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Conference ID: 74412835

There’s always a solution in Steel
Today’s live webinar will begin shortly. Please standby. As a reminder, all lines have been muted. Please type any questions or comments through the Chat feature on the left portion of your screen.

Today’s audio will be broadcast through the internet. Alternatively, to hear the audio through the phone, dial (855) 697-4479

Conference ID: 74412835
With a basic understanding of linear and nonlinear analysis now in hand, it is time to explore and gain hands-on experience in understanding factors that are known to impact structural stability. As an alternative to experimental testing, nonlinear computational analysis can provide a virtual lab for investigating numerous important concepts related to the design for stability. An overview of several learning modules developed for a better understanding of topics such as elastic and inelastic flexural and lateral-torsional buckling, inelastic force redistribution, and second-order effects will be presented.
Learning Objectives

- Become familiar with how non-linear computational analysis can help develop a better understanding of stability concepts.
- Gain hands-on experience in understanding factors that are known to impact structural stability through the use of structural analysis software.
- Become familiar with elastic and inelastic flexural and lateral-torsional buckling, inelastic force redistribution, and second-order effects.
- Develop a better understanding of elastic and inelastic flexural and lateral-torsional buckling, inelastic force redistribution, and second-order effects through design examples and structural analysis software demonstrations.
Course Overview

Session Topics

- Course Intro. and Modern Analysis (1 & 2)
- Resources for Learning Stability by Analysis (3)
- Second-Order Analysis (4)
- Direct Analysis Method (5)
- Low- and Medium-Rise Steel Buildings (6)
- Advanced Application of Stability Design (7)
- Design by Inelastic Analysis (8)

Lectures by members of the Structural Stability Research Council (SSRC)
- Don White and Ron Ziemian
- Great to join AISC in this effort!

Impetus:

Limit States Design

- AISC Ch. C: P-Δ, P-δ (DM)
  - App. 1.1: DM - DMMI
  - App. 1.2: Inelastic
- Design
- Seismic: Pushover Analysis
- Other: Progressive Collapse

Nonlinear Analysis

Available Software: MASTAN2

Research

Education:
- Textbook and Learning Modules
Challenge of Designing Steel Structures

Strength/Weight + Stiffness/Weight + Competitive $

\downarrow

Slender Members and Systems

\downarrow

Design for Stability!

Structural Stability & The Curse of the Differential Equation

At Cinemas October 14
Challenge of Designing Steel Structures

✓ Understanding Structural Stability
  • General Behavior
    - Physical observations (go to the lab!)
    - Virtual observations (go to the computer!)
    - Hear it described in lecture
    - Read about it in the book
  • “Exact” Solutions
    - Differential Equations (limited by assumptions)
    - Computational Analysis (much less limited)

✓ See the forest for the trees
✓ Engage the student - Active Learning

Physical Labs would be ideal, but...
Virtual Laboratory

In early 2000...

- Rewritten to include new chapters on nonlinear analysis
- Educational software MASTAN2 developed and bundled with textbook
  - MATLAB-based, available on all platforms
  - Included suite of nonlinear analysis options
  - “Easy to use” GUI quickly led to MASTAN2 taking on a life independent of the textbook

Virtual Laboratory

2000-present...

- Elastic nonlinear options become the norm in commercial analysis software
- Other educational/research analysis software is developed that includes geometric and material nonlinear capabilities
- MASTAN2 continues to develop
  - Standalone versions available on PC and Mac
  - Available at no cost over the web, www.mastan2.com
  - Adopted at many universities world-wide for use in undergraduate and graduate analysis and design courses
Virtual Laboratory

✓ Needs for simulating structural stability problems
  - Partial yielding accentuated by residual stresses
  - Full cross-section yielding, plastic hinge
  - Local buckling, elastic/inelastic
  - Flexural buckling, elastic/inelastic
  - Torsional buckling, elastic/inelastic
  - Lateral-torsional buckling, elastic/inelastic
  - Flexural-torsional buckling, elastic/inelastic
  - Above buckling strengths reduced by local buckling
  - Account for initial imperfections
    - out-of-plumb, out-of-straightness
  - Second-order effects $P\Delta$, $P\delta$
  - System instability, elastic/inelastic
Virtual Laboratory

✔ Simulating Structural Stability
  ▪ several analytical requirements

✔ Possibilities
  ▪ Commercial FEA software
    ABAQUS, ADINA, ANSYS, PERFORM3D, LARSA4D,…
  ▪ Educational FEA software
    OpenSees, FE++2012, GT-SABRE, BASP, Arcade,
    Dr. Frame, GBTUL, MASTAN2, ...

