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Copyright Materials

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Course Description

More Opportunities - Design by Inelastic Analysis
March 30, 2015

In the 14th edition of the AISC Specification, the provisions for employing inelastic analysis in design have been fully revised. Certain levels of inelastic analysis may now be used in place of the Specification's design equations when confirming the adequacy of the structural system and its components. The associated requirements for this approach will be reviewed and examples presented.

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Learning Objectives

- Become familiar with the history of plastic design.
- Gain an understanding of the opportunities available for designing steel structures by inelastic analysis.
- Comprehend the specific requirements for employing inelastic analysis to design steel structures.
- By understanding the details of several examples to be presented, appreciate the benefits of designing by inelastic analysis.
- Become familiar with the methods of computational structural analysis.

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There's always a solution in steel.

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

Session 8
More Opportunities –
Design by Inelastic Analysis

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

structural STEEL

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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!

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

<u>Session 8</u>

More Opportunities – Design by Inelastic Analysis

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Impetus:

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

Limit States Design

Nonlinear Analysis

Available Software

Education

Research

11

Let's start with some interesting history…

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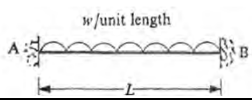
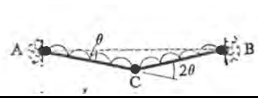
Gábor von Kazinczy (1889-1964)

- Pioneer of the ultimate load method
- In <u>1914</u>, he tested two 6 meter long steel beams with both ends fixed in concrete.
- Upon full loading and unloading, observed permanent kinking deformations at the two ends and at the center.
- Kazinczy called these kinks 'hinges', and he stated that a fixed-ended beam cannot collapse (undergo unbound deflections) until three hinges have formed (mechanism!).
- Together with Maier-Leibnitz, Baker, and van den Broek, Kazinczy made a major contributions to assuring the plastic hinge method was an option within the structural design process (1925–50).





"PLASTIC HINGE"

13

Sir John F. Baker (1901-1985)

- Professor and Head of Department, Cambridge University
- As a result of his efforts, British Standard 449 was modified to permit plastic design in <u>1948</u>
- Several buildings on Cambridge's campus designed by plastic design, with first being the Welding Institute at Abington
- Instrumental to the development of Morrison shelters (mass produced!)

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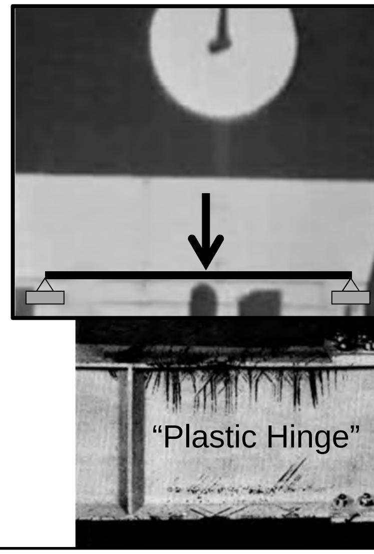
John Baker (1901-1985)

- Technical Officer- Steel Structures Research Committee (1929)
- By late 1950's. plastic design taught in the undergraduate engineering courses at Cambridge U.



15

Determine the Controlling mechanism…

Plastic Theory of Structures

by

MICHAEL R. HORNE

Beyer Professor of Civil Engineering, University of Manchester, England

PERGAMON PRESS

OXFORD · NEW YORK · TORONTO · SYDNEY · PARIS · FRANKFURT

PLASTIC ANALYSIS OF STRUCTURES

PHILIP G. HODGE, Jr., Ph.D.

Professor of Mechanics

McGRAW-HILL BOOK COMPANY, INC.

New York Toronto London

1959

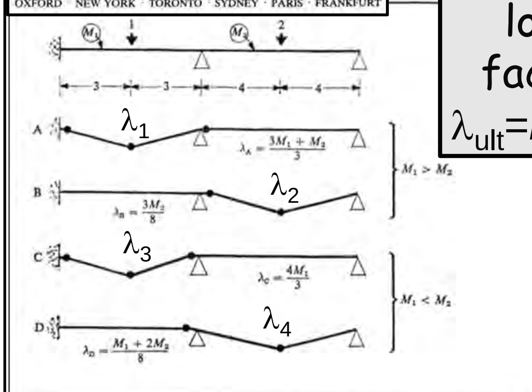


Figure 4.2 Possible design mechanisms for two-span beam

Ultimate load factor

$\lambda_{ult} = min\ \lambda_i$

PLASTIC ANALYSIS OF STRUCTURES

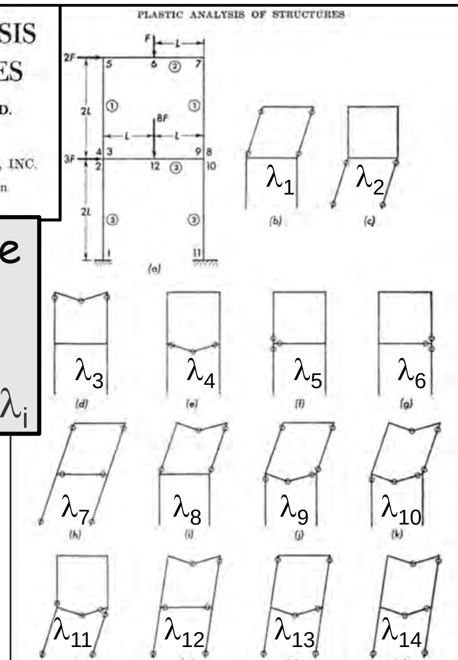


FIG. 2-2. Two-story frame. (a) Loaded frame. (b, c) Elementary panel mechanisms. (d, e) Elementary beam mechanisms. (f, g) Joint mechanisms. (h) Combined panel mechanism. (i–o) Combined panel and beam mechanisms.

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Lynn S. Beedle (1917-2003)

- International authority on stability and the development of code criteria worldwide for steel and composite structures
- Established CRC (later became SSRC) as pre-eminent structural stability organization
- Outstanding contributor to SSRC for 50+ years; Lynn S. Beedle Award
- Leader in promoting plastic design in U.S.

WHY PLASTIC DESIGN

by

Lynn S. Beedle

November, 1956

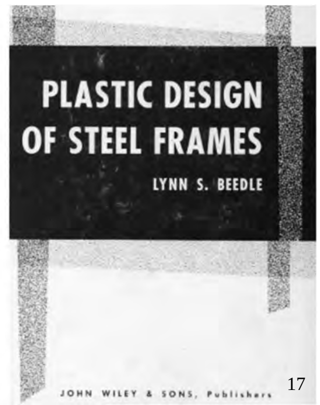
Prepared for delivery to
AISC-USC Conference on

PLASTIC DESIGN IN STRUCTURAL STEEL

Los Angeles, California

5. JUSTIFICATION OF PLASTIC DESIGN

(1) Economy
(2) Simplicity
(3) Rationality



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SPECIFICATION
FOR THE
DESIGN,
FABRICATION
& ERECTION
OF
STRUCTURAL
STEEL FOR
BUILDINGS
(ADOPTED NOVEMBER 30, 1961)

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.

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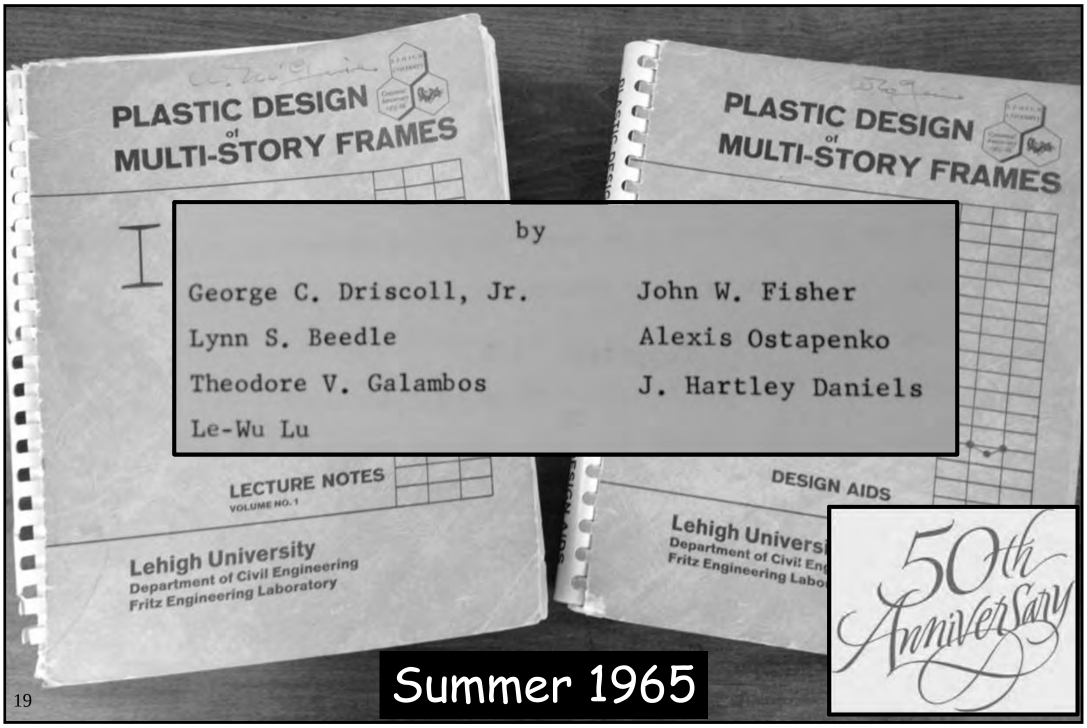
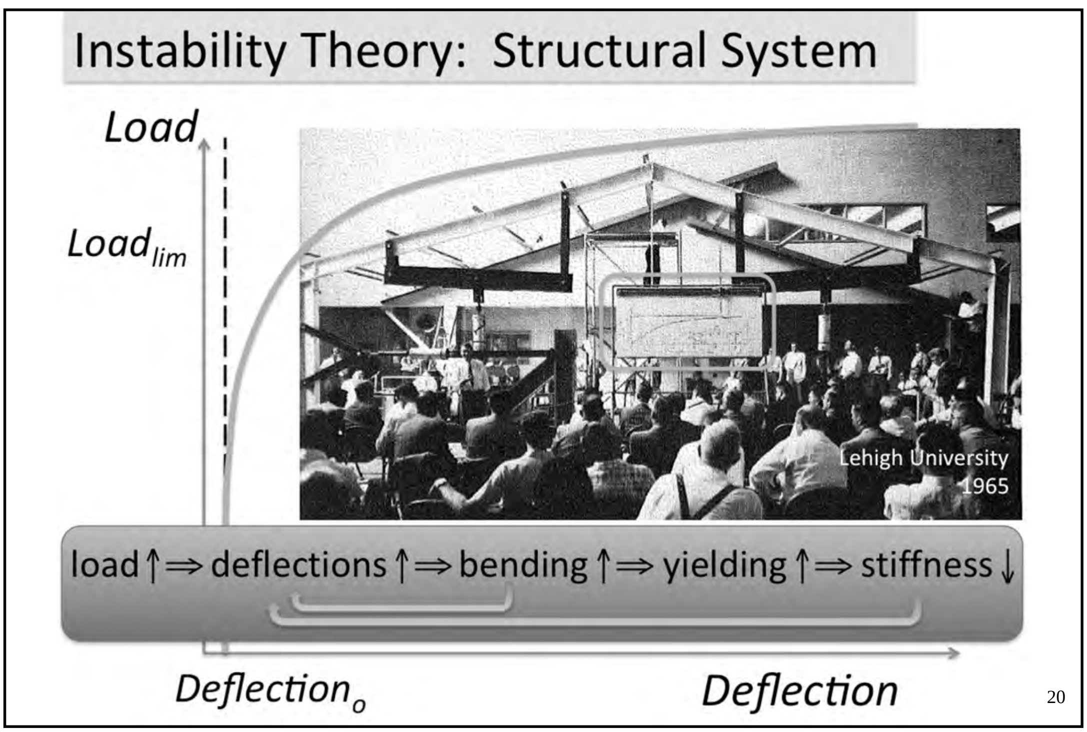
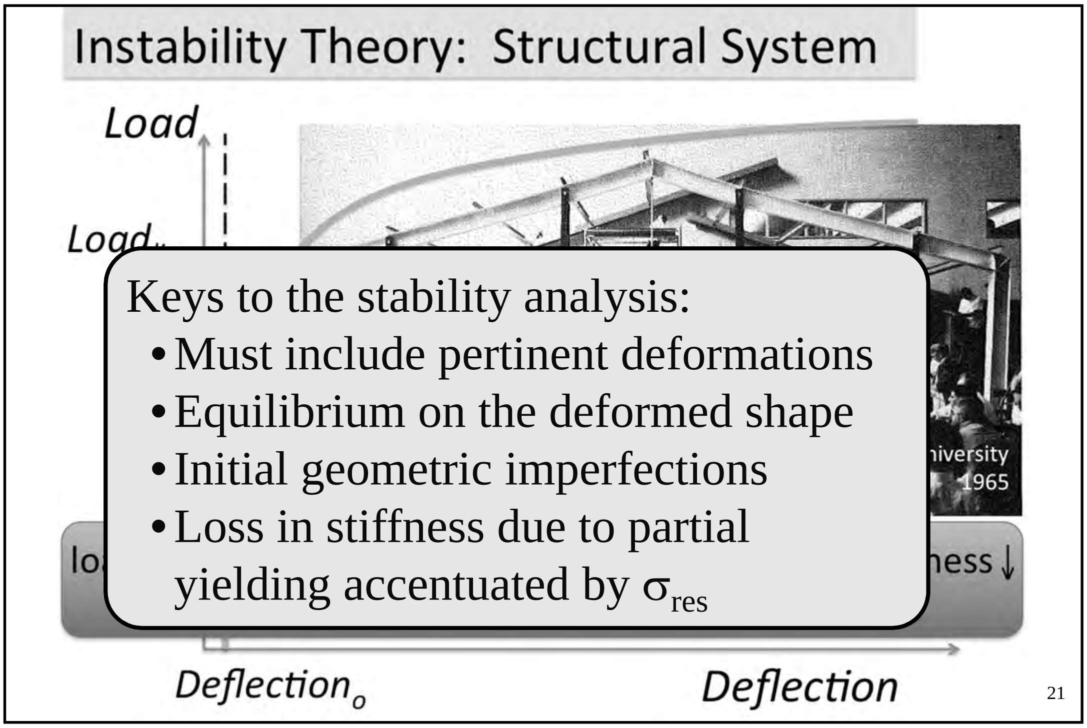
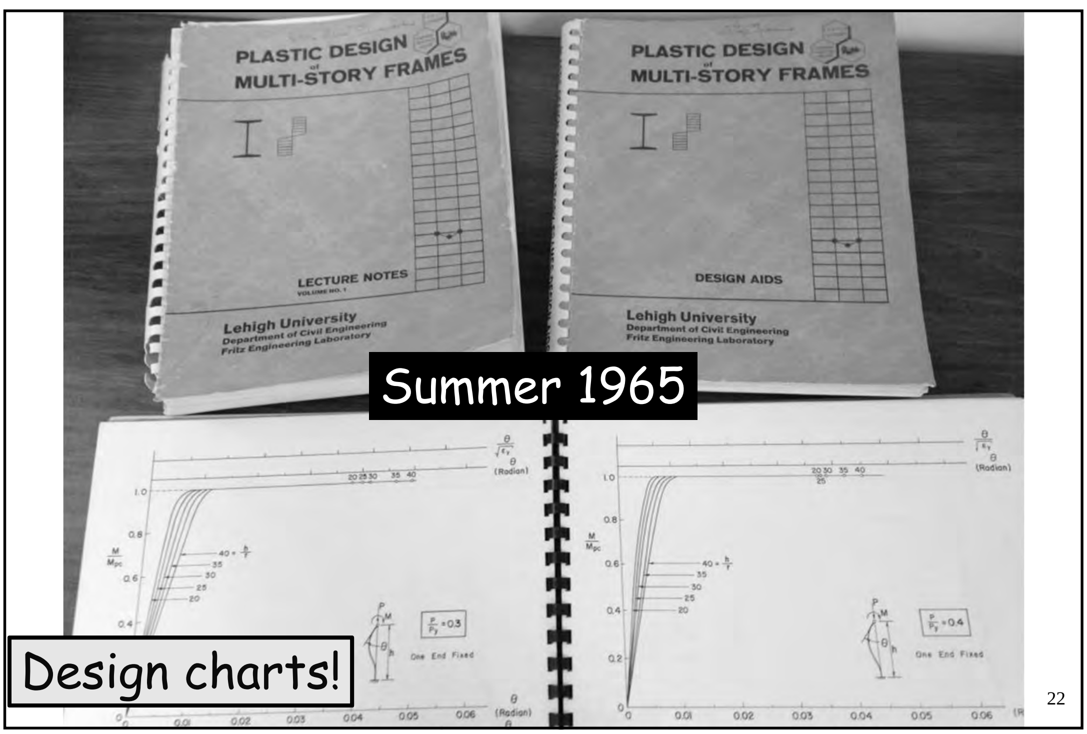

