

AISC Live Webinars

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



AISC Live Webinars

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AISC Live Webinars

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AISC Live Webinars

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."



Smarter.
Stronger.
Steel.

AISC Live Webinars

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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Stronger.
Steel.

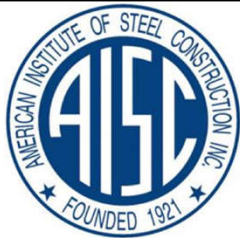
Structural Stability – Letting the Fundamentals Guide Your Judgement April 16, 2020



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



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Stronger.
Steel.



Structural Stability – Letting the Fundamentals Guide Your Judgement

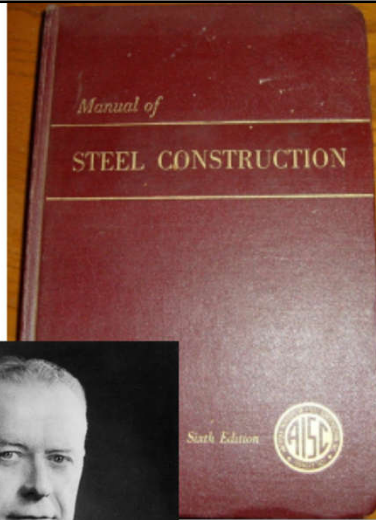
Ron Ziemian

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.



Structural Stability – Letting the Fundamentals Guide Your Judgement

Some thoughts on...

FUNDAMENTALS AND JUDGEMENT



The fundamentals...stability

- 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...stability

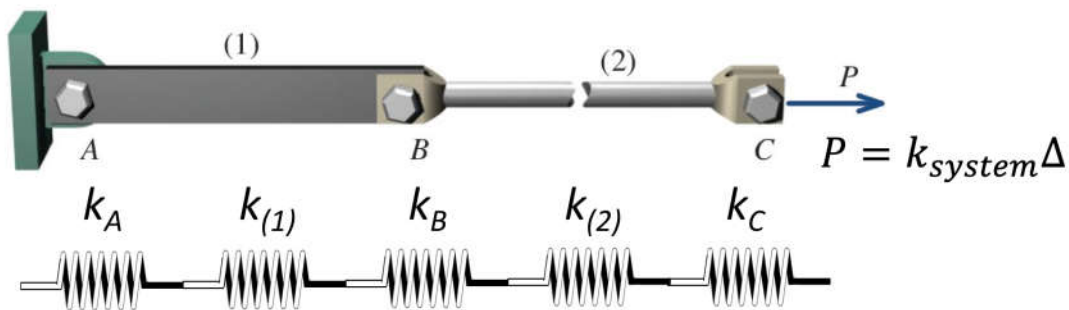
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 - Equilibrium (“forces” must be in agreement!)
 - Compatibility (“displacements” must be in agreement)
 - Constitutive Relationship (“forces” -to- “displacements”)
- Superposition – always so tempting!
 - Linear response (geometric and material)
 - 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!



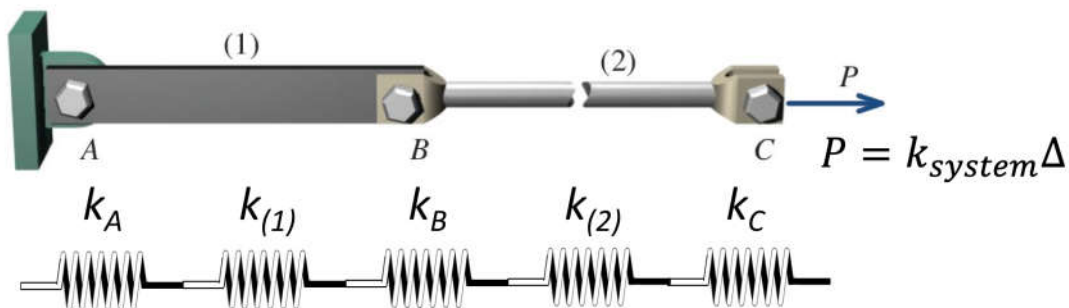
$$k_{system} = \frac{1}{\frac{1}{k_A} + \frac{1}{k_{(1)}} + \frac{1}{k_B} + \frac{1}{k_{(2)}} + \frac{1}{k_C}}$$

$$k_{system} \ll \min(k_A, k_{(1)}, k_B, k_{(2)}, k_C,)$$



Tim Philpot
 MecMovies 13

Stiffness in series degrades horribly!



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!

The diagram shows three vertical columns of different heights and stiffnesses. The left and right columns are labeled (1) and are highlighted in red and blue respectively. The middle column is labeled (2) and is highlighted in green. They are supported by a common base with points A, B, and C. A downward load P is applied at the top. To the right, an equivalent spring system is shown with three springs in parallel, labeled k_{red} , k_{green} , and 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!

The diagram is identical to the one above, showing three parallel columns and their equivalent spring system with stiffnesses k_{red} , k_{green} , and 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

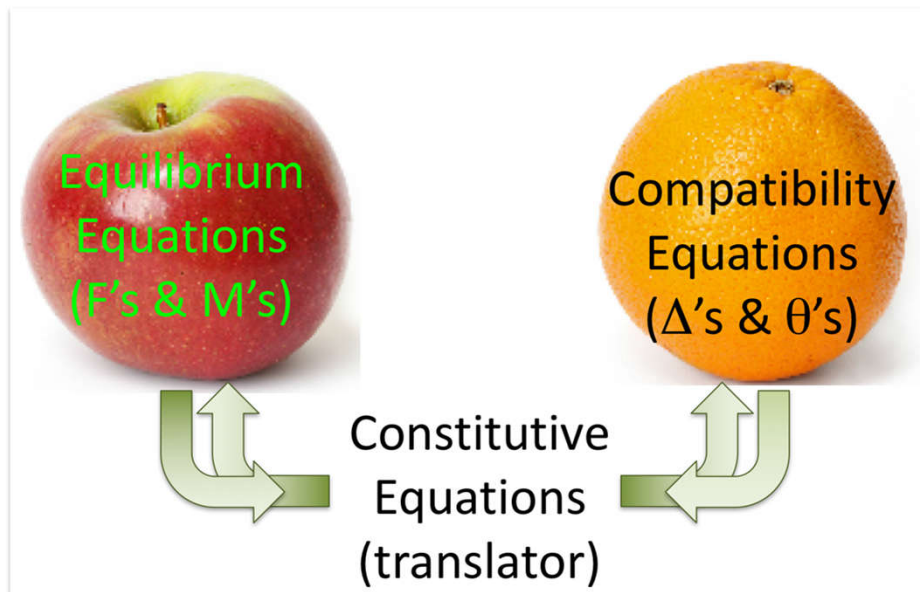
The fundamentals...stability

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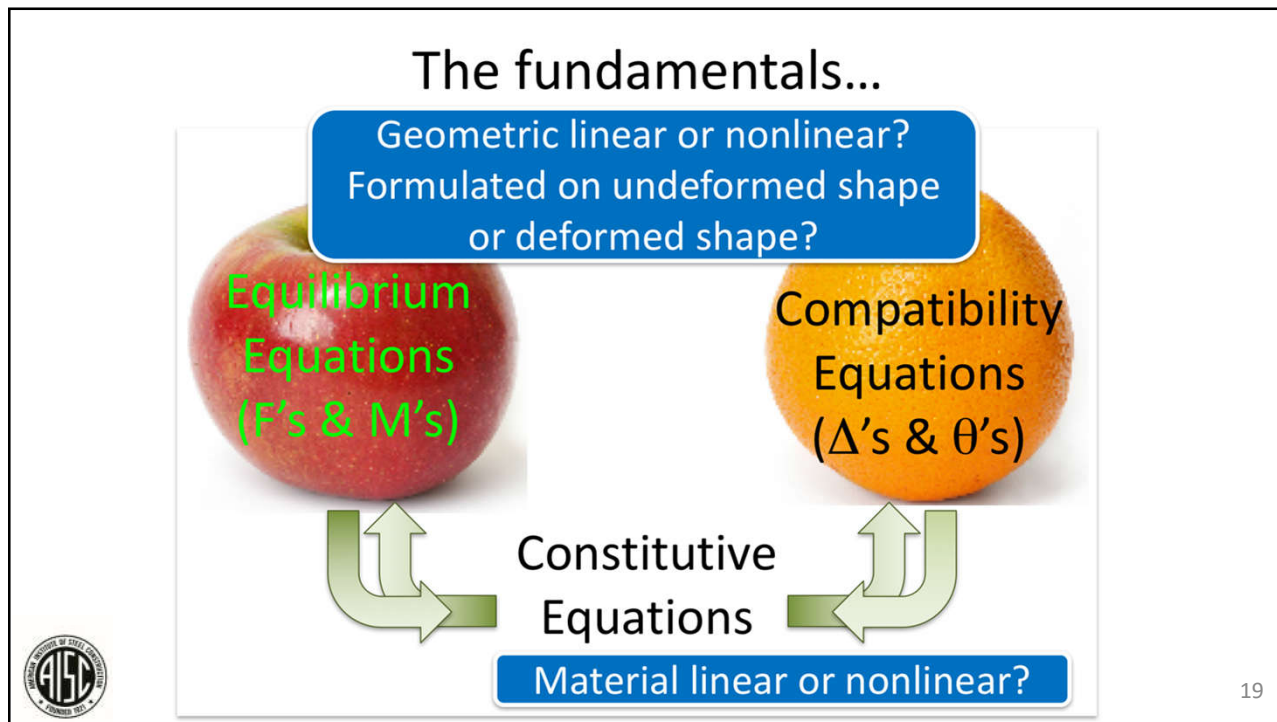


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The fundamentals...




