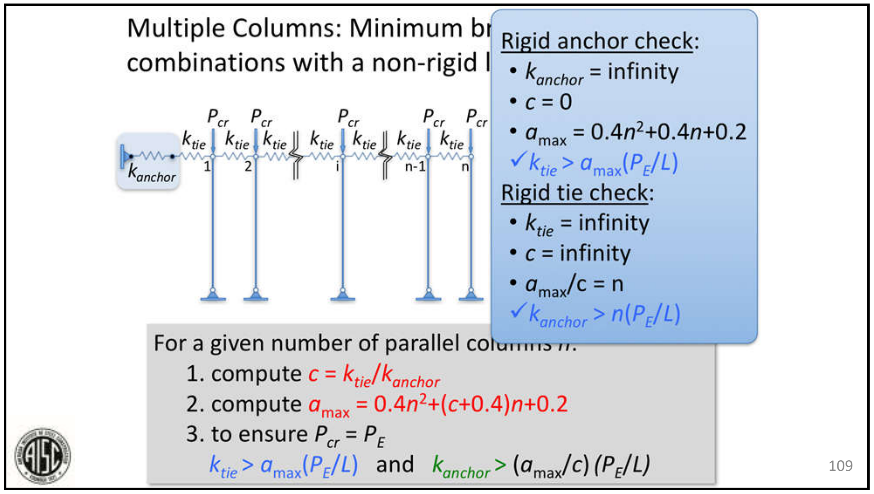
Multiple Columns: Minimum brace stiffness combinations with a non-rigid anchor restraint

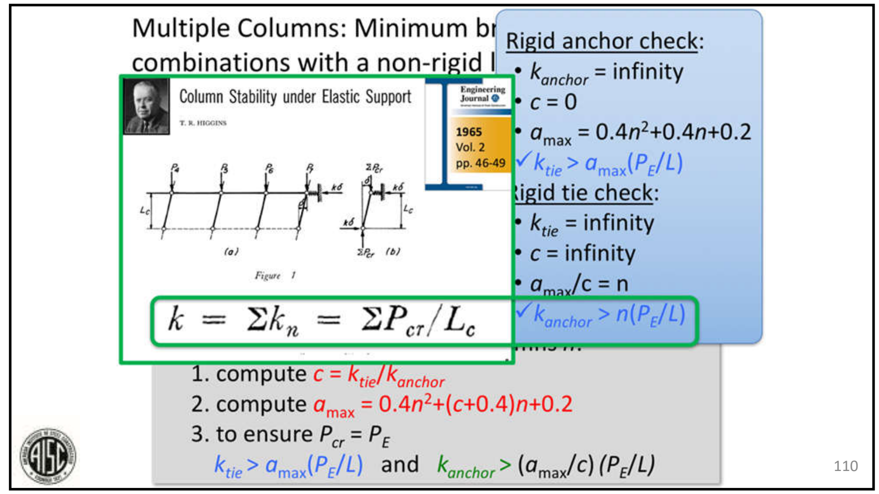


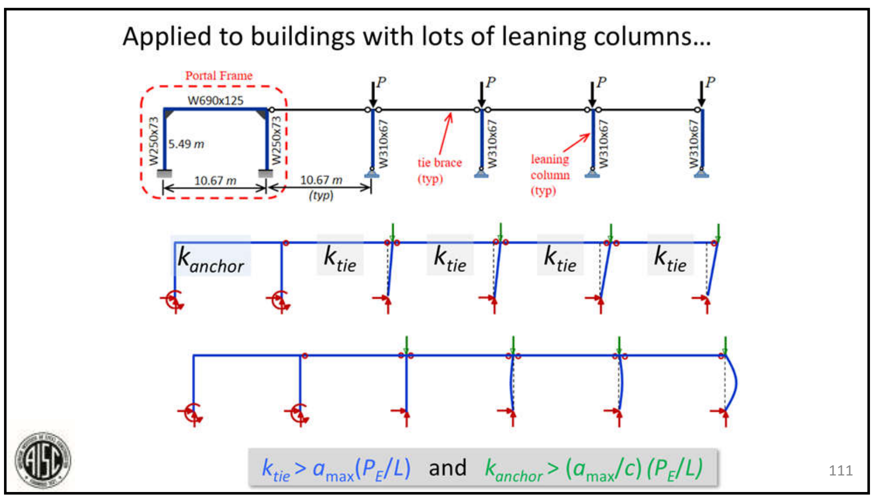
For a given number of parallel columns n:

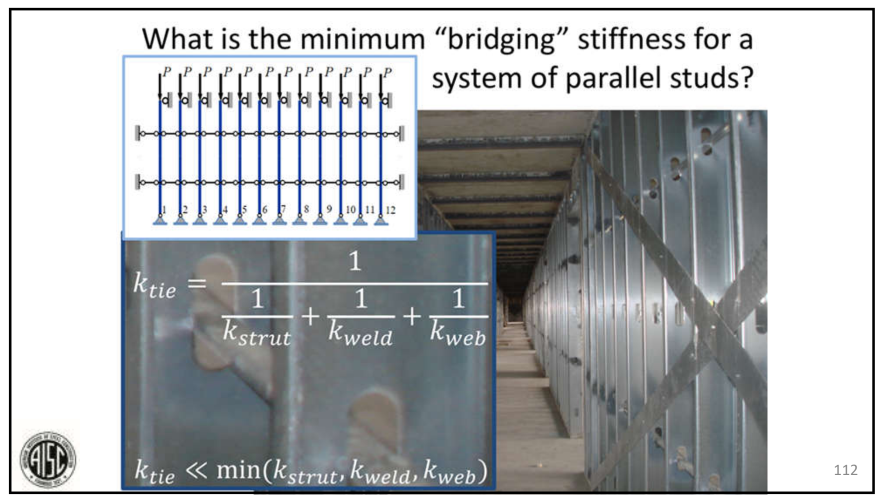
1. compute $c = k_{tie}/k_{anchor}$
2. compute $a_{max} = 0.4n^2+(c+0.4)n+0.2$
3. to ensure $P_{cr} = P_E$
   $k_{tie} > a_{max}(P_E/L)$ and $k_{anchor} > (a_{max}/c)\,(P_E/L)$

108

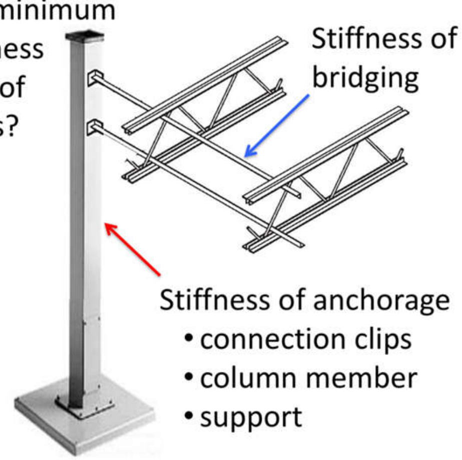

Multiple Columns: Minimum br
combinations with a non-rigid l
P_{cr}
k_{tie}
k_{anchor}
1
2
i
n-1
n
Rigid anchor check:
• k_{anchor} = infinity
• c = 0
• $a_{max} = 0.4n^2+0.4n+0.2$
✓ $k_{tie} > a_{max}(P_E/L)$
Rigid tie check:
• k_{tie} = infinity
• c = infinity
• a_{max}/c = n
✓ $k_{anchor} > n(P_E/L)$
For a given number of parallel columns n:
1. compute $c = k_{tie}/k_{anchor}$
2. compute $a_{max} = 0.4n^2+(c+0.4)n+0.2$
3. to ensure $P_{cr} = P_E$
$k_{tie} > a_{max}(P_E/L)$ and $k_{anchor} > (a_{max}/c)(P_E/L)$
109


Multiple Columns: Minimum br
combinations with a non-rigid l
Column Stability under Elastic Support
T. R. HIGGINS
Engineering Journal
1965
Vol. 2
pp. 46-49
Figure 1
$k = \Sigma k_n = \Sigma P_{cr}/L_c$
Rigid anchor check:
• k_{anchor} = infinity
• c = 0
• $a_{max} = 0.4n^2+0.4n+0.2$
✓ $k_{tie} > a_{max}(P_E/L)$
Rigid tie check:
• k_{tie} = infinity
• c = infinity
• a_{max}/c = n
✓ $k_{anchor} > n(P_E/L)$
1. compute $c = k_{tie}/k_{anchor}$
2. compute $a_{max} = 0.4n^2+(c+0.4)n+0.2$
3. to ensure $P_{cr} = P_E$
$k_{tie} > a_{max}(P_E/L)$ and $k_{anchor} > (a_{max}/c)(P_E/L)$
110


Applied to buildings with lots of leaning columns…
Portal Frame
W690x125
W250x73
5.49 m
10.67 m
10.67 m (typ)
W310x67
tie brace (typ)
leaning column (typ)
P
k_{anchor}
k_{tie}
$k_{tie} > a_{max}(P_E/L)$ and $k_{anchor} > (a_{max}/c)(P_E/L)$
111


What is the minimum "bridging" stiffness for a system of parallel studs?
P
1 2 3 4 5 6 7 8 9 10 11 12
$k_{tie} = \dfrac{1}{\dfrac{1}{k_{strut}} + \dfrac{1}{k_{weld}} + \dfrac{1}{k_{web}}}$
$k_{tie} \ll \min(k_{strut}, k_{weld}, k_{web})$
112

What is the minimum bracing stiffness for a system of parallel joists?