PLASTIC DESIGN of MULTI-STORY FRAMES
LECTURE NOTES
VOLUME NO. 1
Lehigh University
Department of Civil Engineering
Fritz Engineering Laboratory
PLASTIC DESIGN of MULTI-STORY FRAMES
DESIGN AIDS
by
George C. Driscoll, Jr.
Lynn S. Beedle
Theodore V. Galambos
Le-Wu Lu
John W. Fisher
Alexis Ostapenko
J. Hartley Daniels
50th Anniversary
Summer 1965
19


Instability Theory: Structural System
Load
Load$_{lim}$
Lehigh University
1965
load↑⇒ deflections↑⇒ bending↑⇒ yielding↑⇒ stiffness↓
Deflection$_o$
Deflection
20


Instability Theory: Structural System
Load
Load
Keys to the stability analysis:
• Must include pertinent deformations
• Equilibrium on the deformed shape
• Initial geometric imperfections
• Loss in stiffness due to partial yielding accentuated by σres
1965
Deflection
Deflection
21


PLASTIC DESIGN of MULTI-STORY FRAMES
LECTURE NOTES
Lehigh University
Department of Civil Engineering
Fritz Engineering Laboratory
PLASTIC DESIGN of MULTI-STORY FRAMES
DESIGN AIDS
Lehigh University
Department of Civil Engineering
Fritz Engineering Laboratory
Summer 1965
Design charts!
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Plastic Design of a 14-Story Apartment Building

WILLIAM A. BENNETT

AISC ENGINEERING JOURNAL
APRIL / 1967

THE SUBJECT of this paper is the plastic design of the steel frame of the 14-story Binghamton Apartment Tower in Binghamton, N. Y. (Fig. 1). The design method used was that advanced by the authors of the Lehigh University lecture notes entitled *Plastic Design of Multi-Story Frames.*

The Lehigh notes provide analytical methods for both braced and unbraced frames. The unbraced frame method was used for this project because architectural considerations prevented the use of X-bracing or shear walls.

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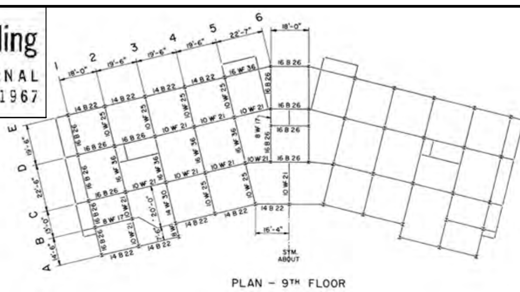
Plastic Design of a 14-Story Apartment Building

WILLIAM A. BENNETT

AISC ENGINEERING JOURNAL
APRIL / 1967

Figure 1

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



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Plastic Design of a 14-Story Apartment Building

WILLIAM A. BENNETT — AISC ENGINEERING JOURNAL APRIL / 1967

1967

Rational

Economy

Initial Δ_o's

It is possible by this method to determine whether hinges will form at the girder ends or at the column ends depending on whether there is a strong column, weak girder condition or the opposite. The greater the number of plastic hinges which can be developed, the more economical the design will be. It is also possible to limit the number of plastic hinges consistent with design requirements. Initial drift conditions due to unbalanced gravity loads may be large enough to require that the resulting shear be added or subtracted to the shear due to wind and the $P\Delta$ effect in computing story moments. For this frame initial drift conditions were not large and therefore disregarded.

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Plastic Design of a 14-Story Apartment Building

WILLIAM A. BENNETT — AISC ENGINEERING JOURNAL APRIL / 1967

1967

STRUCTURAL ANALYSIS

Track limit state response

Included 2nd-order effects

Through the application of a semigraphical method, the total lateral deformation behavior of a story can be determined. The members selected from a preliminary design will then be adequate if the load-deformation behavior of the story is satisfactory. This method takes into account the additional moment due to the $P\Delta$ effect, as well as the wind moment. (In a given column the axial force, P, displaced by an amount Δ, produces an additional overturning moment commonly referred to as the $P\Delta$ moment. This moment has been found to cause significant reductions in frame strength and must be accounted for in the analysis.) The ultimate load deflection index used is $\Delta/h = 0.02$, where h equals the story height. An initial graphical solution suited to any

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Plastic Design of a 14-Story Apartment Building

WILLIAM A. BENNETT

AISC ENGINEERING JOURNAL
APRIL / 1967

1967

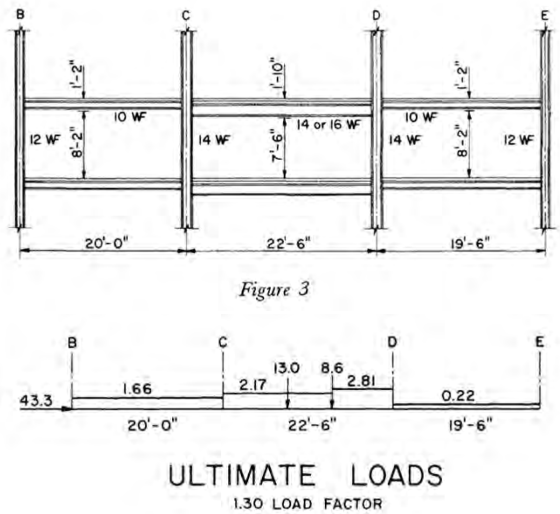
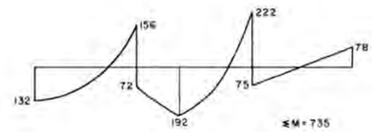
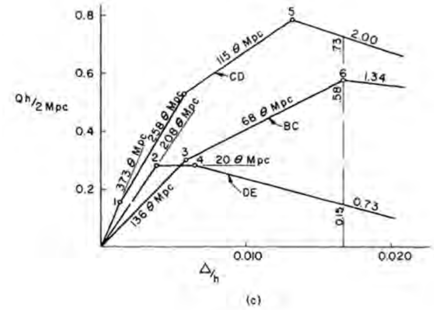


Figure 3

(a)



Limit state response:



Plastic hinge sequence:

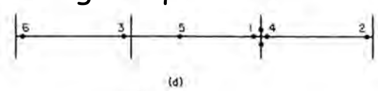


Figure 6

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Plastic Design of a 14-Story Apartment Building

WILLIAM A. BENNETT

AISC ENGINEERING JOURNAL
APRIL / 1967

1967

Quickly and accurately obtain an economical design

Flexibility in the design process

CONCLUSIONS

A complete analysis of all design factors was not intended in this article. It was assumed that frame buckling analysis for the condition where drift is minimal is easily handled. It would govern only the top few stories of the frame, and for these reasons was not discussed.

The writer feels that there are important advantages in the use of the plastic or ultimate strength method. After the designer has acquired the "feel" of the new method he can quickly and accurately determine frame requirements knowing that he has the most economical method available.

The designer has more freedom in evaluating how the frame will best meet varied architectural requirements. For instance, in the frame of the Binghamton Apartment Tower, beams for exterior bays were kept to a 10-in. depth and exterior columns to a 12-in. nominal

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1967

Plastic Design of a 14-Story Apartment Building

WILLIAM A. BENNETT

AISC ENGINEERING JOURNAL
APRIL / 1967

CONCLUSIONS

depth. Since the interior bay consists of heavier 14-in columns with 16-in. beams, an unbalanced design bent existed with flexible exterior bays and stiff interior bays. The writer feels that the shear, moment and deflection requirements for this condition were best solved by the use of the plastic method.

The plastic design method also enables the designer to better understand the rotational and deflection characteristics of the beams and columns in frames where stability is important.

Significant weight savings were achieved by the use of plastic design for the project described in this paper. A design comparison with a first order elastic analysis using a horizontal drift limitation of 0.0025 shows a 3.5 percent savings in weight compared to the total steel tonnage in the building. This savings amounts to about 38 tons.