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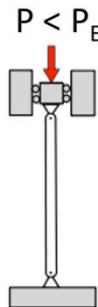


First stability analysis...

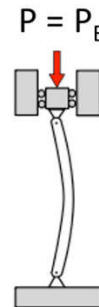
- Leonhard Euler, 1744 and 1757
- Assumptions!
 - prismatic member
($I = \text{constant}$)
 - small deflections after buckling
 - no bending prior to bifurcation
 - perfectly straight
 - concentrically loaded
 - linear elastic behavior
($E = \text{constant}$)
 - pinned-roller supports
(frictionless)




$P < P_E$



$P = P_E$





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Euler Buckling (2)

Equilibrium:

$$\sum M_* = 0$$

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

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:

Boundary Conditions!

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

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

- 1) $C_2 = 0$ "trivial solution"
- 2) $\sin\left(\sqrt{\frac{P_E}{EI}} L\right) = 0 \Rightarrow \sqrt{\frac{P_E}{EI}} L = n\pi \Rightarrow$

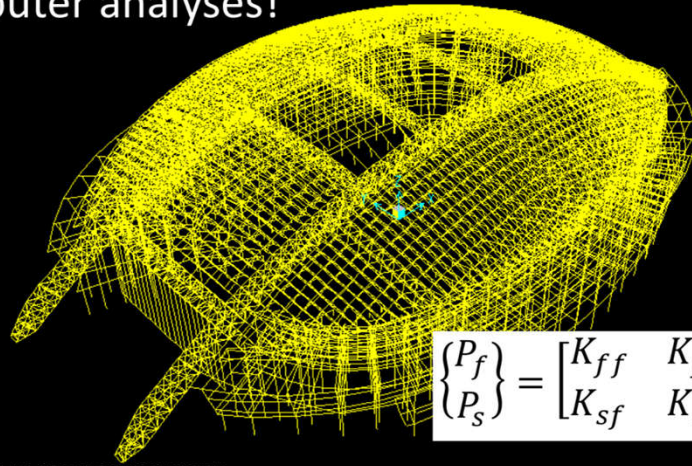
$$P_E = \frac{n^2 \pi^2 EI}{L^2}$$

$$n = 1, 2, 3, \dots$$

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Equilibrium, Compatibility, Constitutive...

From Euler to today's awesome
computer analyses!



$$\begin{Bmatrix} P_f \\ P_s \end{Bmatrix} = \begin{bmatrix} K_{ff} & K_{fs} \\ K_{sf} & K_{ss} \end{bmatrix} \begin{Bmatrix} \Delta_f \\ \Delta_s \end{Bmatrix}$$



★ DALLAS COWBOYS STADIUM
ARLINGTON, TEXAS

WALTER P MOORE

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The fundamentals...stability

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$\sigma = P/A$

σ_{yield}

Elastic

Perfectly Plastic ($E = 0$)

E

P

L

$L + \Delta$

$\epsilon = \Delta/L$

Amazing ductility of steel does not guarantee component ductility...

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$\sigma = P/A$

σ_{yield}

Elastic

Perfectly Plastic ($E = 0$)

P

L

$L + \Delta$

$\epsilon = \Delta/L$

Amazing ductility of steel does not guarantee component ductility...

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Egor Popov '72
Omer Blodgett '83
Roberto Leon '93
Bill Thornton '95
Hassan Astaneh '98
Mike Engelhardt '99
Duane Miller '01
John Barsom '03
Larry Kloiber '04
Charles Roeder '11
Larry Muir '14
Bo Dowswell '20

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More fun of designing with steel:

Strength/Weight

Stiffness/Weight

Competitive \$

Slender Systems, Members, and Cross-sections

Design for Stability!

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“Buckling” Design Methods:

Load

Load_{lim}

Deflection₀

Deflection

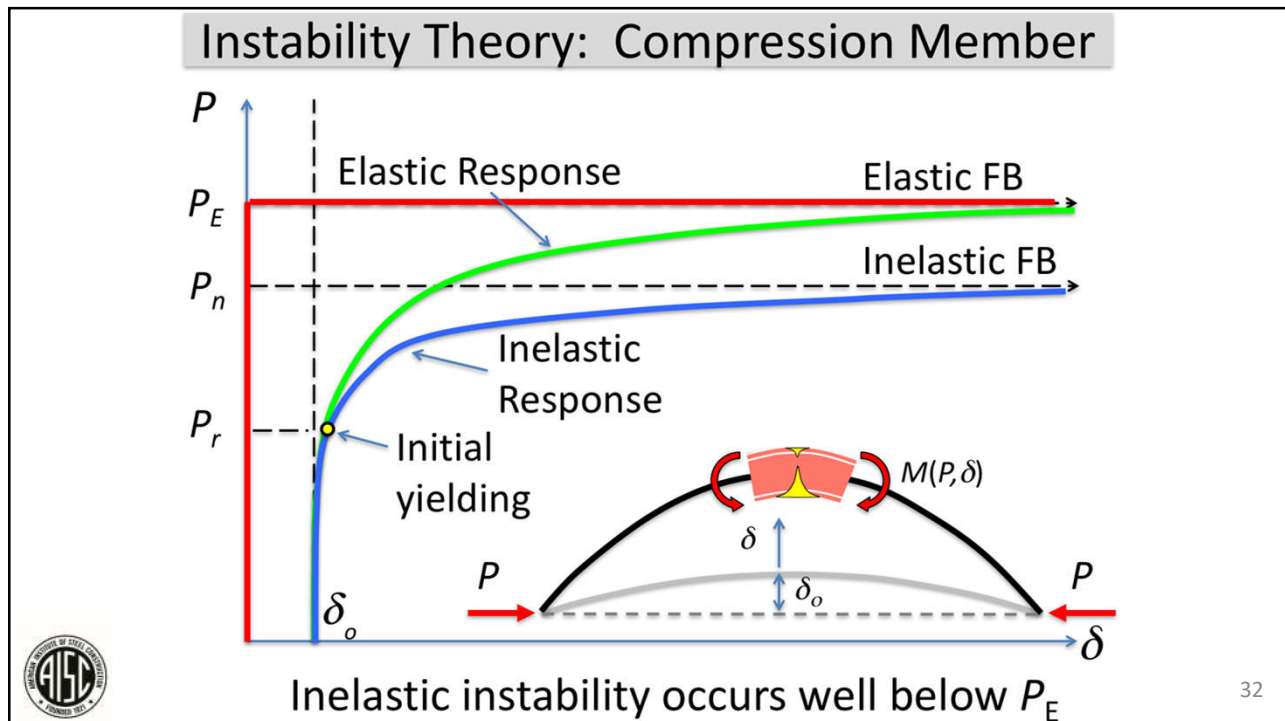
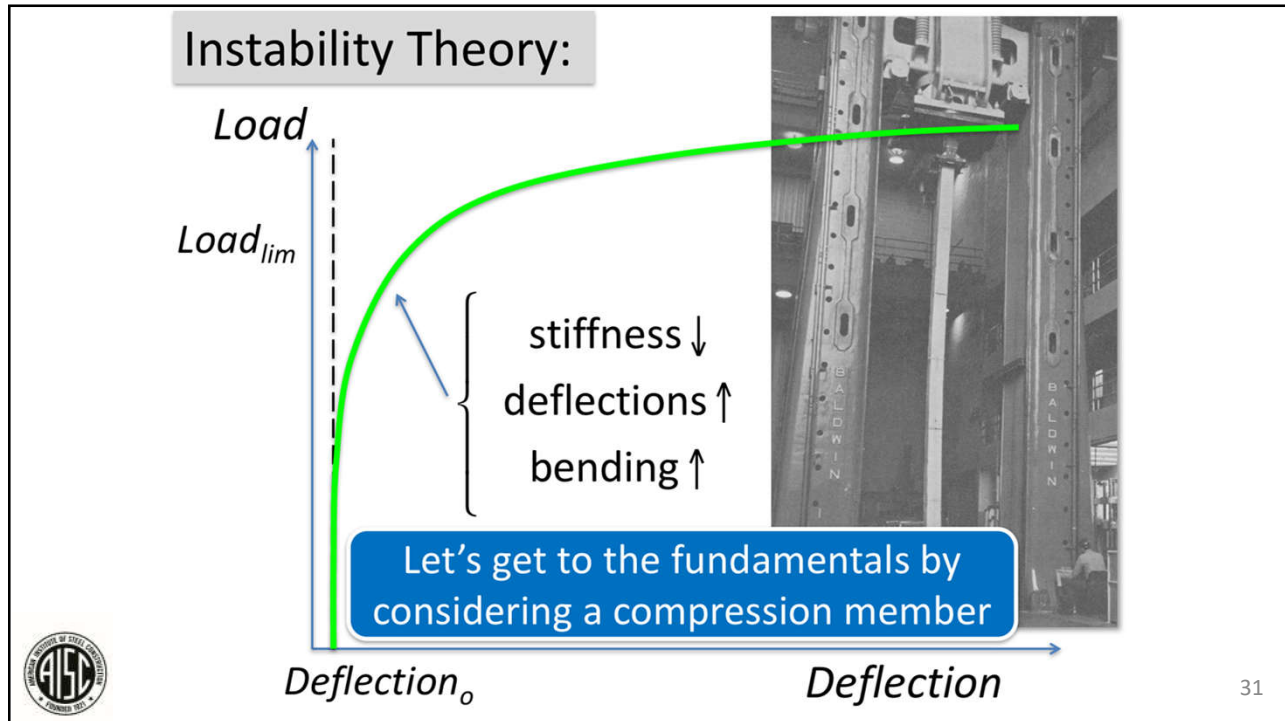
Bifurcation Theory