✔ Considerations for making the choice
  ▪ Price and availability
  ▪ Ease of use--- Learning curve!
  ▪ Experience

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

What if:
1. different unbraced length $L_b$?
2. different W-shape is employed?
3. different loading conditions?
4. different support conditions?
5. inelastic effects ex/included?
6. imperfection ex/included?
7. warping ex/included?

Overview of Learning Modules

✓ Objectives
- Have “fun” focusing on the stability of members and systems (sorry, no local buckling; CU-FSM!)
- Alternative to experimental laboratory
- Hands-on (“active learning”); what if scenarios?
- Software independent

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

✓ Students of all ages!
  - Undergraduates
  - Graduate students
  - Professionals

✓ Courses of all types
  - Steel design / Behavior of metal structures
  - Structural stability
  - Workshops and AISC Night School!

✓ Similar in concept to others
  - Prof. K. Martini, U.Va.-Architecture, Arcade
  - Prof. G. Miller, U.W.-CEE, Dr-Frame
Available Learning Modules

1. Elastic Column Buckling and the Effect of End Restraint
2. Factors Influencing the Flexural Buckling Strength of Compression Members
3. Effective Length $K$-factors for Frame Members
4. Factors Influencing the Strength of Flexural Members
5. Lateral-Torsional Buckling of Beams with Moment Gradient
6. Beam Design by Elastic and Inelastic Analyses
7. Second-order ($P$-$\Delta$ and $P$-$\delta$) Effects
8. Strength of Beam-Columns
9. Design by the Direct Analysis Method
LM1. Elastic Column Buckling and the Effect of End Restraint

Learning Objectives

- Verify theoretical elastic column buckling solutions
- Observe impact of end restraint on capacity and buckled shape
- Confirm the $K$-factors appearing in AISC Table C-A-7.1
First big Q: # of elements to model compression member?

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

<table>
<thead>
<tr>
<th></th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
<th>(e)</th>
<th>(f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical K value</td>
<td>0.5</td>
<td>0.7</td>
<td>1.0</td>
<td>1.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Buckled shape of column is shown by dashed line

P = 1 k

Compute 10 modes
Mode 1:
\[ P_{cr} = 273.6 \]
\[ K = \frac{\pi}{L} \sqrt{\frac{EI}{P_{cr}}} = 2.0 \]

Mode 2:
\[ P_{cr} = 273.6 \]
\[ K = \frac{\pi}{L} \sqrt{\frac{EI}{P_{cr}}} = 2.0 \]
Mode 3:

\[ P_{cr} = 1094.5 \]

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

Mode 4:

\[ P_{cr} = 1094.5 \]

\[ K = \frac{\pi}{L} \sqrt{\frac{EI}{P_{cr}}} = 1.0 \]
Mode 5:

\[ P_{cr} = 2239.2 \]

\[ K = \frac{\pi}{L} \sqrt{\frac{EI}{P_{cr}}} = 0.7 \]
Mode 9:

\[ P_{cr} = 4380 \]

\[ K = \frac{\pi}{L} \sqrt{\frac{EI}{P_{cr}}} = 0.5 \]

More Fun!

Vary beam size w/

\[ I_{\text{Beam Top}} = I_{\text{Beam Bottom}} \]

More Fun!