Better understanding of stability and strength limit state behavior has resulted in a better design

29

"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

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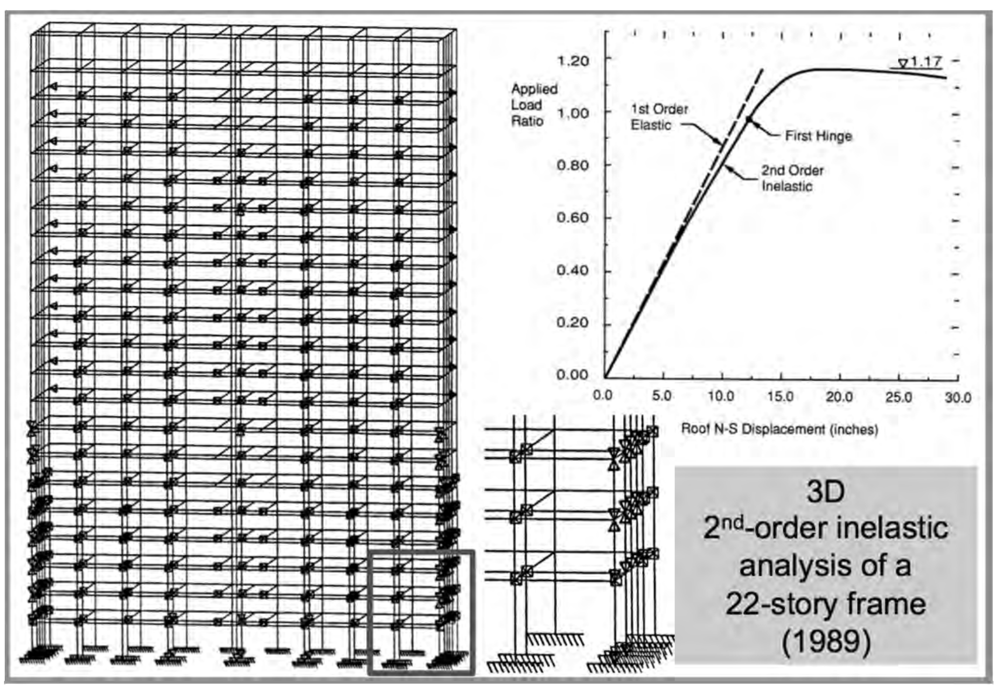
Computer programs – lots of further research…

1970's

- Computing hardware
- Graphical user interfaces
- Material nonlinear:
  - Plastic hinge vs. zone
- Geometric nonlinear:
  - 2^{nd}-order effects

1990's

32



3D 2^{nd}-order inelastic analysis of a 22-story frame (1989)

33

Computer programs – lots of further research…

1970's → 1990's

- Computing hardware
- Graphical user interfaces
- Material nonlinear:
  - Plastic hinge vs. zone
- Geometric nonlinear:
  - 2nd-order effects

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

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

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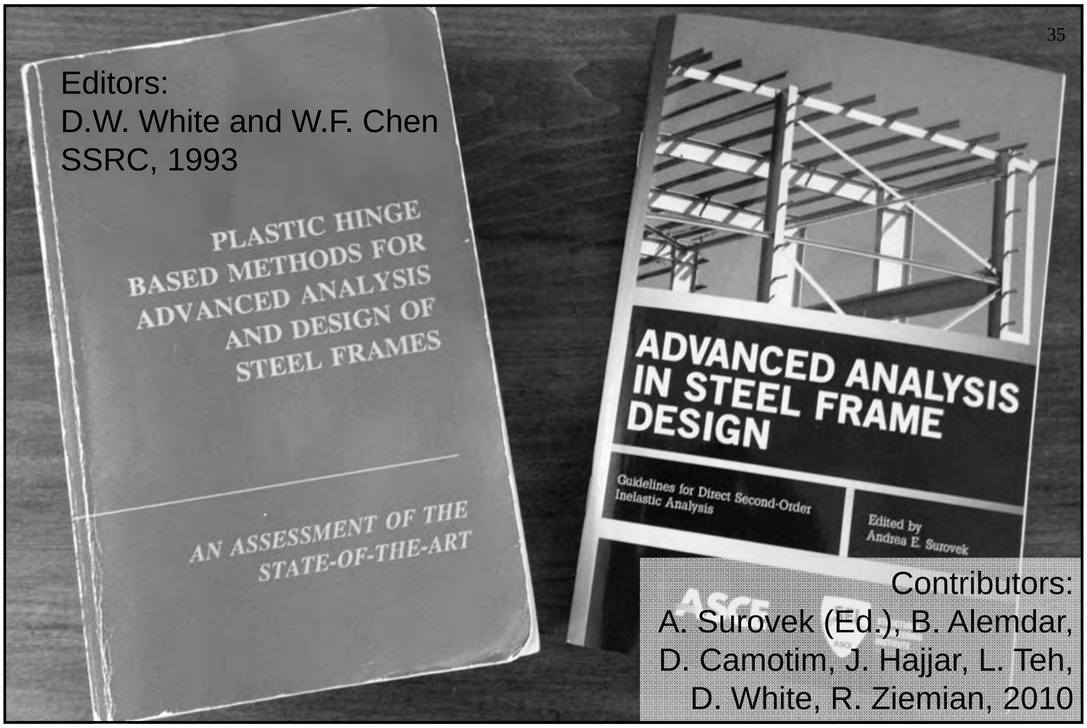
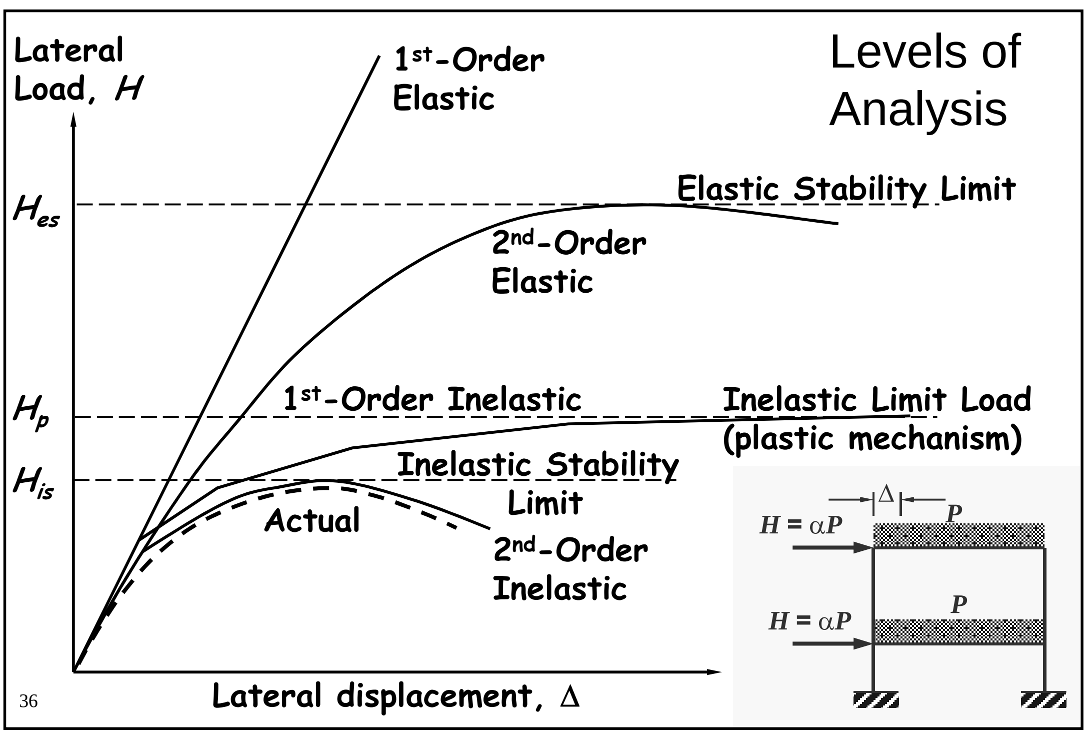

35
Editors:
D.W. White and W.F. Chen
SSRC, 1993
PLASTIC HINGE BASED METHODS FOR ADVANCED ANALYSIS AND DESIGN OF STEEL FRAMES
AN ASSESSMENT OF THE STATE-OF-THE-ART
ADVANCED ANALYSIS IN STEEL FRAME DESIGN
Guidelines for Direct Second-Order Inelastic Analysis
Edited by Andrea E. Surovek
Contributors:
A. Surovek (Ed.), B. Alemdar, D. Camotim, J. Hajjar, L. Teh, D. White, R. Ziemian, 2010


Levels of Analysis
Lateral Load, H
1st-Order Elastic
Elastic Stability Limit
2nd-Order Elastic
1st-Order Inelastic
Inelastic Limit Load (plastic mechanism)
Inelastic Stability Limit
Actual
2nd-Order Inelastic
Hes
Hp
His
Lateral displacement, Δ
H = αP
P
Δ
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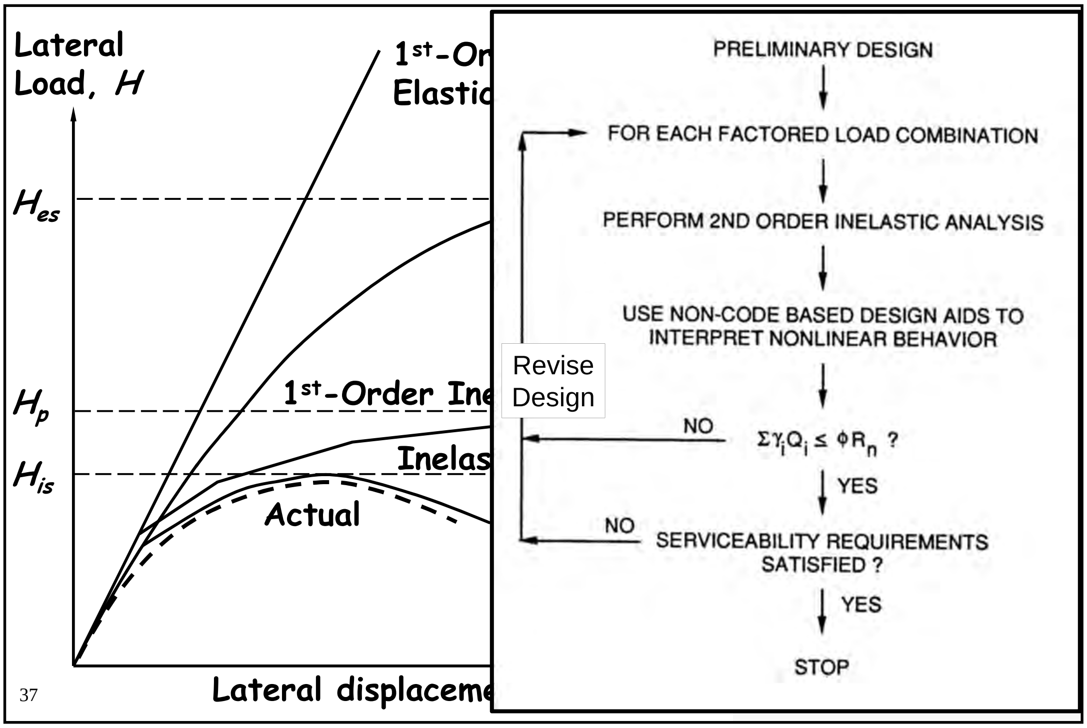

AISC Sub-Committee on Inelastic Analysis and Design (2007-2010)

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

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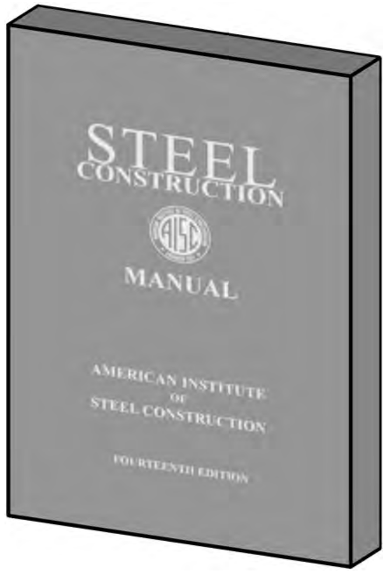
AISC 2010 Specification

Chapters A-N, provisions for design by elastic analysis.