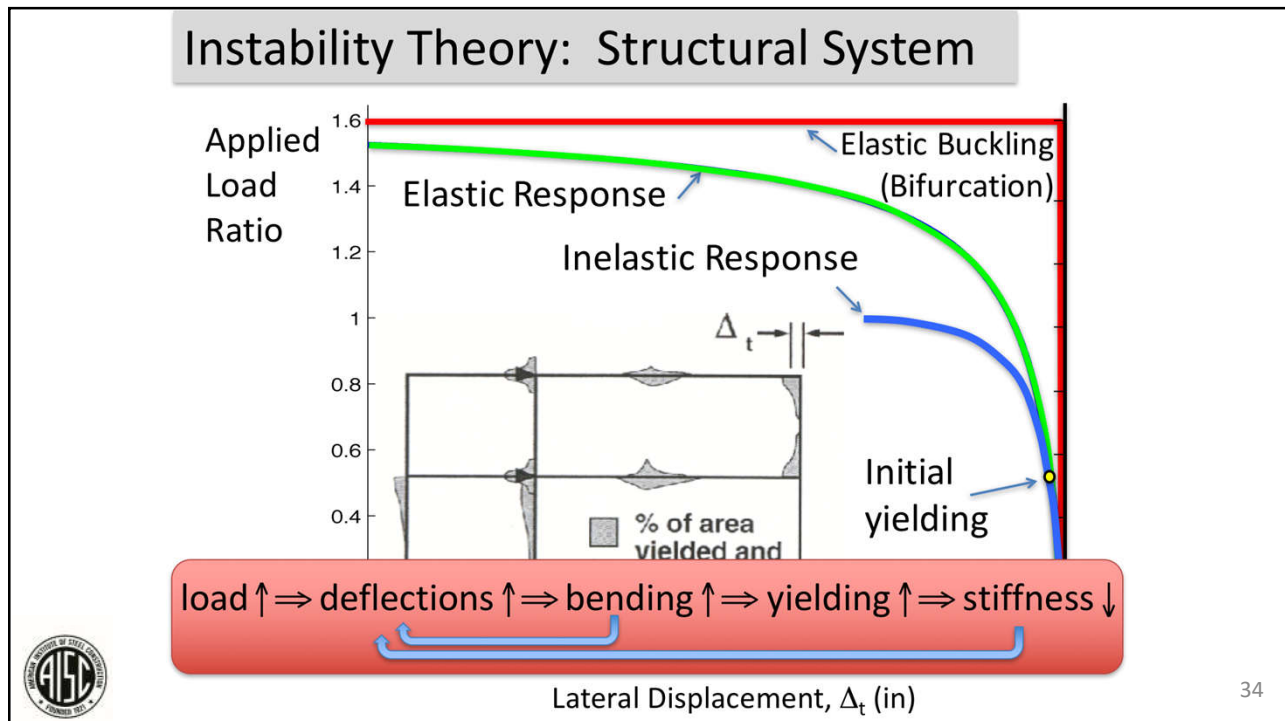
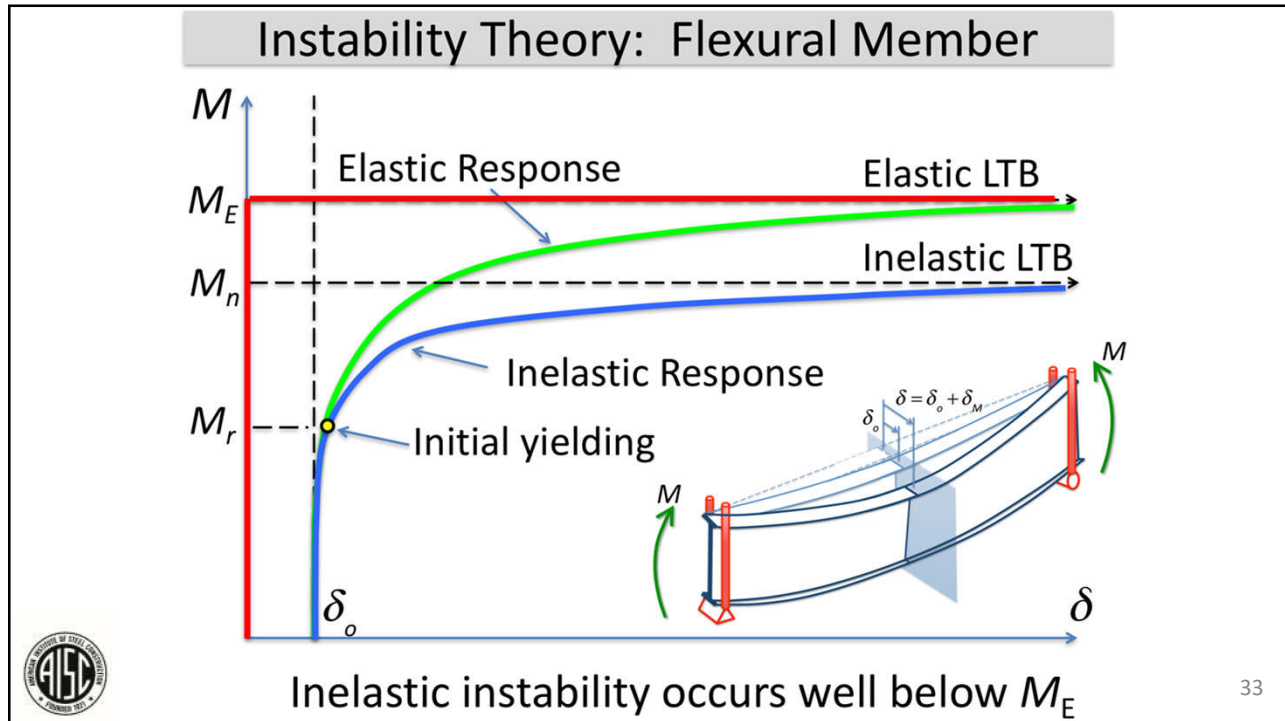
Instability Theory

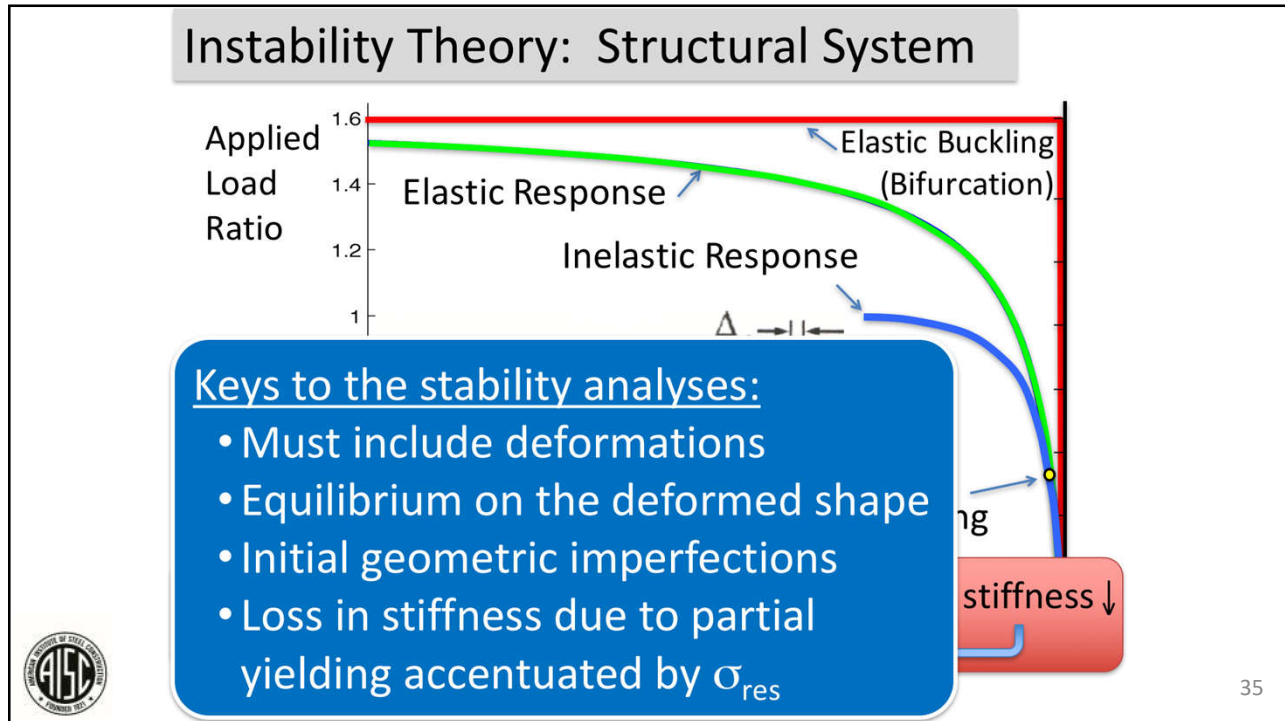
stiffness ↓
deflections ↑
bending ↑

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

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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

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.