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LM2. Factors Influencing the Flexural Buckling Strength of Compression Members

Learning Objectives

- Recognize limitations of theoretical Euler buckling solution
- Prepare column curves ($F_{cr}$ vs. $L/r$)
- Observe impact of initial imperfections and residual stresses
- Compare results to AISC column curve
LM2

- W14x53 (A992)
- \( L/r_y = 5 \) to 190
- For each \( L/r_y \), investigate 9 cases:
  - Full yield
  - Euler
  - AISC
  - Computational analysis
    - Incremental
      - no imperfection \( \delta_0 / \sigma_{\text{res}} \)
      - imperfection \( \delta_0 / \sigma_{\text{res}} \)
      - no imperfection \( \delta_0 / \sigma_{\text{res}} \)
      - imperfection \( \delta_0 / \sigma_{\text{res}} \)
    - Critical Load (eigenvalue)
      - elastic
      - inelastic
Euler
AISC
no $\delta_o$ / no $\sigma_{res}$
$\delta_o$ / no $\sigma_{res}$
no $\delta_o$ / $\sigma_{res}$
$\delta_o$ / $\sigma_{res}$
ECL
ICL

Compr. Strength vs. L/r

Thanks to Dan Tamarkin
LM3. Effective Length $K$-factors for Frame Members

Learning Objectives

- Elastic/inelastic buckling of frames with sidesway inhibited/uninhibited
- Back-calculate $K$-factors from elastic/inelastic critical load analyses
- Employ alignment charts to obtain elastic/inelastic $K$-factors and assess alignment chart assumptions
- Compare alignment chart and computational results
LM4. Factors Influencing the Strength of Flexural Members

Learning Objectives
- Recognize limitations of theoretical elastic lateral-torsional buckling solution
- Prepare beam curves ($M_n$ vs. $L_b$).
- Impact that partial yielding/residual stresses and out-of-straightness on elastic/inelastic LTB strength
- Compare with AISC beam strength curve

Sister to LM2...

- W14x53 (A992)
- $L_b = 1.2$ to $31.1$ ft.
- For each $L_b$, investigate 9 cases:
  - Full yield
  - Theoretical elastic LTB
  - AISC
  - Computational analysis
    - Incremental
      - no imperfection $\delta_0 / no \sigma_{res}$
      - imperfection $\delta_0 / no \sigma_{res}$
      - no imperfection $\delta_0 / \sigma_{res}$
      - imperfection $\delta_0 / \sigma_{res}$
    - Elastic critical load (eigenvalue)
    - FEA shell elements (ADINA)
LM5. Lateral-Torsional Buckling of Beams with Moment Gradient

Learning Objectives

- Effect of non-uniform moment distribution on elastic LTB strength
- Back-calculate $C_b$ from critical load analyses
- Compute $C_b$ from well-established equations and compare with computational results
- Investigate moment gradient distributions of linear, bi-linear, and parabolic
- Study impact of adding an interior brace point

Fig. C-F1.2. Nominal flexural strength as a function of unbraced length and moment gradient.
\[ C_b = \frac{12.5 M_{\text{max}}}{2.5 M_{\text{max}} + 3 M_A + 4 M_B + 3 M_C} \]
Thanks to Yue Hua

Wong and Driver, AISC EJ, 2010
Time for you to take it for a spin…

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

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

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

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

$M_{cr} (\text{nonuniform}) = 300 \text{ kip-ft}$

**Observations:**

<table>
<thead>
<tr>
<th>$M_{cr}$ (kip-in)</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_1/M_2 = -1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_1/M_2 = +1$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Warping resistance included in analysis

Warping resistance not included in analysis

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

\[ = 300 \text{ kip-ft} \]
### Case 1

- $M_1/M_2 = -1$: $3,602$
- $M_1/M_2 = +1$: $9,838$

### Case 2

- $M_1/M_2 = -1$: $12,120$
- $M_1/M_2 = +1$: $27,414$
### Observations:

- $M_{cr}$ increases as $L_b$ is reduced
- $M_{cr}$ increases as moment gradient increases
- An inflection point is not a brace point!