Chapter C:
Design for Stability
Elastic analysis details for obtaining required strengths



Appendix 1:
Design by Inelastic Analysis

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Goals of Appendix 1

- Address application of a wide range of current and emerging methods of inelastic analysis
- Mirror the elastic stability provisions of Ch. C; Direct Analysis Method
- Eye toward the future and moving to Performance Based Design
- Transparent and reasonably self-contained

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One Appendix Fits All

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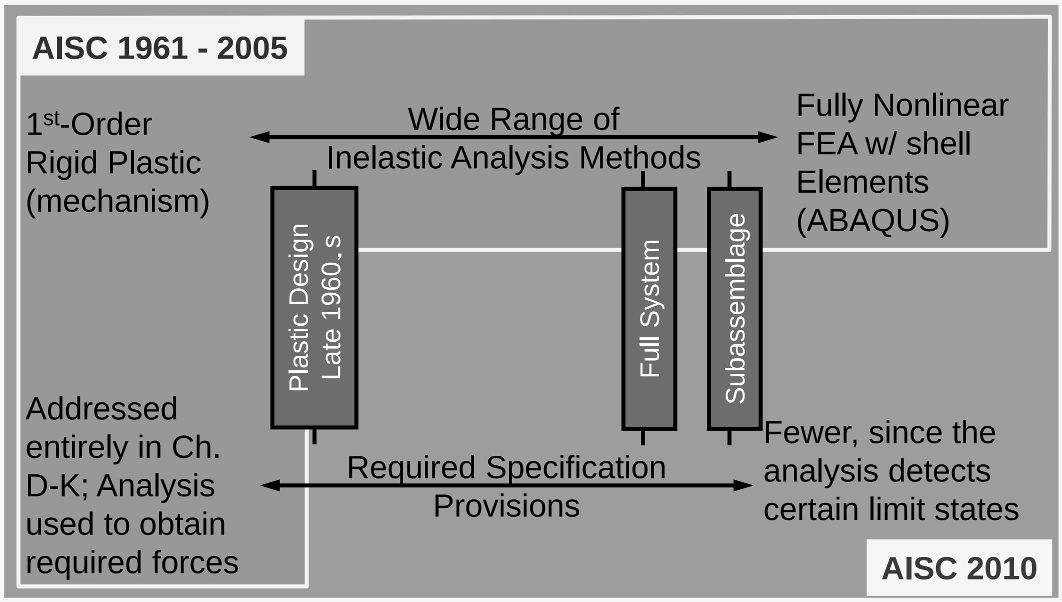

Mirror Ch. C - Design for Stability (Elastic)

- First provide general requirements
- Followed by the statement
  Any method…satisfies these requirements … is permitted
- Provide details for a specific method
  - Ch. C: Direct Analysis Method
  - Appendix 1: Plastic hinge (concentrated plasticity) analysis

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Eye Towards the Future

- Performance-Based Engineering
  - Performance levels/objectives are quantified for owner/society
  - Performance is predicted analytically
  - Full life-cycle costs are included in design
- App. 1 - Design by Inelastic Analysis
  - Long way from PBE, but signs are there...
  - General concept of making more use of an analysis to assess performance by comparing demand vs. capacity

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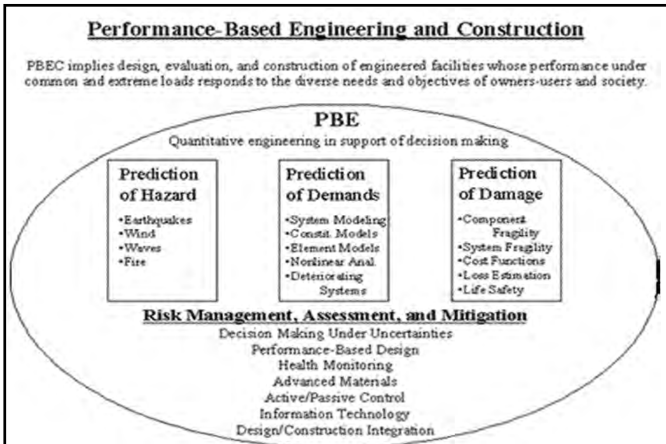
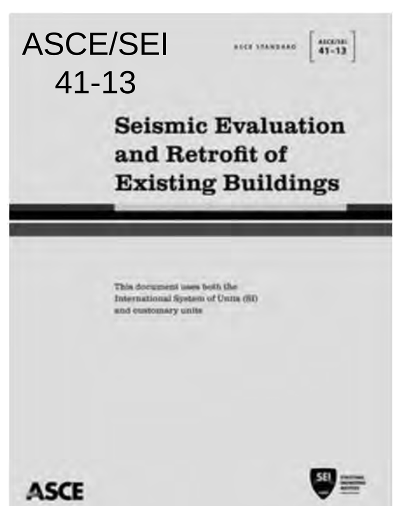


Stanford University
Structural Engineering and Geomechanics

ASCE/SEI 41-13



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Appendix 1 – Design by Inelastic Analysis

- 3 Sections
  - General Requirements (all levels of analysis)
  - Ductility Requirements (specific to plastic hinge)
  - Analysis Requirements (specific to plastic hinge)
- Concise (not overly prescriptive)
  - Specification (5 pages!)
  - Commentary (8 pages, but many references)
- Intended designer
  - well-versed in geometric and material nonlinear analysis, as well as Specification provisions

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General Requirements (1)

Inelastic Analysis must account for:

"The Big 5" consistent with Ch. C:

- All deformations contributing to structural displacements
- 2^{nd}-order effects (P-Δ and P-δ)
- Geometric imperfections (Δ_o and δ_o)
- Residual stresses and partial yielding
- Uncertainty in strength and stiffness

Allows for incorporating probabilistic modeling as long as AISC Spec. level of reliability is provided.

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General Requirements (2)

- LRFD (Not for ASD)
  - AISC Specification recognize both
- Does not apply to seismic
  - "equivalent" static loads assumed some level of yielding and inelastic force redistribution
  - ductility requirements provided are unique to inelastic design for non-seismic loads
  - Go to AISC341…

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General Requirements (3)

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"Strength limit states detected by an inelastic analysis that incorporates all of the above requirements are not subject to the corresponding provisions of the Specification…"

Limit State	Provision
Flexural buckling (in/elastic)	Ch. E
Torsional buckling (in/elastic)	Ch. E
Lateral torsional buckling (in/elastic)	Ch. F
Shear (yielding or local buckling)	Ch. G
Flexural torsional buckling (in/elastic)	Ch. H
Composite Systems	Ch. I
Connections	Ch. J, K

Prior to 2010, all provision checks required regardless of level of inelastic analysis

"Any method that uses inelastic analysis to proportion member and connections to satisfy these general requirements is permitted."

Some examples…

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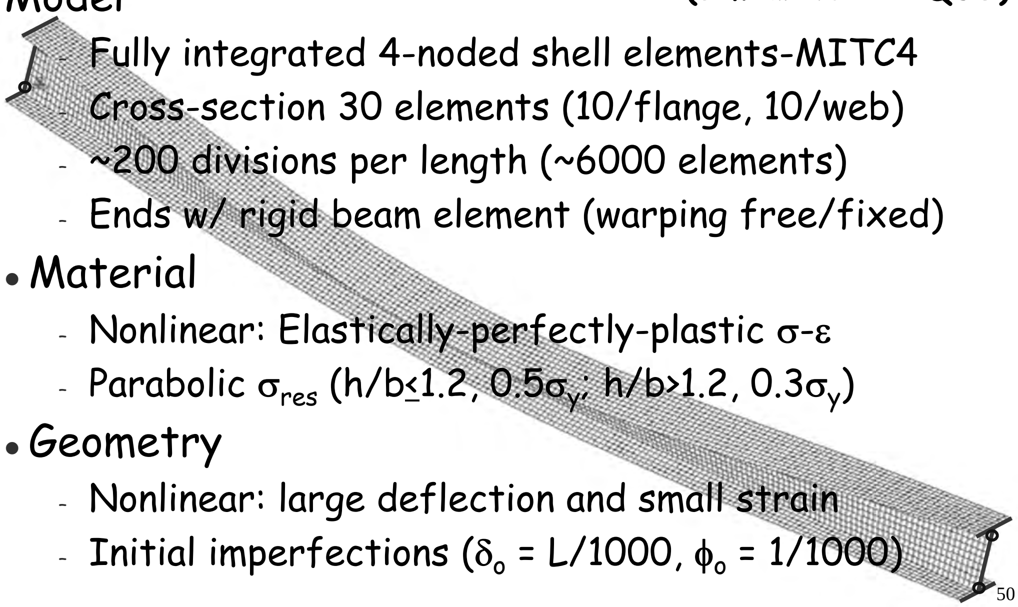
ADINA FEA

(similar to ABAQUS)



- Model
  - Fully integrated 4-noded shell elements-MITC4
  - Cross-section 30 elements (10/flange, 10/web)
  - ~200 divisions per length (~6000 elements)
  - Ends w/ rigid beam element (warping free/fixed)
- Material
  - Nonlinear: Elastically-perfectly-plastic σ-ε
  - Parabolic σ_{res} ($h/b \leq 1.2$, $0.5\sigma_y$; $h/b > 1.2$, $0.3\sigma_y$)
- Geometry
  - Nonlinear: large deflection and small strain
  - Initial imperfections ($\delta_o = L/1000$, $\phi_o = 1/1000$)

50

MASTAN2 (Frame Analyses 1 and 2)

- $[K_e + K_g + K_m]\{\Delta U\} = \{\Delta P\}$
- 2nd-Order: k_g and U. L. Formulation
- Inelastic Behavior:
  - Yield surface, $\Phi(P/P_y, M_x/M_{px}, M_y/M_{py})$
  - Tangent Modulus, $E_t = \tau E$
    - Frame Analysis 1: $\tau = 1$
    - Frame Analysis 2: $\tau = f(P, M_x, M_y) \leq 1$
- 14 d.o.f. line element (6+nonuniform torsion)
- Warping resistance
  - modeled as free, fixed, or continuous

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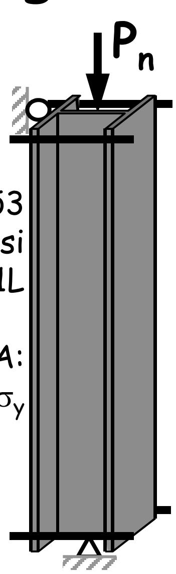
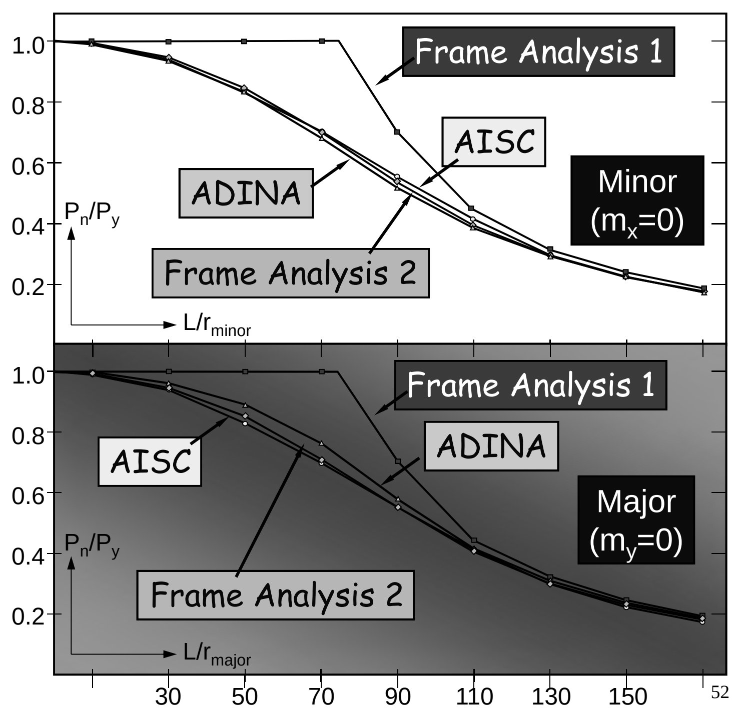
Column Strength