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

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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 frames and members
- Connection flexibility
- Strain Hardening
- Contributions of slab to strength
- Load effects
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stability. The direct Appendix 7.



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- ✓ Behavior of steel structures
 - ✓ Material 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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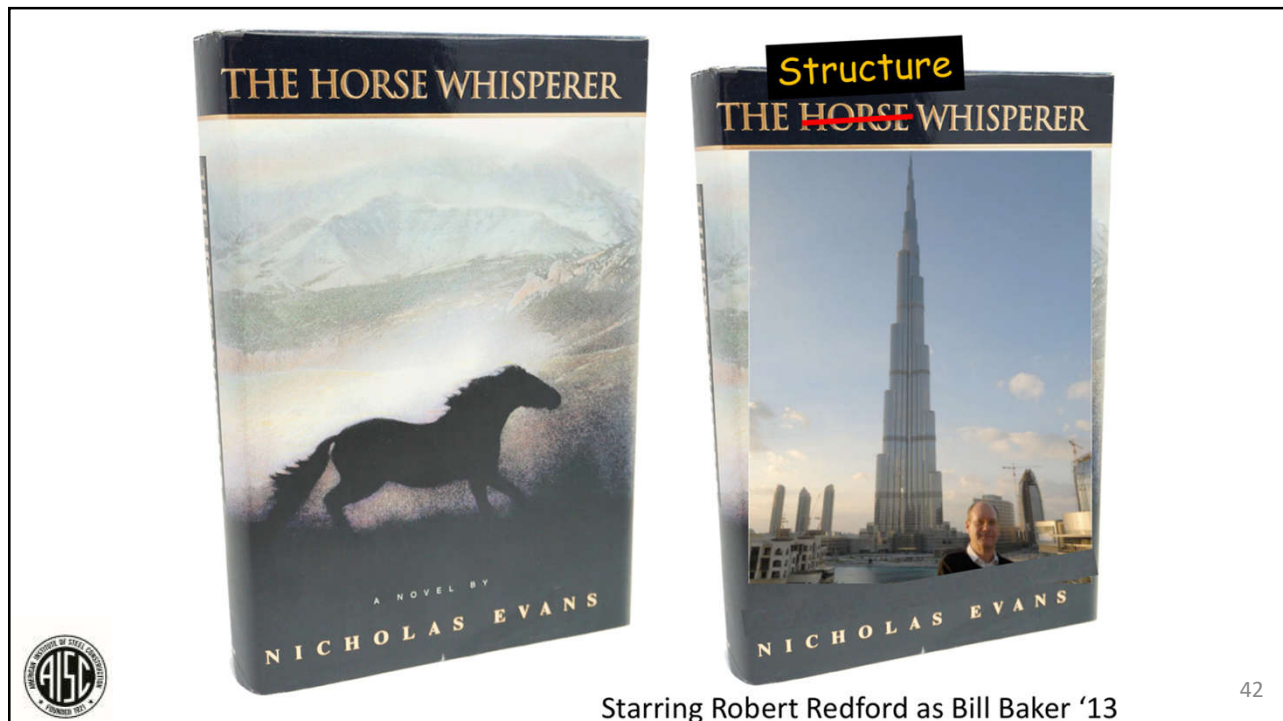
40

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Starring Robert Redford as Bill Baker '13

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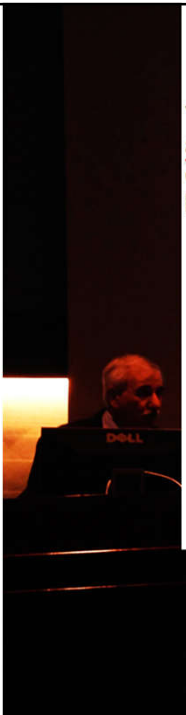

The structural engineer of the future?

- Increasing
 - building code prescription
 - computing and artificial intelligence capabilitythreatens 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...

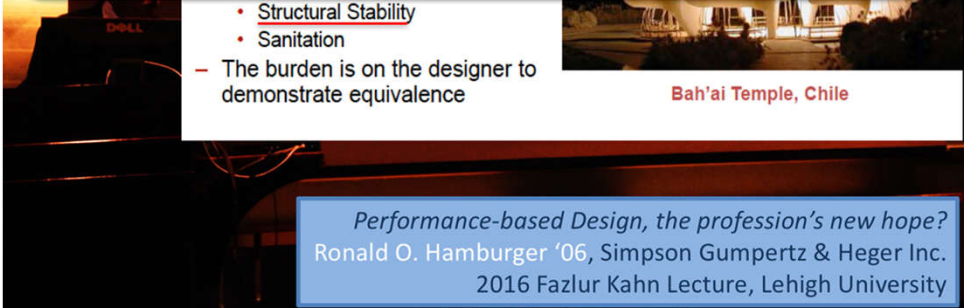

In general, when judgement is no longer required and/or exercised, then so goes the need for the structural engineer...

- Structural Stability
- Sanitation

– The burden is on the designer to demonstrate equivalence

Bah'ai Temple, Chile

Performance-based Design, the profession's new hope?
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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 trusses and members
- Connection flexibility
- Strain Hardening
- Contributions of slab to strength and stiffness
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“Buckling” Design Methods:

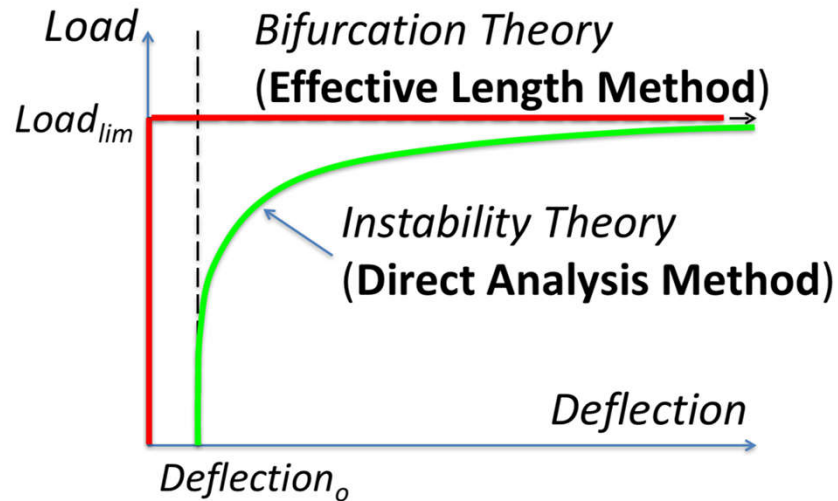


Figure applicable to system and member behavior

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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
 - $M = B_1 M_{nt} + B_2 M_{lt}$
- 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

- Indicators include:

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

$$B_2 = \frac{1}{1 - \frac{\alpha P_{story}}{P_{e\ story}}} \quad P_{e\ story} = R_M \frac{HL}{\Delta H}$$

- 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 ($B_2 > 1.5$)



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

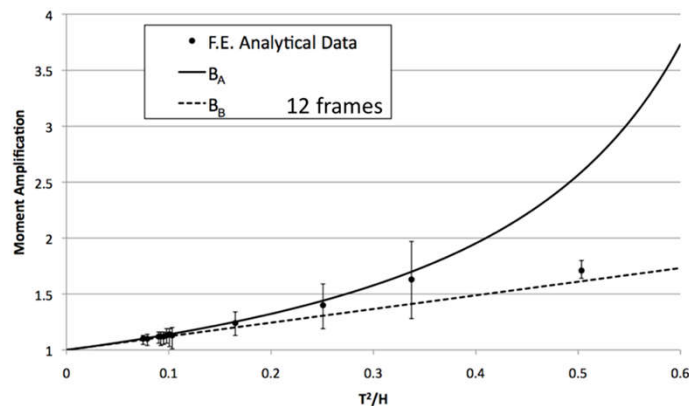
$$B_B = 1 + \frac{3gT^2}{8\pi^2 H}$$



*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. Statler¹, R.D. Ziemian², L.E. Robertson³



Note: Most important to also plot the mode shape



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

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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 ($B_2 < 1.1$)



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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!)



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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 connections, has led to a new type of tier building.

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



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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???



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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???

Lou Geschwindner '00



59

Effective Length Method

- Does the K-factor really account for those system stability effects?
 - Indirectly, through its conservatism...
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 - be very careful!
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 - $KL = \pi\sqrt{EI/P}$
 - 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.



$$KL/r \rightarrow P_n = \#$$

$$\lambda L/r \rightarrow q_n = ??$$



61

“General” Direct Analysis Method

Shankar Nair '07

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



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

$$R_u \leq \phi R_n$$

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



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-section resistance
- Design process will not permit 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 directly modeling effects known to impact system, member, and cross-section resistance
- Design process will not permit 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!