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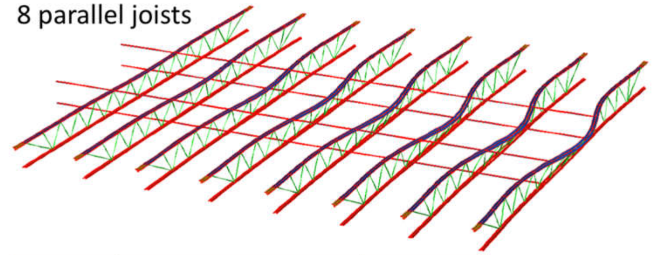
8 parallel joists



$$k_{8,ideal} \approx \left(0.4\times 8^2 + 0.4\times 8 + 0.2\right)\times k_{1,ideal}$$

$$k_{8,ideal} \approx 29\times k_{1,ideal} \neq 8\times k_{1,ideal}$$

114

Always time for a joist story…

Details…

SOME CLOSING THOUGHTS ON EDUCATION

116

Start by teaching structural stability in the first grade!

117

Stability Education for all ages…

- University
  - Behavior of metal structures
  - Merging analysis and design courses
- Profession
  - Online courses (e.g. AISC's Night School)
  - Interoffice conversations and challenges
- Virtual laboratories for all ages
  - Guided explorations with nonlinear analysis software
  - Stability fun!

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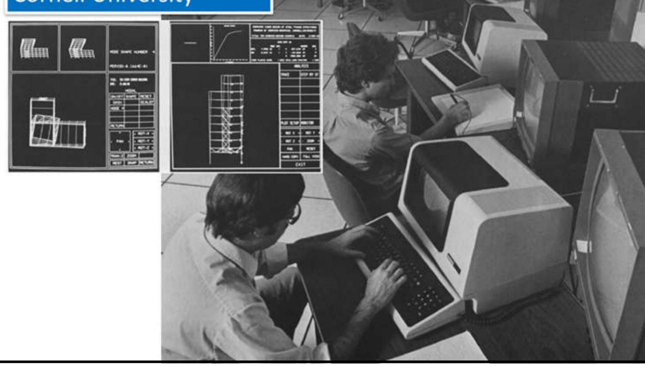

Computer-Aided Design Instructional Facility (CADIF) in the 1980's at Cornell University

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Today's steel design classroom

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Future of Advanced Analysis in Design

- Focus will shift to better modeling the load effects…Dynamic loading due to Earth, Wind, & Fire
- Future speeds of computer hardware/software will permit amazingly sophisticated nonlinear time history analyses…yeah!
- But…if we could suddenly increase the speed of our computers by 1,000x, would the SE profession?
  a) Use existing analysis capabilities, but quadruple the number of load cases currently being investigated
  b) Continue to investigate the same number of load cases, but perform much more sophisticated analyses of many of them
- Virtual reality, artificial intelligence, and big data?

Maria Garlock '16

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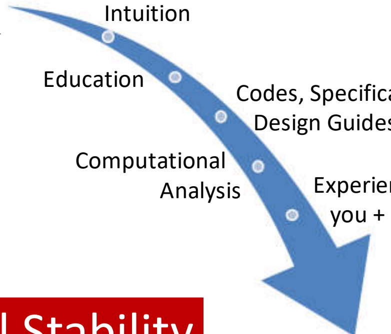
Fundamentals!



Structural Stability

Guide (not replace) your judgement

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AISC | Questions?

Smarter. Stronger. Steel.

CEU / PDH Certificates

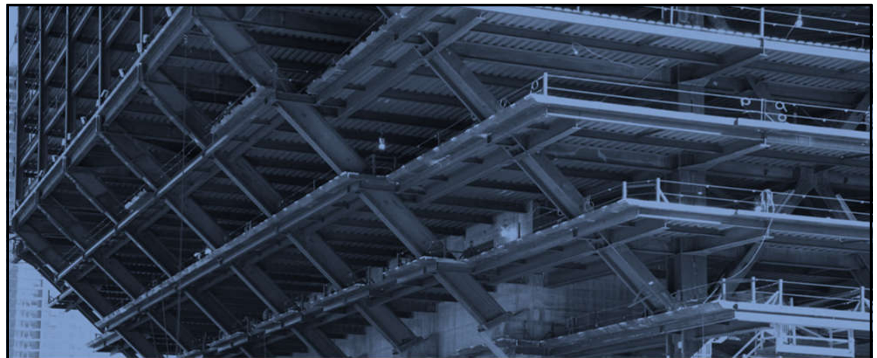
- You will receive an email on how to report attendance from: registration@aisc.org.
- Be on the lookout: Check your spam filter! Check your junk folder!
- Completely fill out online form. Don't forget to check the boxes next to each attendee's name!

Smarter. Stronger. Steel.

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.

Smarter.
Stronger.
Steel.



AISC | Thank you

Smarter.
Stronger.
Steel.