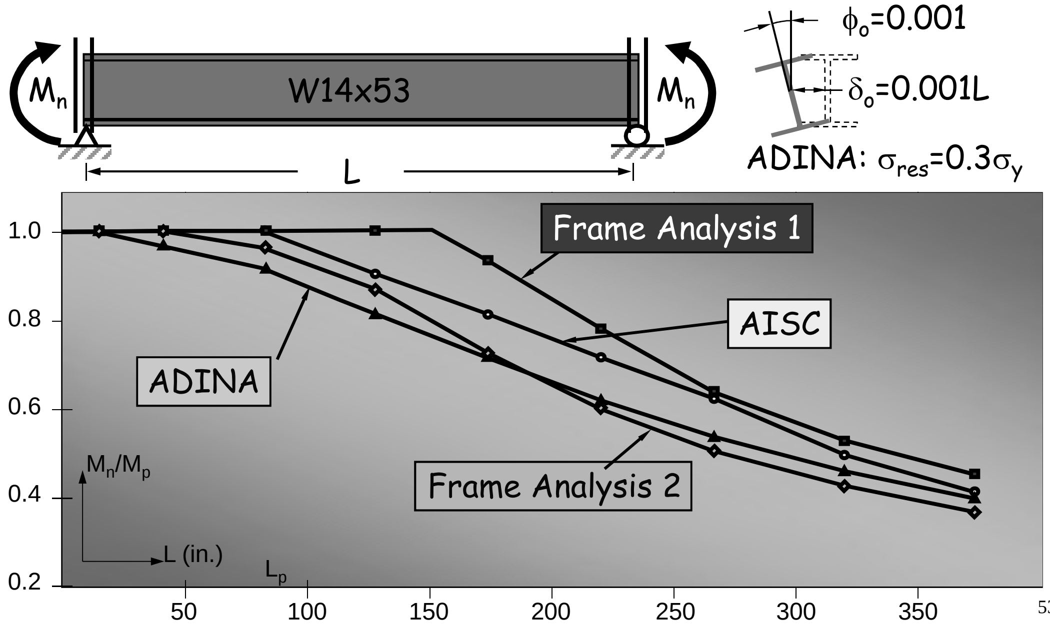
W14x53
σ_y=50ksi
δ_o=0.001L

ADINA:
σ_{res}=0.3σ_y



52

Flexural Strength



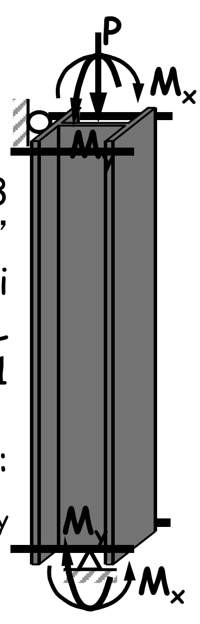
53

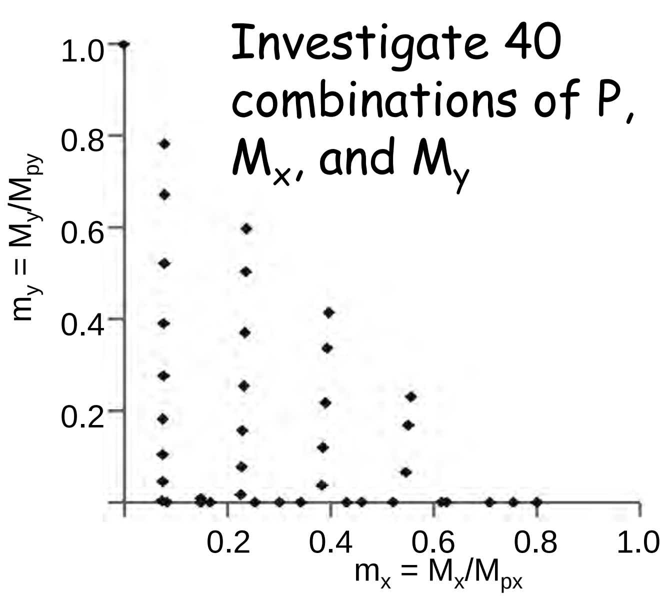
Beam-Column Study

54

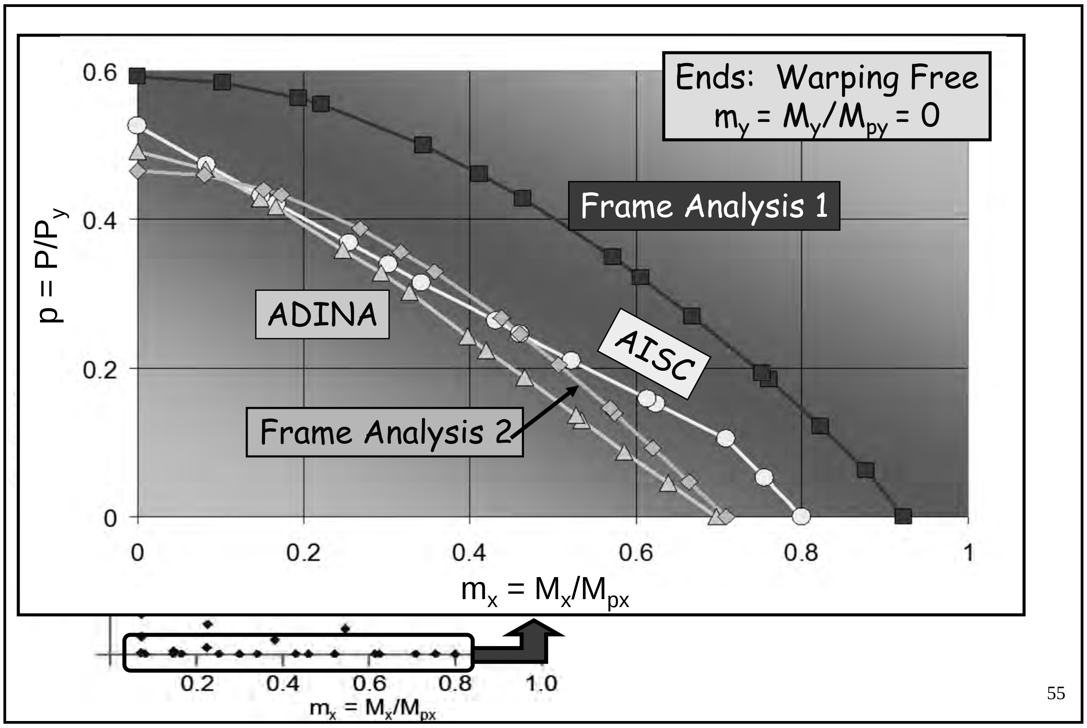
W14x53
L=15'-0"
σ_y=50ksi
δ_o=0.001L
ϕ_o=0.001

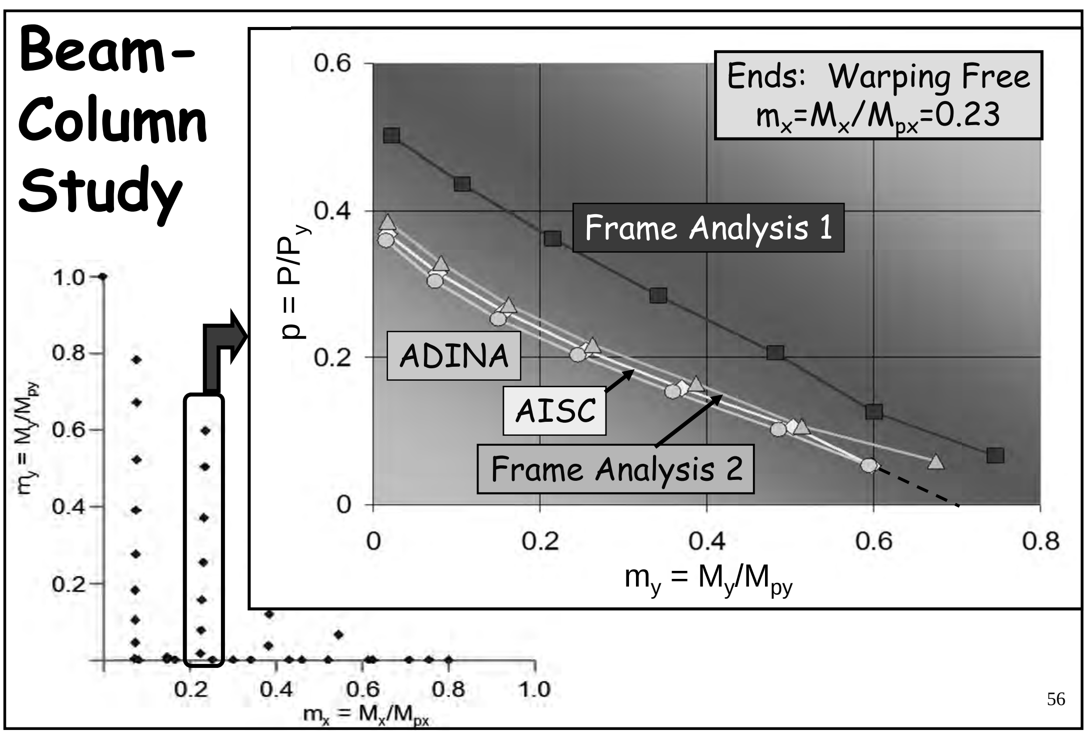
ADINA:
σ_{res}=0.3σ_y





Investigate 40 combinations of P, M_x, and M_y


Ends: Warping Free
$m_y = M_y/M_{py} = 0$
Frame Analysis 1
ADINA
AISC
Frame Analysis 2
$p = P/P_y$
$m_x = M_x/M_{px}$
0.2
0.4
0.6
0.8
1.0
55

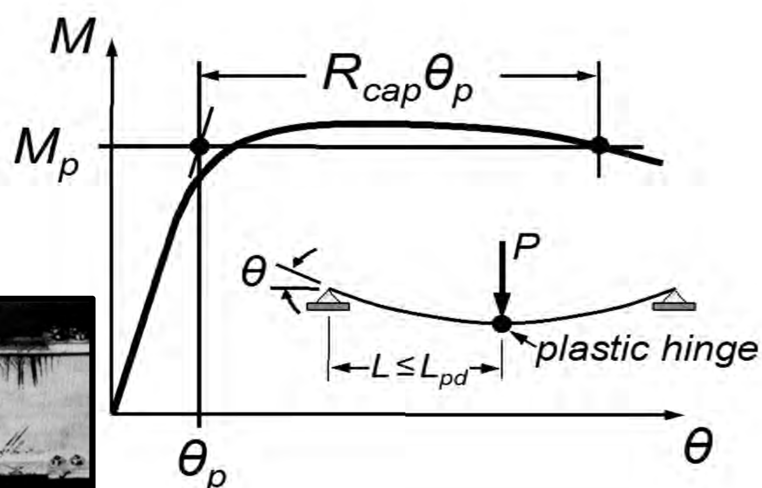

Beam-Column Study
Ends: Warping Free
$m_x=M_x/M_{px}=0.23$
Frame Analysis 1
ADINA
AISC
Frame Analysis 2
$p = P/P_y$
$m_y = M_y/M_{py}$
$m_x = M_x/M_{px}$
56

General Requirements (5)

- Yielded members and connections must be shown to have adequate ductility
- Force redistribution due to rupture is not permitted
- Specific details for one such method (distributed/concentrated plasticity) is provided in remainder of appendix
  - 1.2 Ductility requirements
  - 1.3 Analysis requirements

57

Inelastic Ductility Requirements (1)



58

Inelastic Ductility Requirements (2)

Two approaches recognized:

1. Explicitly compare deformation demands to deformation capacities,
   e.g. $\Theta_{hinge} \leq \Theta_{capacity}$
2. Meet requirements
   - Material, $F_y \leq$ 65 ksi (450 MPa)
   - Cross-section compactness, b/t_f, h/t_w
   - Unbraced length, $L_b \leq L_{pd}$
   - Axial force in compression members, $P_u \leq 0.75\phi_c P_y$

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Analysis Requirements

- Material Properties and Yield Criteria
  - Incorporate ϕ-factors reducing E and F_y by 0.9
  - Elastic-perfectly-plastic material (no E_{st})
  - Inelastic response to include P, M_x, and M_y
- Geometric Imperfections
  - Frame: out-of-plumb / Member: out-of-straight
  - Explicitly modeled or handled by notional loads
- Residual Stresses and Partial Yielding
  - Explicitly modeled or handled by notional loads