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

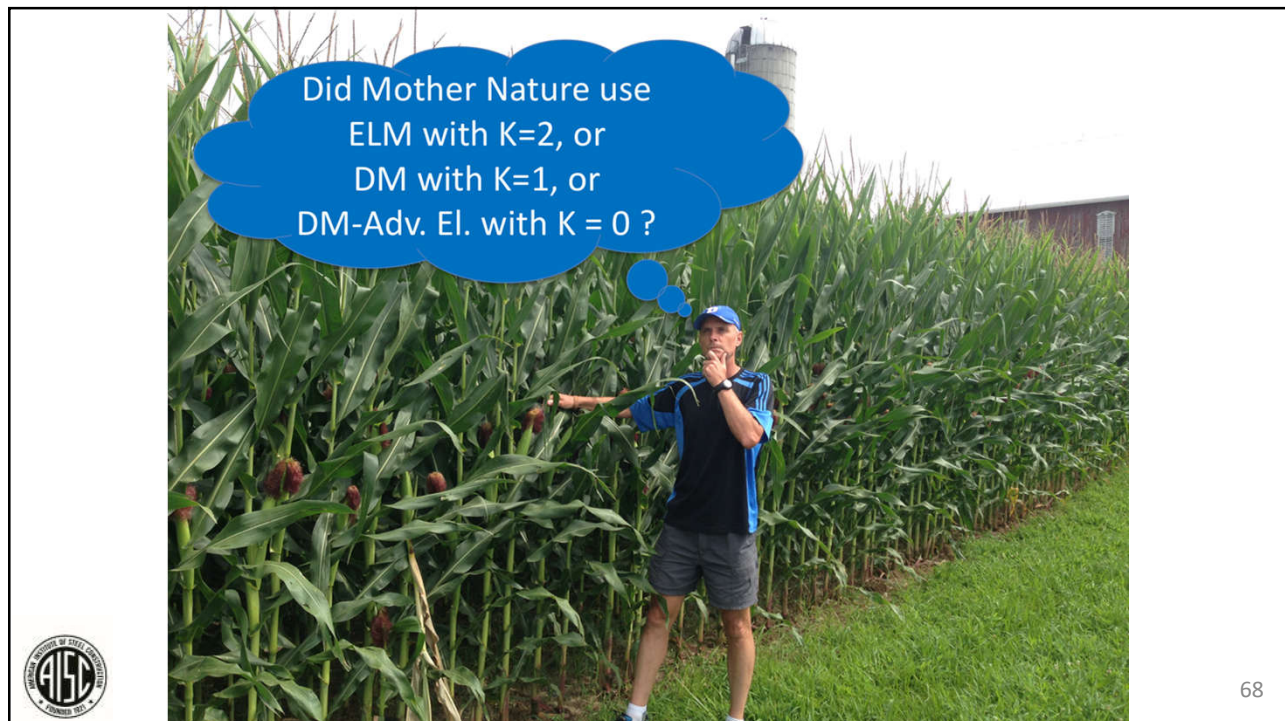
M_u increasing
 ELM
 DM ($\Delta_o, 0.8\tau$)
 DM-Adv. El. ($\Delta_o, 0.8\tau, \delta_o$)

P_n increasing
 ELM (KL > L)
 DM (KL = L)
 Adv. El. ($P_n = A_e F_y$)

Methods often give very similar designs




67



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?*

The diagram features a horizontal red double-headed arrow. Above the arrow, the text 'Prescriptive specification equations' is written in green, with 'More' in green to its left and 'Less' in green to its right. Below the arrow, the text 'Directly modeling effects impacting stability' is written in blue, with 'Less' in blue to its left and 'More' in blue to its right. The phrase 'Given Design Situation' is written in red in the center of the arrow.




69

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?*

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70



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...
- Real question is *where does an engineer have the most knowledge and confidence for a given design situation?*





71




72




More ← Prescriptive specification equations → Less
Less ← Given Design Situation → More
Directly modeling effects impact ↑ stability



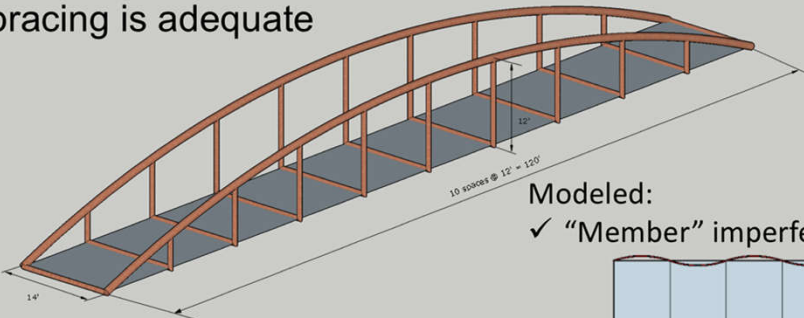
DM-Adv. Elastic


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

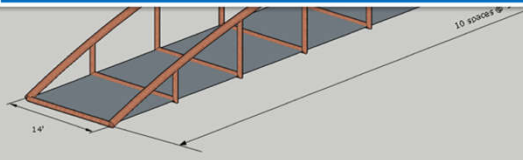




Larry Griffis '94
WALTER P MOORE
74

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

75

WALTER P. MOORE



AISC's Direct Analysis Method (2010-16)

Inelastic Analysis

← for 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 computation

Simplifications granted:

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

DM- Adv. Inelastic

76





More ← Prescriptive specification equations → Less
Less ← Directly modeling effects impacting stability → More

Given Design Situation

DM-Inelastic

Excuse me, will you please comment on those ladder columns


Sure, they were designed using AISC's Appendix 1



77

Detailed description: This slide features a diagram at the top with two horizontal arrows. The top arrow points left and is labeled 'More' at its tip and 'Less' at its tail, with the text 'Prescriptive specification equations' above it. The bottom arrow points right and is labeled 'Less' at its tip and 'More' at its tail, with the text 'Directly modeling effects impacting stability' below it. A red arrow points upwards from the right side of the diagram towards a red box labeled 'DM-Inelastic'. Below the diagram is a photograph of a man in a suit speaking at a podium to an audience. A blue speech bubble from the audience says 'Excuse me, will you please comment on those ladder columns'. Another blue speech bubble from the speaker says 'Sure, they were designed using AISC's Appendix 1'. An inset image shows a modern building with a large tree in front. The AISC logo is in the bottom left, and the LeMessurier logo is in the bottom right. The number 77 is in the bottom right corner.

Thoughts on future of advanced analysis in design...

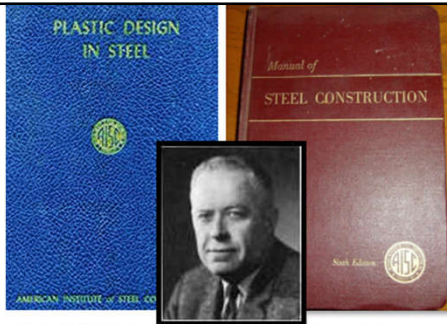


Starting with some history from TR Higgins's days...

Fifty-foot Two-span Continuous Gabled Frame Test at Lehigh University

78

Detailed description: This slide features a black and white photograph of a large-scale structural test. A complex steel frame is being tested in a laboratory. Several people are visible around the structure, some on ladders. A blue banner at the top reads 'Thoughts on future of advanced analysis in design...'. A blue banner at the bottom reads 'Starting with some history from TR Higgins's days...'. The AISC logo is in the bottom left. The caption 'Fifty-foot Two-span Continuous Gabled Frame Test at Lehigh University' is at the bottom center. The number 78 is in the bottom right corner.



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.



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

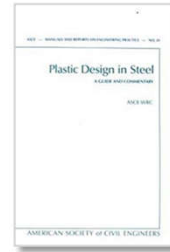
Plastic Design of a 14-Story Apartment Building
WILLIAM A. BENNETT
AISC ENGINEERING JOURNAL
APRIL / 1967

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...