### Learning Objectives

- Compare designs of continuous beams using elastic and inelastic analyses
- Observe pros and cons of each design method
- Employ AISC’s 9/10ths moment redistribution allowance
- Investigate force/moment redistribution that occurs as a result of member yielding.
LM6: Elastic vs. Inelastic Design

**4 Cases:**
1. All members W16x31, \( P_u = ? \)
2. W27x84, W16x31, W18x35, \( P_u = ? \)
3. All members same size, \( P_u = 200k \), min. weight?
4. Members sizes may vary, \( P_u = 200k \), min. weight?

**3 AISC Designs:**
- Elastic vs. Elastic 9/10 vs. Inelastic

### Case 2: Inelastic Analysis

\[ P_u = 101.3 \text{ kip} \]
\[ W_t = 1.881 \text{ kip} \]
\[ P_u / W_t = 53.84 \]
LM7. Second-order Effects
(P-Δ and P-δ) Effects

Learning Objectives

- Employ second-order elastic analysis
- Observe the relationship between extent of moment amplification and \( P/P_e \)
- Investigate the impact of single or double(reverse) curvature bending has on the degree of moment amplification
- Compute and assess the AISC moment amplification factor \( B_1 \) defined in App. 8

1st-order vs. 2nd-order

\[
M_1/M_2 = \pm 0.75, 0.0, -0.75
\]

\[
P/P_e = 0, 0.1, 0.2, ..., 0.9
\]

Rigorous vs. \( B_1, B_2 \)

\[
P/P_e =
\begin{align*}
0.000, \\
0.122, \\
0.244, \\
0.367,
\end{align*}
\]

\[
P/P_e =
\begin{align*}
0.000, \\
0.326, \\
0.489, \\
0.652,
\end{align*}
\]
**Session 3: Modules for Learning Structural Stability**

- $M_{1\text{max}} = 200 \text{ k-in}$
- $M_{2\text{max}} = 391 \text{ k-in}$
- $B_1^{\text{Computation}} = \frac{391}{200} = 1.96$

- $M_1^{\text{1st}} = -150 \text{ k-in}$
- $M_2^{\text{1st}} = +200 \text{ k-in} \left( = M_{\text{max}}^{\text{1st}} \right)$
- $C_m = 0.6 - 0.4(-150/200) = 0.9$
- $P/P_e = 0.5 \left( B_1^{\text{AISC}} = \frac{0.9}{1-0.5} = 1.8 \right)$
- $M_{2\text{max}} = B_1^{\text{AISC}} M_{\text{max}}^{\text{1st}}$
- $M_{2\text{max}} = 1.8 \times 200 = 360 \text{ k-in}$

---

**Discussion**

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

*Thanks to Dan Tamarkin*
LM8. Strength of Beam-Columns

Learning Objectives

- Axial plus major- or minor-axis flexure
- Strength limit state behavior of beam-columns, including full yielding to elastic/inelastic flexural and lateral torsional buckling
- Prepare interaction curves \( (P/P_y - M/M_p) \)
- Compare results of the AISC interaction equation and computational analysis

Mother to LM2 and LM4...
W14x53 (A992), $L_b = 15$ ft.

Investigated:
- $P-M_{\text{major}}$
- $P-M_{\text{minor}}$

- Provided range of $P-M_{\text{end}}$'s that satisfy AISC interaction eq. H1-1 (student’s to confirm)
- Determined strength according to 2nd-order inelastic analysis
- Wide range of failure modes including: full yielding, elastic/inelastic -LTB, -FTB

![Diagram showing LM8 with end moments and loads](image)

![Graph showing deflected shape and load-moment interaction](image)
LM9. Design by the Direct Analysis Method

Learning Objectives

- Apply the Direct Analysis Method.
- 2nd-order analyses to determine \( P_u \)’s and \( M_u \)’s
- Utilize notional loads in place of direct modeling of \( \Delta_0 \) and \( \tau_b \)
- Practice with interaction equation
- Use the ratio of 2nd- to 1st-order drifts as an indicator of a system’s sensitivity to 2nd-order effects.
Two Parts:
1. With \( Q_u = 100 \text{ kips} \), check design:
   a. DM with explicit modeling of \( \Delta_0 \) and \( \tau_0 \)
   b. DM with equivalent notional loads
2. Determine maximum \( Q_u \) that satisfies AISC Spec. by employing DM with explicit modeling of \( \Delta_0 \) and \( \tau_0 \)
1st-Order Elastic