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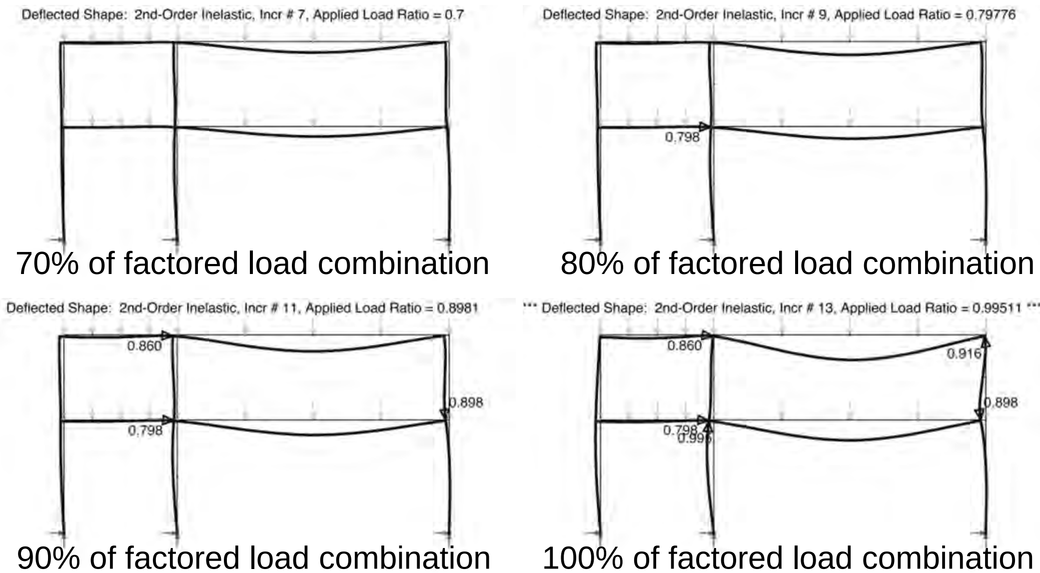
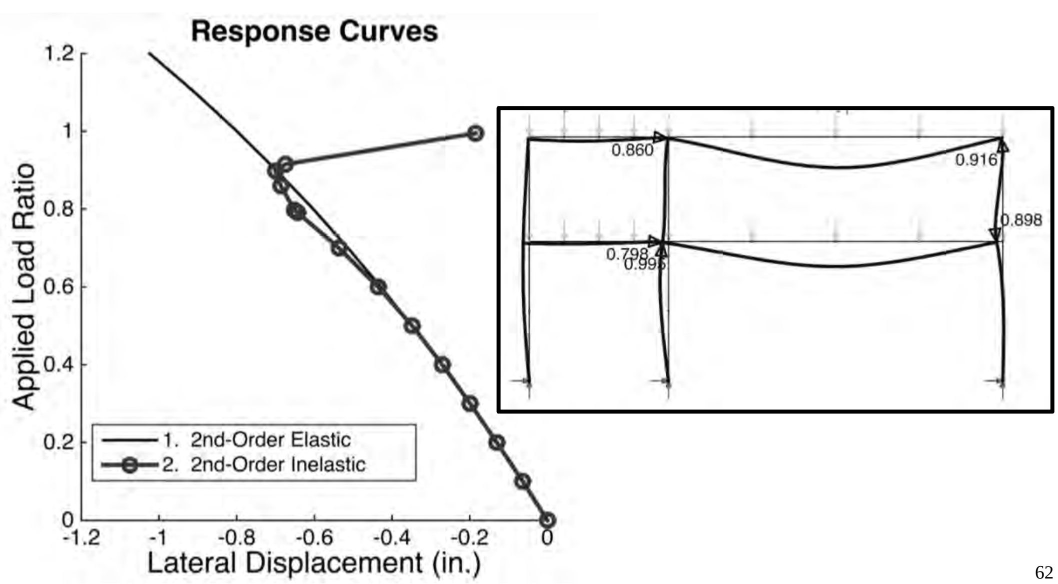
2nd-Order Inelastic Analysis to Assess Strength Limit State Behavior



2nd-Order Inelastic Analysis to Assess Strength Limit State Behavior



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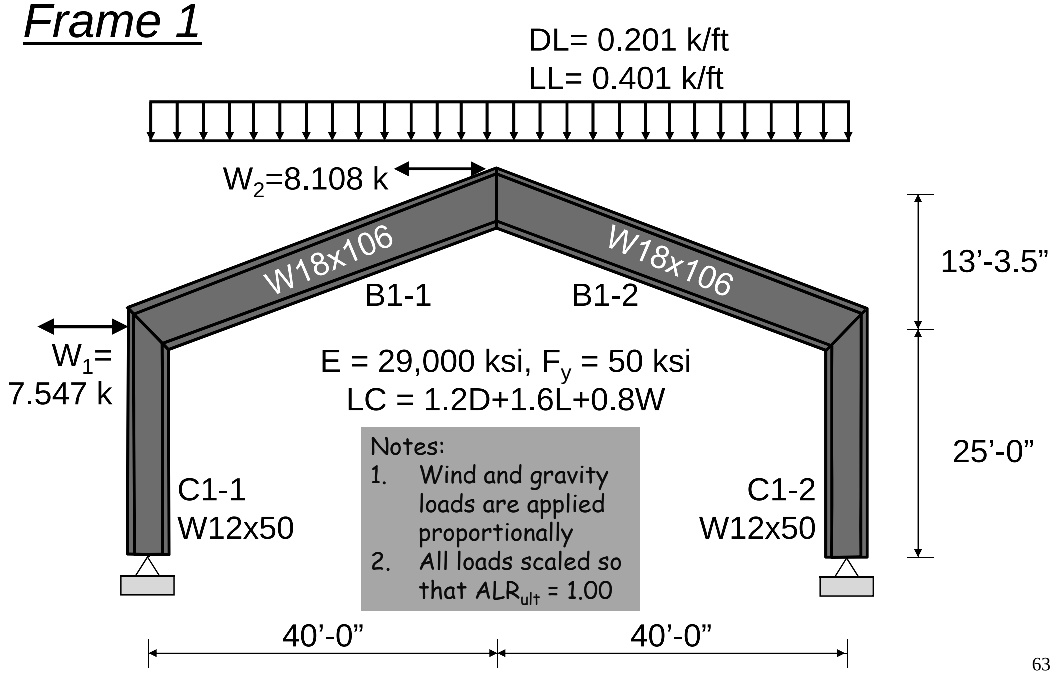
Frame 1



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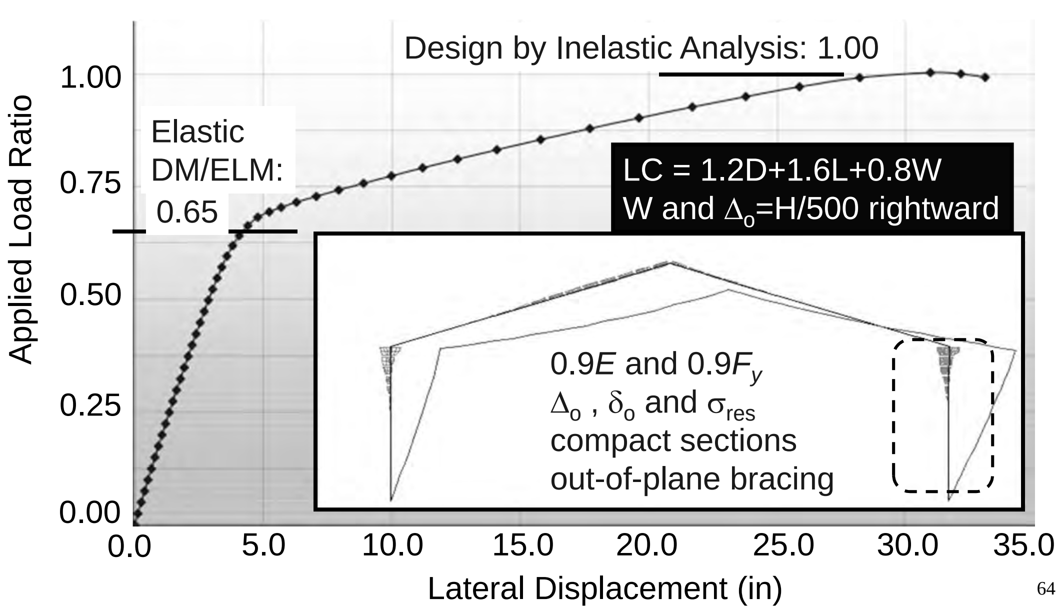
App 1: 2nd-Order Inelastic Analysis (0.9E 0.9F_y Δ_o's)



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Chapter C – Reqt's based on elastic analysis

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M_u increasing ↓
- ELM
- DM (Δ_o,0.8τ)
- DM-DMMI (Δ_o,0.8τ,δ_o)

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

P_n increasing ↓
- ELM (KL>L)
- DM (KL=L)
- DMMI ($P_n = A_e F_y$)

Methods often give very similar designs, but how about design by inelastic analysis?

AISC Spec. (Ch. C) 2nd-Order Elastic analysis

LC: 1.2D + 1.6L + 0.8W (w/ Δ_o right)

All $P_u/P_y \le 0.5$, $\tau_b = 1.0$

Case 1: Imperfection: direct modeling; Stiffness adjustment: 0.8E and τ_b = 1.0

1	Eq. H1-1 at Applied Load Ratio = 1.00						Applied Load Ratio when Eq. H1-1 = 1.00					
	DM: K = 1			DM-DMMI: $P_n = P_y$			DM: K = 1			DM-DMMI: $P_n = P_y$		
Member	$P_u/\phi P_n$	$M_u/\phi M_n$	Eq. H1-1	$P_u/\phi P_n$	$M_u/\phi M_n$	Eq. H1-1	$P_u/\phi P_n$	$M_u/\phi M_n$	ALR	$P_u/\phi P_n$	$M_u/\phi M_n$	ALR
C1-1	0.058	0.151	0.180	0.045	0.151	0.174	0.152	0.927	2.965	0.119	0.942	2.975
C1-2	0.080	1.562	1.602	0.062	1.562	1.593	0.051	0.974	0.645	0.040	0.982	0.650
B1-1	0.010	0.434	0.439	0.007	0.434	0.437	0.019	0.993	2.115	0.014	0.996	2.120
B1-2	0.024	0.488	0.500	0.018	0.488	0.497	0.044	0.983	1.830	0.032	0.986	1.835

Case 2: Imperfection: Notional Loads (NL); Stiffness adjustment: 0.8E and no NL

2	Eq. H1-1 at Applied Load Ratio = 1.00						Applied Load Ratio when Eq. H1-1 = 1.00					
	DM: K = 1			DM-DMMI: $P_n = P_y$			DM: K = 1			DM-DMMI: $P_n = P_y$		
Member	$P_u/\phi P_n$	$M_u/\phi M_n$	Eq. H1-1	$P_u/\phi P_n$	$M_u/\phi M_n$	Eq. H1-1	$P_u/\phi P_n$	$M_u/\phi M_n$	ALR	$P_u/\phi P_n$	$M_u/\phi M_n$	ALR
C1-1	0.058	0.159	0.188	0.045	0.159	0.182	0.153	0.922	2.985	0.120	0.944	3.000
C1-2	0.080	1.554	1.594	0.062	1.554	1.585	0.051	0.977	0.650	0.040	0.977	0.650
B1-1	0.010	0.433	0.438	0.007	0.433	0.437	0.019	0.994	2.120	0.014	0.997	2.125
B1-2	0.024	0.486	0.498	0.018	0.486	0.495	0.044	0.981	1.835	0.032	0.987	1.845

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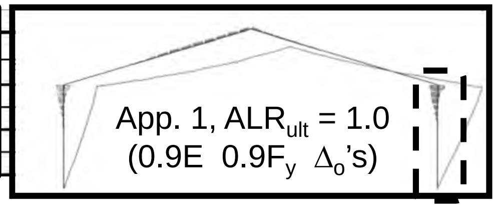
AISC Spec. (Ch. C)
2^{nd}-Order Elastic analysis

LC: 1.2D + 1.6L + 0.8W (w/ Δ_o right)

All $P_u/P_y \leq 0.5$, $\tau_b = 1.0$

Case 1: Imperfection: direct modeling; Stiffness adjustment: 0.8E and τ_b = 1.0

1	Eq. H1-1 at Applied Load Ratio = 1.00					
	DM: K = 1			DM-DMMI: $P_n = P_y$		
Member	$P_u/\phi P_n$	$M_u/\phi M_n$	Eq. H1-1	$P_u/\phi P_n$	$M_u/\phi M_n$	Eq. H1-1
C1-1	0.058	0.151	0.180	0.045	0.151	0.174
C1-2	0.080	1.562	1.602	0.062	1.562	1.593
B1-1	0.010	0.434	0.439	0.007	0.434	0.437
B1-2	0.024	0.488	0.500	0.018	0.488	0.497