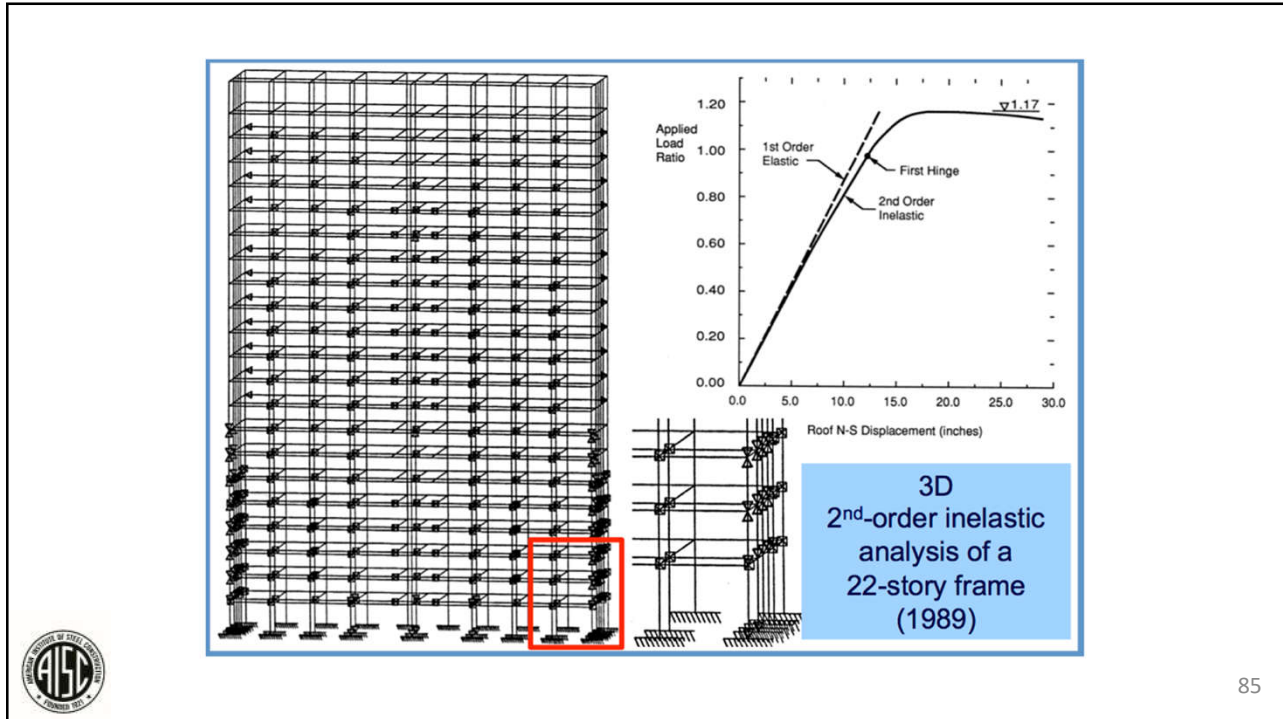
1970's

- Computing hardware
- Graphical user interfaces
- Geometric nonlinear:
 - 2nd-order effects ($P-\Delta$, $P-\delta$)
- Material nonlinear:
 - Plastic hinge vs. zone

1990's



84



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 ($P-\Delta$, $P-\delta$)
- Material nonlinear:
 - Plastic hinge vs. zone

1990's

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



87


AS 4100 - 1990
Australian Standard™

Steel structures



Wow!

APPENDIX D
ADVANCED STRUCTURAL ANALYSIS
(Normative)

Building Code of Australia
primary referenced Standard

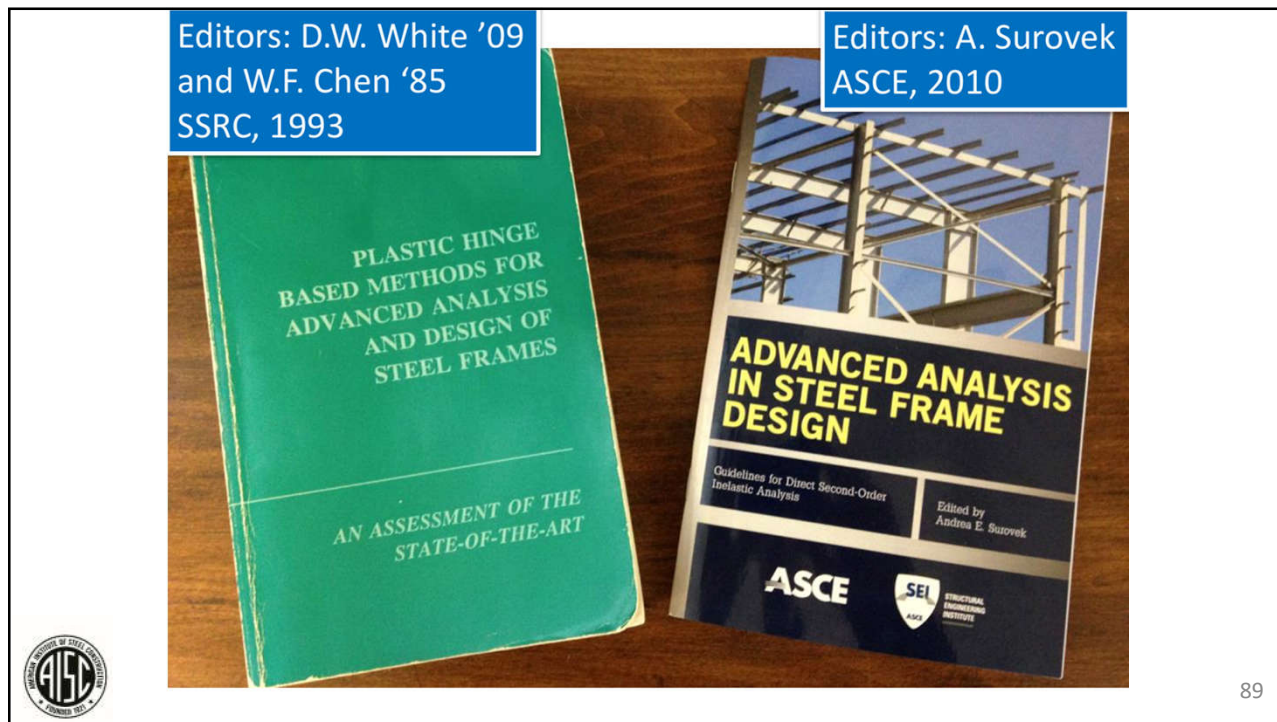


ABCB
Australian Building Codes Board



88





89

SPECIFICATION

For Structural Steel Buildings

June 22, 2010

2010

APPENDIX 1

DESIGN BY INELASTIC ANALYSIS

This appendix addresses design by *inelastic analysis*, in which consideration of the redistribution of member and connection forces and moments as a result of localized yielding is permitted.

The appendix is organized as follows:

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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92



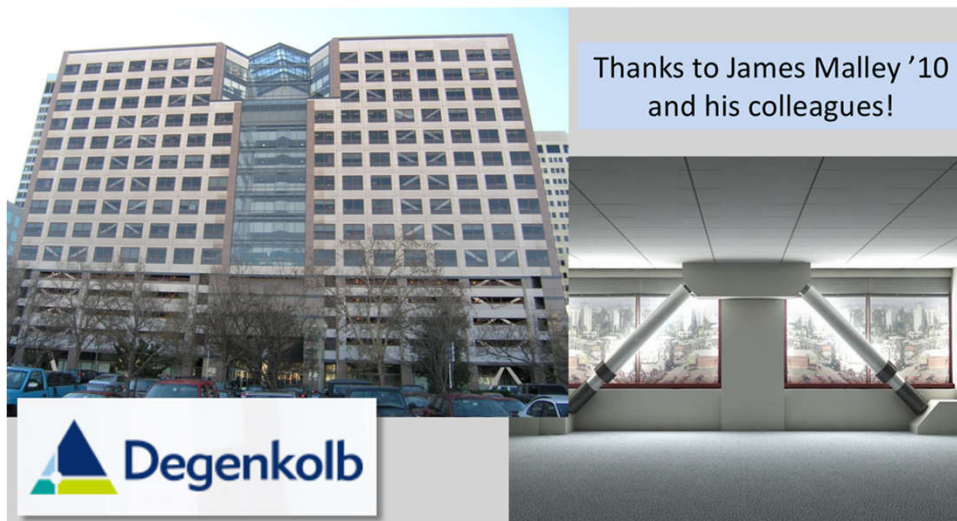
Inelastic analysis and seismic design, perfect together...

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 - AISC 341 may include a new Appendix 1 - Design Verification Using Nonlinear Response History Analysis



93

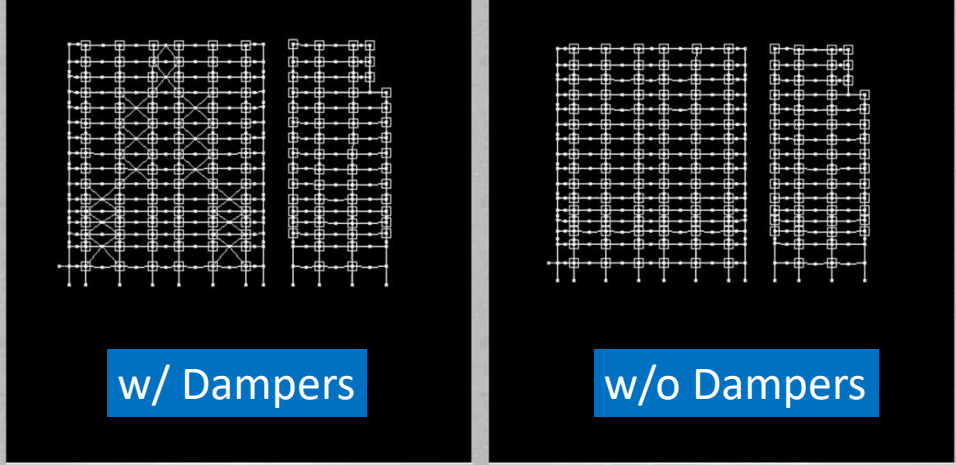
Caltrans District 4 Office Building retrofitted with viscous dampers (Oakland, CA)