Frame 1

Vertical load $P$ has no impact on M-diagram

2nd-Order Elastic

Frame 1

Vertical load $P$ has 44% increase on M-values (P-$\Delta$ lives!)
**LM9**

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

<table>
<thead>
<tr>
<th>Member</th>
<th>$P_a$ (kips)</th>
<th>$\phi_0 P_a$ (kips)</th>
<th>$M_u$ (kip-in)</th>
<th>$\phi_0 M_u$ (kip-in)</th>
<th>AISC Eq. H1-1a/b</th>
<th>OK/NG?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Column</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Column</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Also includes making a comparison with 2nd-order inelastic analysis according to AISC Appendix 1 provisions.

- More Fun!
  - Requests design check by Effective Length Method and 1st-Order Analysis Method, both appearing in AISC Appendix 7
  (DM: $K = 1$, $P_n = 603k$ and ELF: $K = 2.1$, $P_n = 275k$)
- Very interesting comparisons...
Lessons Learned

✓ All modules fully tested in my CENG405-Design of Steel Structures course and now, many others worldwide...

✓ Students (and Practitioners!):
  ▪ Learn to read and follow instructions
  ▪ Find MS Excel LM spreadsheets key to quickly prepare comparative tables
  ▪ Enjoy the LM Tutorials available on YouTube.com
  ▪ Welcome opportunity to employ nonlinear structural analysis software
  ▪ Benefited from the hands-on approach to learning structural stability

Future Modules

✓ Your suggestions!
  ▪ e-mail me at ziemian@bucknell.edu

✓ Yura’s Five Useful Stability Concepts
  ▪ leaning column
  ▪ bracing (nearly complete!)
  ▪ some already included in LM’s...

✓ Stability of slender cross-sections
  ▪ CU-FSM
Summary

✓ Virtual Laboratory
✓ Reviewed 9 Learning Modules related to structural stability, 3 with MASTAN2
✓ Each Module includes:
  ▪ Assignment (PDF, MS Word)
  ▪ MS Excel Spreadsheet of key tables
  ▪ Links to LM tutorials on YouTube.com
✓ Encourage you to try some or all...
✓ Customizing of LM’s permitted!

Questions?
Up Next...

- Session 4: February 23 – Second-Order Elastic Analysis – Getting it Right by D.W. White, PhD
- Various methods of second-order elastic frame analysis, ranging from intelligent application of amplification factors with first-order analysis to three-dimensional matrix structural analysis models, are reviewed. Emphasis is on the sufficiency of the methods for different problems, methods of sanity checking and ensuring that the analysis is correct, and various essential concepts important for design application.

Individual Webinar Registrants

CEU/PDH Certificates

Within 2 business days...

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

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There’s always a solution in Steel

---

Individual Webinar Registrants

CEU/PDH Certificates

Within 2 business days...

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

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8-Session Registrants

CEU/PDH Certificates

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

Access to the quiz: Information for accessing the quiz will be emailed to you by Wednesday. It will contain a link to access the quiz. EMAIL COMES FROM NIGHTSCHOOL@AISC.ORG

Quiz and Attendance records: Posted Tuesday mornings. www.aisc.org/nightschool - click on Current Course Details.

Reasons for quiz:

- EEU – must take all quizzes and final to receive EEU
- CEUs/PDHS – If you watch a recorded session you must take quiz for CEUs/PDHs.
- REINFORCEMENT – Reinforce what you learned tonight. Get more out of the course.

NOTE: If you attend the live presentation, you do not have to take the quizzes to receive CEUs/PDHs.
8-Session Registrants

Access to the recording: Information for accessing the recording will be emailed to you by this Wednesday. The recording will be available for two weeks. For 8-session registrants only. EMAIL COMES FROM NIGHTSCHOOL@AISC.ORG.

CEUs/PDHs – If you watch a recorded session you must take AND PASS the quiz for CEUs/PDHs.

Thank You

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