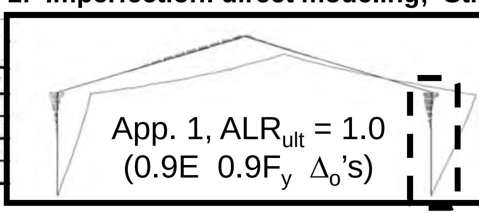
1	Eq. H1-1 at Applied Load Ratio = 1.00					
	DM: K = 1			DM-DMMI: $P_n = P_y$		
Member	$P_u/\phi P_n$	$M_u/\phi M_n$	Eq. H1-1	$P_u/\phi P_n$	$M_u/\phi M_n$	Eq. H1-1
C1-1	0.058	0.151	0.180	0.045	0.151	0.174
C1-2	0.080	1.562	1.602	0.062	1.562	1.593
B1-1	0.010	0.434	0.439	0.007	0.434	0.437
B1-2	0.024	0.488	0.500	0.018	0.488	0.497

AISC Spec. (Ch. C)
2^{nd}-Order Elastic analysis

LC: 1.2D + 1.6L + 0.8W (w/ Δ_o right)

All $P_u/P_y \leq 0.5$, $\tau_b = 1.0$

Case 1: Imperfection: direct modeling; Stiffness adjustment: 0.8E and τ_b = 1.0



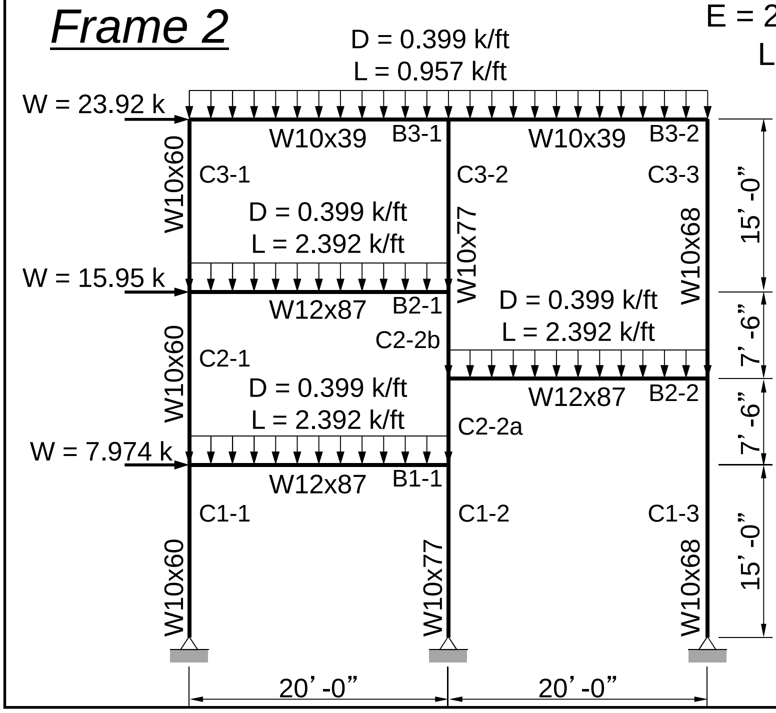
Applied Load Ratio when Eq. H1-1 = 1.00					
DM: K = 1			DM-DMMI: $P_n = P_y$		
$P_u/\phi P_n$	$M_u/\phi M_n$	ALR	$P_u/\phi P_n$	$M_u/\phi M_n$	ALR
0.152	0.927	2.965	0.119	0.942	2.975
0.051	0.974	0.645	0.040	0.982	0.650
0.019	0.993	2.115	0.014	0.996	2.120
0.044	0.983	1.830	0.032	0.986	1.835

1	Applied Load Ratio when Eq. H1-1 = 1.00					
	DM: K = 1			DM-DMMI: $P_n = P_y$		
Member	$P_u/\phi P_n$	$M_u/\phi M_n$	ALR	$P_u/\phi P_n$	$M_u/\phi M_n$	ALR
C1-1	0.152	0.927	2.965	0.119	0.942	2.975
C1-2	0.051	0.974	0.645	0.040	0.982	0.650
B1-1	0.019	0.993	2.115	0.014	0.996	2.120
B1-2	0.044	0.983	1.830	0.032	0.986	1.835

Frame 2

E = 29,000 ksi, F_y = 50 ksi
LC = 1.2D+1.6L+0.8W

Notes:
1. Wind and gravity loads are applied proportionally
2. All loads scaled so that ALR_{ult} = 1.00



Originally from:
Virginia Tech Study

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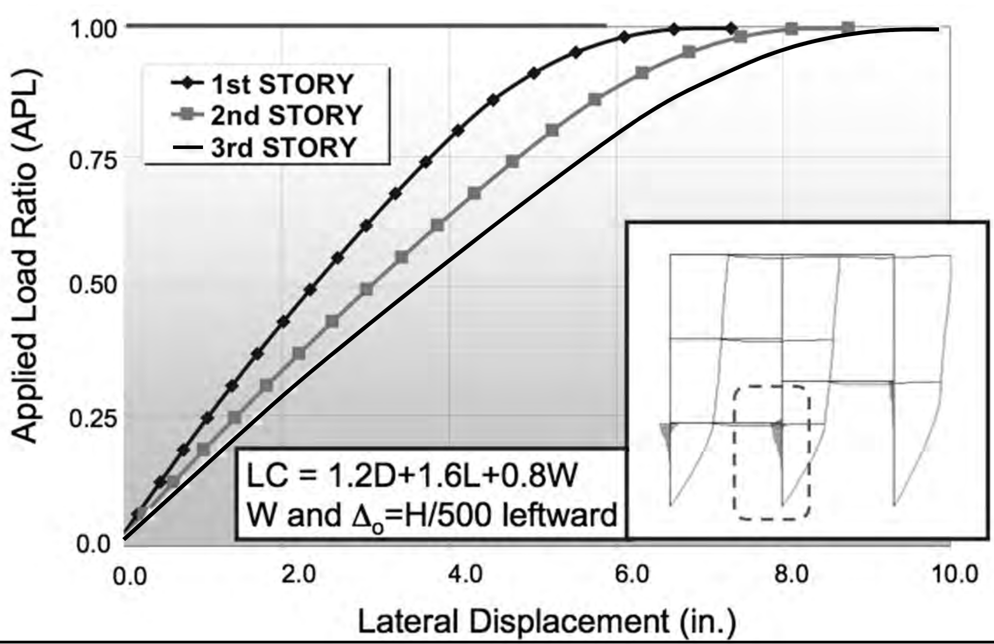
App. 1: 2nd-Order Inelastic Analysis (0.9E 0.9F_y Δ_o's)



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AISC Spec. (Ch. C)
2nd-Order Elastic analysis

LC: 1.2D + 1.6L + 0.8W (w/ Δ_o right)

All $P_u/P_y \le 0.5$, $\tau_b = 1.0$

Case 1: Imperfection: direct modeling; Stiffness adjustment: 0.8E and τ_b = 1.0

1	Eq. H1-1 at Applied Load Ratio = 1.00						Applied Load Ratio when Eq. H1-1 = 1.00					
	DM: K = 1			DM-DMMI: $P_n = P_y$			DM: K = 1			DM-DMMI: $P_n = P_y$		
Member	$P_u/\phi P_n$	$M_u/\phi M_n$	Eq. H1-1	$P_u/\phi P_n$	$M_u/\phi M_n$	Eq. H1-1	$P_u/\phi P_n$	$M_u/\phi M_n$	ALR	$P_u/\phi P_n$	$M_u/\phi M_n$	ALR
C1-1	0.072	0.891	0.927	0.064	0.891	0.923	0.076	0.965	1.060	0.067	0.965	1.060
C1-2	0.222	0.997	1.108	0.197	0.997	1.096	0.204	0.898	0.920	0.183	0.910	0.930
C1-3	0.126	0.633	0.696	0.096	0.633	0.681	0.172	0.915	1.340	0.133	0.934	1.360
C2-1	0.062	0.099	0.130	0.055	0.099	0.127	0.191	0.906	3.385	0.170	0.917	3.395
C2-2a	0.124	0.291	0.353	0.120	0.291	0.351	0.254	0.844	2.145	0.247	0.848	2.150
C2-2b	0.101	0.435	0.485	0.098	0.435	0.484	0.199	0.904	1.955	0.194	0.907	1.960
C3-1	0.021	0.019	0.029	0.019	0.019	0.028	ICLC	ICLC	> 4.66	ICLC	ICLC	> 4.66
C3-2	0.047	0.269	0.292	0.042	0.269	0.289	0.150	0.928	3.335	0.134	0.937	3.355
C3-3	0.034	0.279	0.296	0.026	0.279	0.292	0.108	0.949	3.060	0.083	0.963	3.090
B1-1	0.007	0.952	0.956	0.007	0.952	0.956	0.007	0.998	1.040	0.007	0.998	1.040
B2-1	0.012	0.520	0.526	0.010	0.520	0.525	0.023	0.993	1.835	0.020	0.993	1.835
B2-2	0.001	0.588	0.589	0.001	0.588	0.589	0.003	1.002	1.565	0.003	1.002	1.565
B3-1	0.047	0.633	0.656	0.038	0.633	0.652	0.071	0.968	1.515	0.057	0.975	1.525
B3-2	0.019	0.509	0.518	0.015	0.509	0.516	0.034	0.987	1.900	0.027	0.990	1.905

DM: KL = 7'-6" for C2-2a and C2-2b

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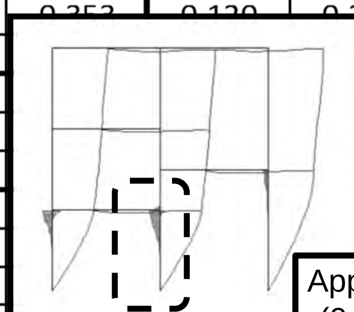
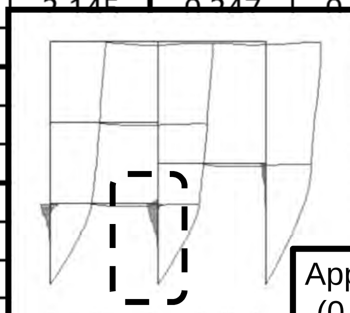
1	Eq. H1-1 at Applied Load Ratio = 1.00					
	DM: K = 1			DM-DMMI: $P_n = P_y$		
Member	$P_u/\phi P_n$	$M_u/\phi M_n$	Eq. H1-1	$P_u/\phi P_n$	$M_u/\phi M_n$	Eq. H1-1
C1-1	0.072	0.891	0.927	0.064	0.891	0.923
C1-2	0.222	0.997	1.108	0.197	0.997	1.096
C1-3	0.126	0.633	0.696	0.096	0.633	0.681
C2-1	0.062	0.099	0.130	0.055	0.099	0.127
C2-2a	0.124	0.291	0.353	0.120	0.291	0.351
C2-2b	0.101	0.435	[illegible]	[illegible]	[illegible]	0.484
C3-1	0.021	0.019	[illegible]	[illegible]	[illegible]	0.028
C3-2	0.047	0.269	[illegible]	[illegible]	[illegible]	0.289
C3-3	0.034	0.279	[illegible]	[illegible]	[illegible]	0.292
B1-1	0.007	0.952	[illegible]	[illegible]	[illegible]	0.956
B2-1	0.012	0.520	[illegible]	[illegible]	[illegible]	0.525
B2-2	0.001	0.588	[illegible]	[illegible]	[illegible]	[illegible]
B3-1	0.047	0.633	[illegible]	[illegible]	[illegible]	[illegible]
B3-2	0.019	0.509	0.518	0.015	0.509	0.516



App. 1, ALR_{ult} = 1.0
(0.9E 0.9F_y Δ_o's)

1	Applied Load Ratio when Eq. H1-1 = 1.00					
	DM: K = 1			DM-DMMI: $P_n = P_y$		
Member	$P_u/\phi P_n$	$M_u/\phi M_n$	ALR	$P_u/\phi P_n$	$M_u/\phi M_n$	ALR
C1-1	0.076	0.965	1.060	0.067	0.965	1.060
C1-2	0.204	0.898	0.920	0.183	0.910	0.930
C1-3	0.172	0.915	1.340	0.133	0.934	1.360
C2-1	0.191	0.906	3.385	0.170	0.917	3.395
C2-2a	0.254	0.844	[illegible]	[illegible]	[illegible]	2.150
C2-2b	0.199	0.904	[illegible]	[illegible]	[illegible]	1.960
C3-1	ICLC	ICLC	[illegible]	[illegible]	[illegible]	> 4.66
C3-2	0.150	0.928	[illegible]	[illegible]	[illegible]	3.355
C3-3	0.108	0.949	[illegible]	[illegible]	[illegible]	3.090
B1-1	0.007	0.998	[illegible]	[illegible]	[illegible]	1.040
B2-1	0.023	0.993	[illegible]	[illegible]	[illegible]	1.835
B2-2	0.003	1.002	[illegible]	[illegible]	[illegible]	[illegible]
B3-1	0.071	0.968	[illegible]	[illegible]	[illegible]	[illegible]
B3-2	0.034	0.987	1.900	0.027	0.990	1.905