94





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



w/ Dampers

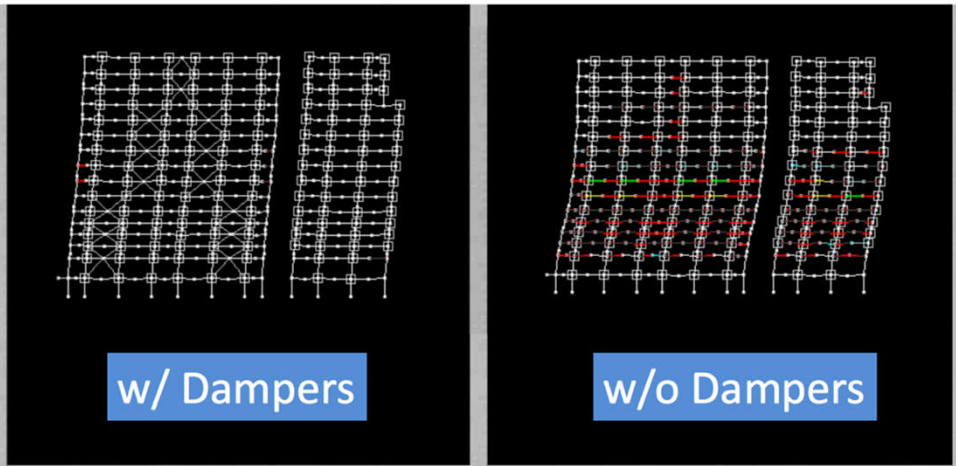
w/o Dampers

Nonlinear time history analysis results



95



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



w/ Dampers

w/o Dampers

Nonlinear time history analysis results



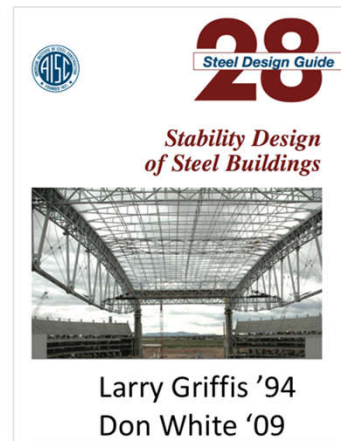
96





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)



97

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

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

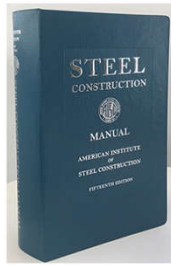
Ronald D. Ziemian^{a,*}, Constance W. Ziemian^b

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.

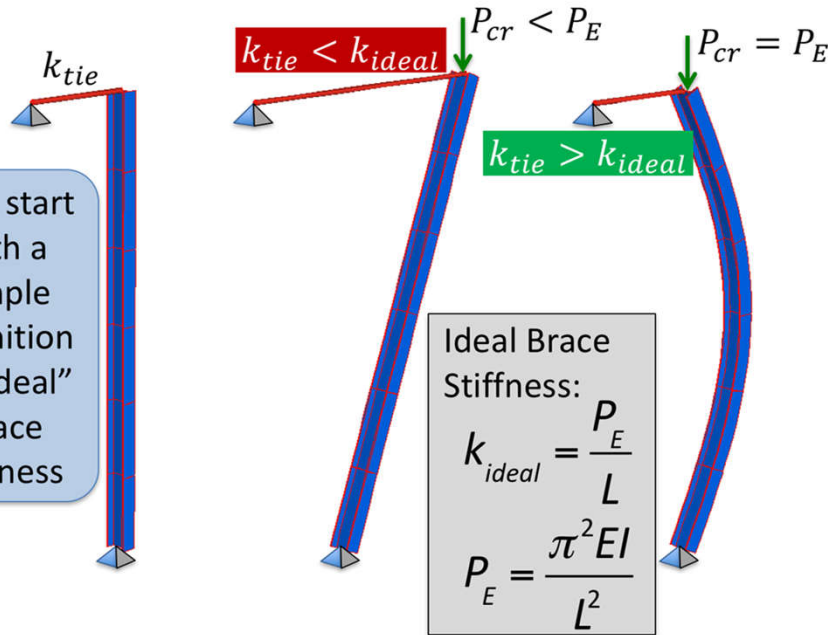
6.1. GENERAL PROVISIONS

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




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

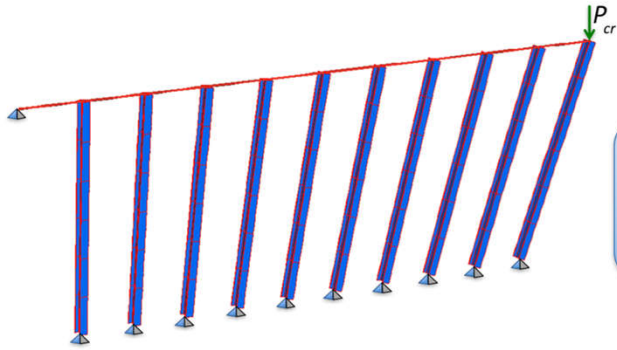
$k_{ideal} = \frac{P_E}{L} = \frac{\pi^2 EI}{L^3}$

$k_{tie} < k_{ideal}$
 $P_{cr} < P_E$

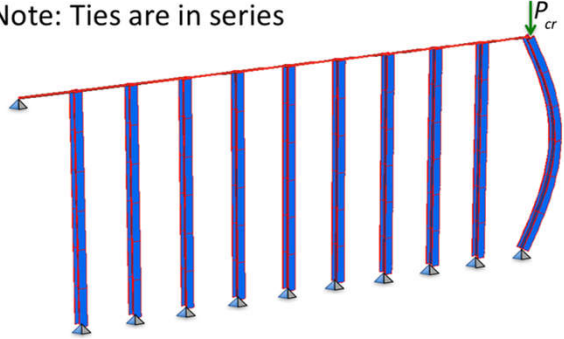
$k_{tie} > k_{ideal}$
 $P_{cr} = P_E$



102




Note: Ties are in series

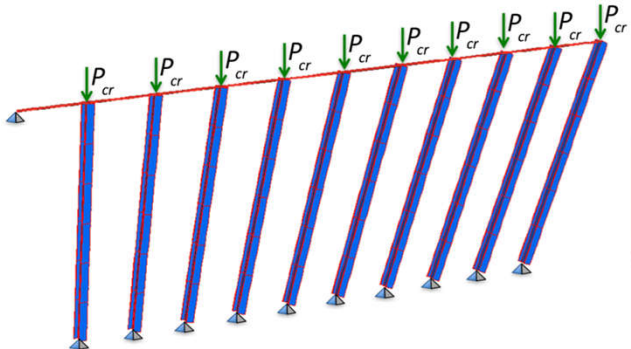
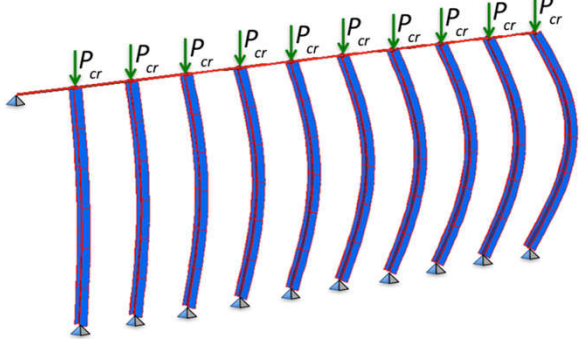


$$k_{ideal} = \frac{P_E}{L} = \frac{\pi^2 EI}{L^3}$$

$k_{tie} < 10 k_{ideal}$
 $P_{cr} < P_E$

$k_{tie} > 10 k_{ideal}$
 $P_{cr} = P_E$



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 compatibility on the deformed shape!)
 - Curved-fitted parabolic function

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



105

So, where did that threshold of 44.8 come from?

- Advanced analysis – trial and error using elastic critical load (eigenvalue) analyses
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 - Curved-fitted parabolic function

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



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

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

$$k_{tie} < a_{max} k_{ideal}$$

$$P_{cr} < P_E$$

$$k_{tie} > a_{max} k_{ideal}$$

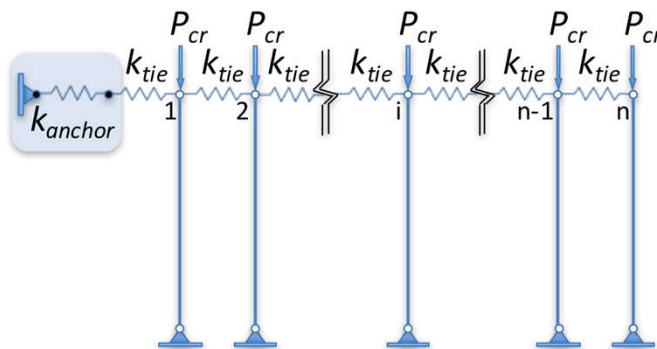
$$P_{cr} = P_E$$

Very Cool!