App. 1, ALR_{ult} = 1.0
(0.9E 0.9F_y Δ_o's)

Future Directions and Research Needs

- Seismic design
- Singly-symmetric and non-symmetric shapes
- Ductility requirements for high axial forces
- High-strength steels
- Time for real-world applications…

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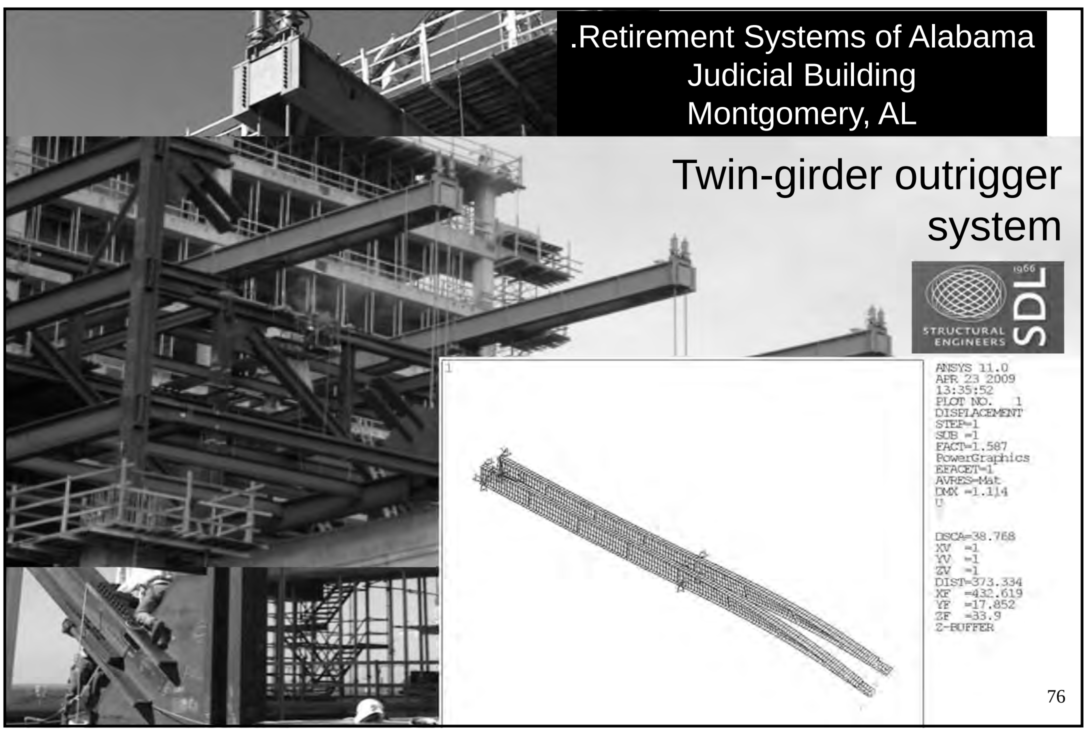
Raspberry Island
Schubert Club Band Shell
St. Paul, Minnesota, USA

SOM
structures

75

.Retirement Systems of Alabama
Judicial Building
Montgomery, AL

Twin-girder outrigger system



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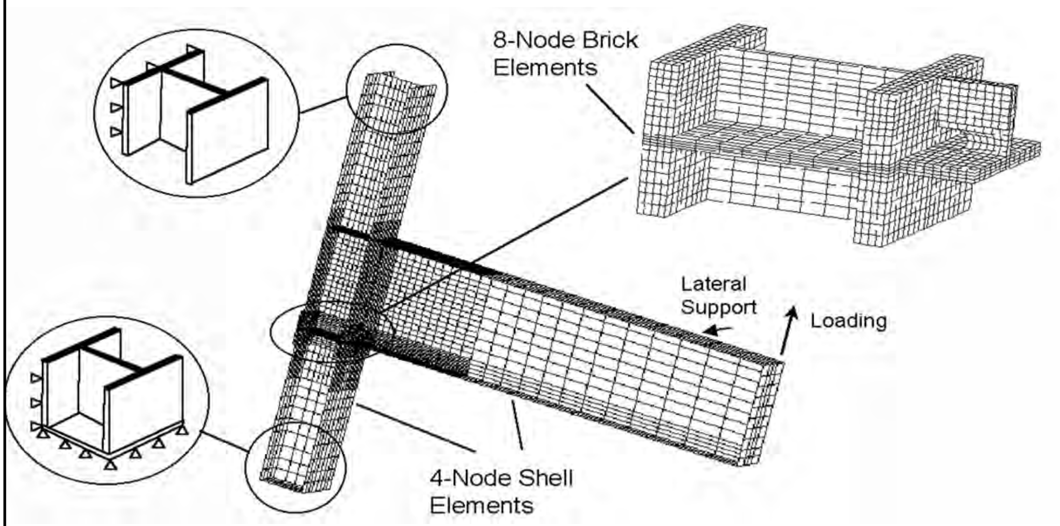
Ductility of FR Welded Connections



S. El-Tawil, University of Michigan 77

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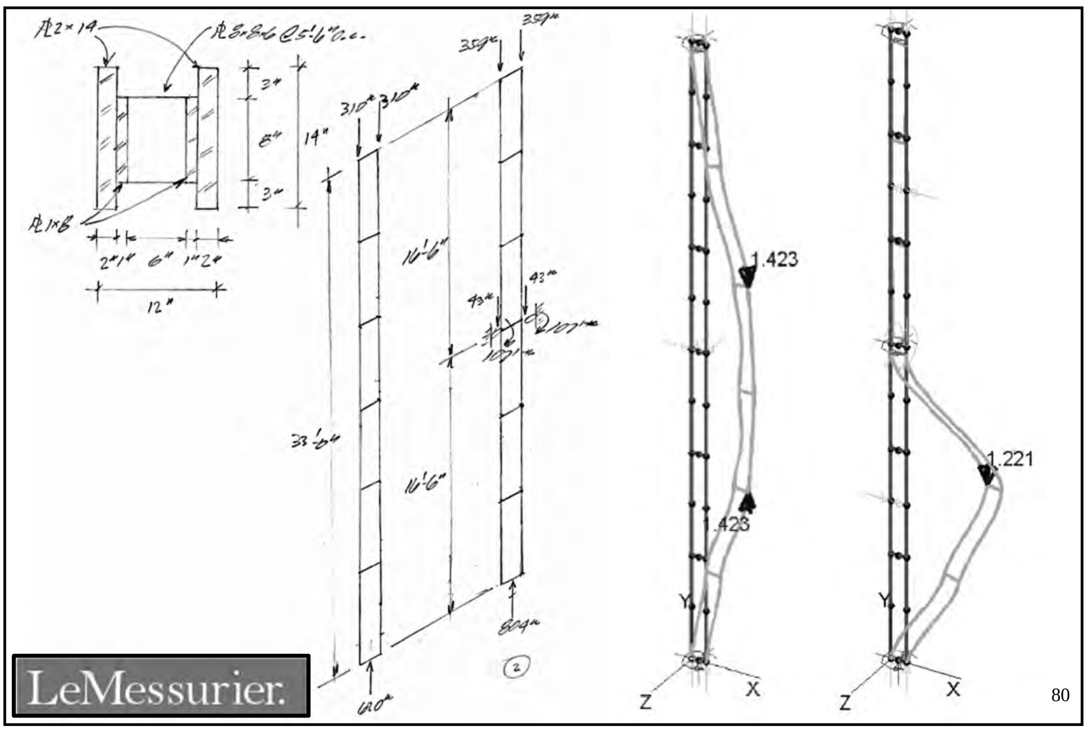
Tata Hall
Harvard Business School

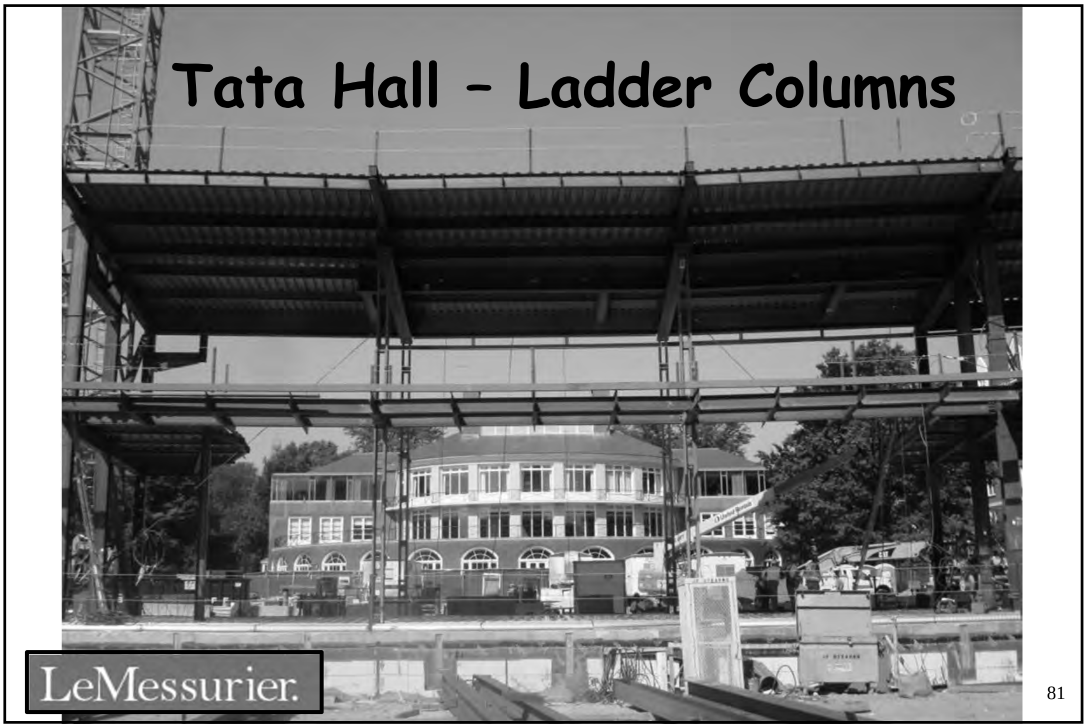
Tata Hall, Rendering: Dongik Lee/
William Rawn Architects

Tata Hall – Ladder Columns

79



80


Tata Hall – Ladder Columns
LeMessurier.
81


LeMessurier.
Tata Hall
Atrium Ladder
Columns

83

Summary (the takeaway…)

- Many more opportunities in the U.S. for engineers to take full advantage of inelastic analysis in designing steel structures.
- To do so, engineer must be proficient (well educated) in:
  - behavior of steel structures
  - nonlinear analysis

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Method: / Effect:	AISC 2010 Specification: Effective Length, ELM (App. 7)	AISC 2010 Specification: Direct Analysis, DM (Ch. C)	AISC 2016: DM-DMMI	AISC 2010: Inelastic Analysis (App. 1)
Member Inelasticity				Inelastic Analysis
Initial Out-of-Plumbness (Erection Tol.)				Direct Modeling
Initial Out-of-Straightness (Fab. Tol.)				Direct Modeling
Strength Check				Analysis
Axial Strength Term, P_n	Bas…		…tion	N/A

5. JUSTIFICATION OF PLASTIC DESIGN

(1) Economy
(2) Simplicity
(3) Rationality

AISC, pre-2005

Analysis

Design

Analysis

Design

AISC, post-2005

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Course Overview (Done!)

- 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 have joined AISC in this effort!

Questions?

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Individual Webinar Registrants

CEU/PDH Certificates

Within 2 business days…

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

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CEU/PDH Certificates

Within 2 business days…

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

8-Session Registrants

CEU/PDH Certificates

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

Certificates will be distributed the week of April 20th.

8-Session Registrants

Final Exam: The final exam will be distributed on Wednesday, April 8.

The final exam is due Friday, April 17.

EEUs will be distributed on the week of April 20th.

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8-Session Registrants

Access to the quiz: Information for accessing the quiz will be emailed to you by Thursday. 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.

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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.

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Thank You

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

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