107



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



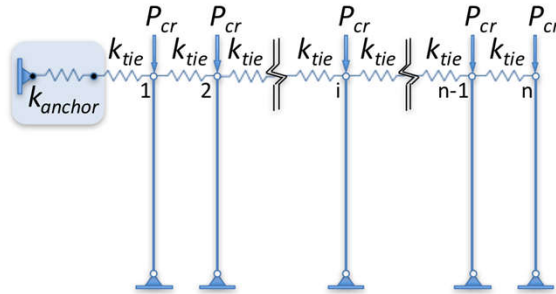
For a given number of parallel columns n :

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 bracing combinations with a non-rigid anchor



Rigid anchor check:

- $k_{anchor} = \text{infinity}$
- $c = 0$
- $a_{max} = 0.4n^2 + 0.4n + 0.2$
- ✓ $k_{tie} > a_{max}(P_E/L)$

Rigid tie check:

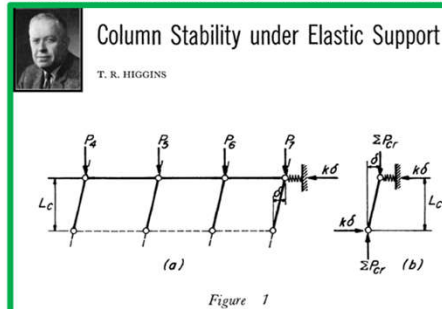
- $k_{tie} = \text{infinity}$
- $c = \text{infinity}$
- $a_{max}/c = n$
- ✓ $k_{anchor} > n(P_E/L)$

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 $k_{anchor} > (a_{max}/c)(P_E/L)$



Multiple Columns: Minimum bracing combinations with a non-rigid anchor



$$k = \sum k_n = \sum P_{cr}/L_c$$

Rigid anchor check:

- $k_{anchor} = \text{infinity}$
- $c = 0$
- $a_{max} = 0.4n^2 + 0.4n + 0.2$
- ✓ $k_{tie} > a_{max}(P_E/L)$

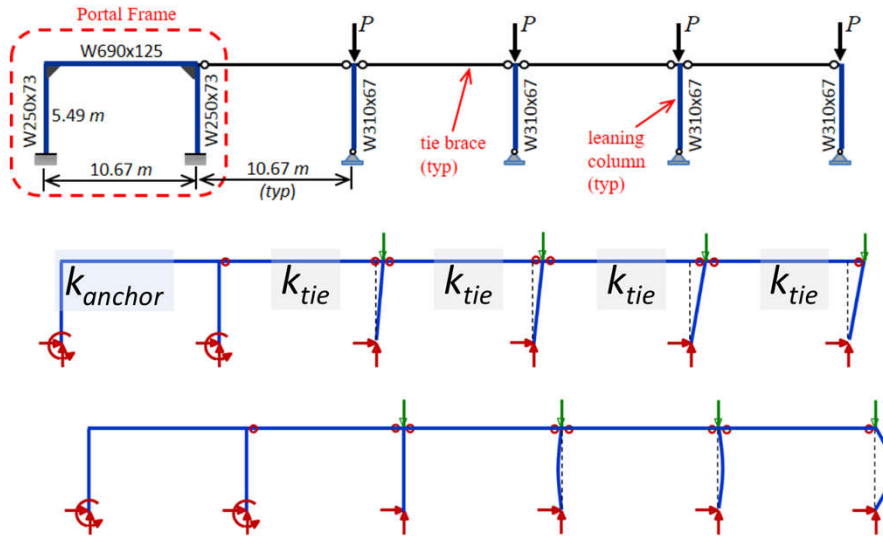
Rigid tie check:

- $k_{tie} = \text{infinity}$
- $c = \text{infinity}$
- $a_{max}/c = n$
- ✓ $k_{anchor} > n(P_E/L)$

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 $k_{anchor} > (a_{max}/c)(P_E/L)$



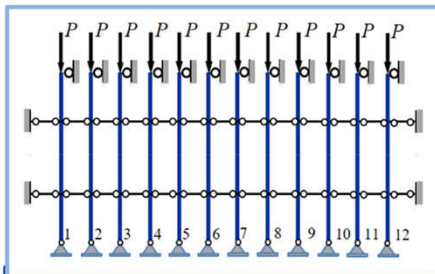
Applied to buildings with lots of leaning columns...



$$k_{tie} > a_{max}(P_E/L) \quad \text{and} \quad k_{anchor} > (a_{max}/c)(P_E/L)$$

111

What is the minimum “bridging” stiffness for a system of parallel studs?



$$k_{tie} = \frac{1}{\frac{1}{k_{strut}} + \frac{1}{k_{weld}} + \frac{1}{k_{web}}}$$

$$k_{tie} \ll \min(k_{strut}, k_{weld}, k_{web})$$


112

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

Stiffness of bridging

Stiffness of anchorage


- connection clips
- column member
- support



113

8 parallel joists

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

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


114

Always time for a joist story... $1.2 \times 250 = 300 \text{ lb}$

Ted Galambos '81 Matt Kawczenski Matt Emerson

Details...


SOME CLOSING THOUGHTS ON EDUCATION





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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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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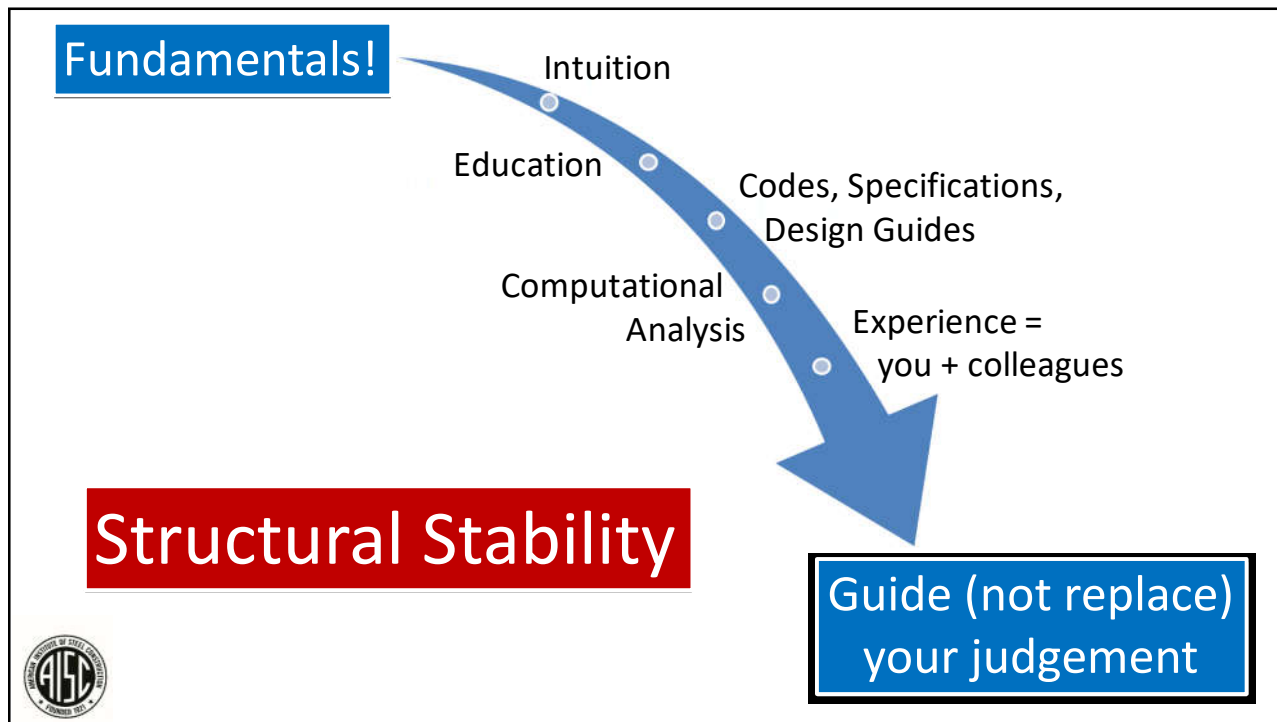
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AISC | Questions?



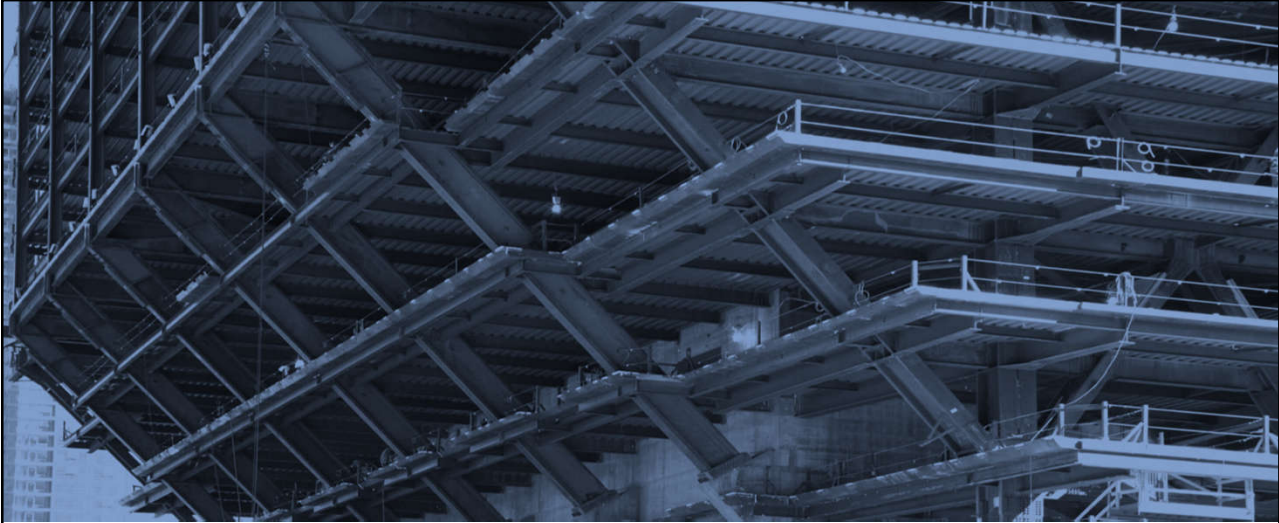
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AISC | Thank you

