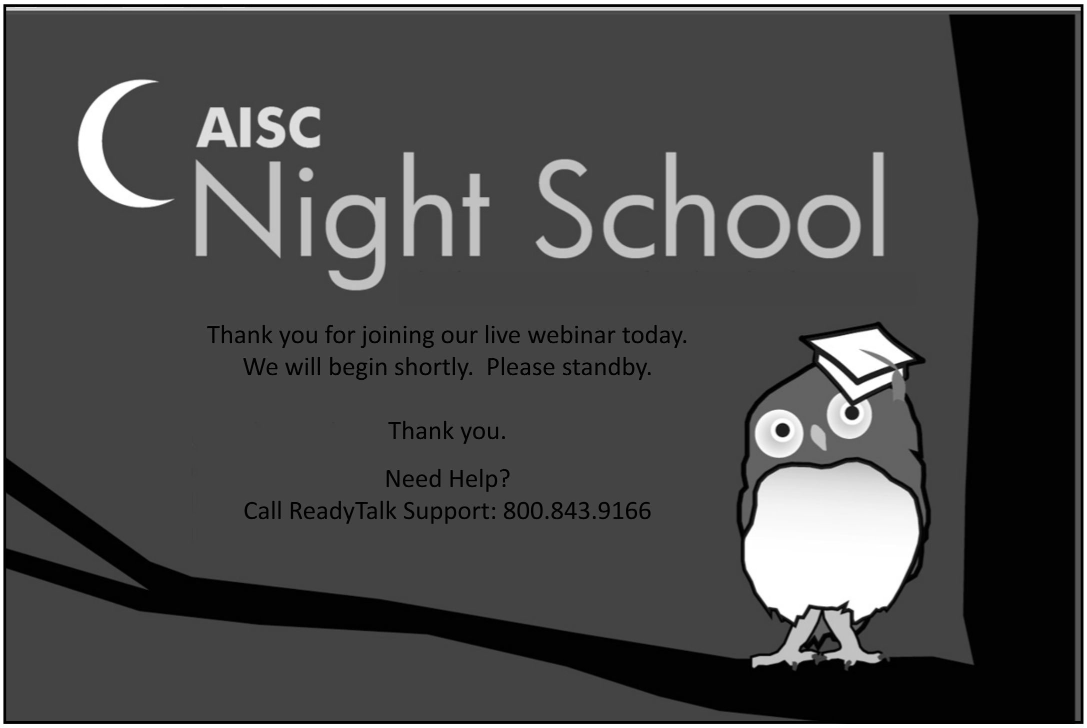

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Course Description

Modern Methods of Structural Analysis,

from Linear to Nonlinear – Part I

January 26, 2015

AISC's Direct Analysis Method is based on the principle that simplifications in the design process can be granted as more and more factors known to impact structural stability are included in the analysis. After providing an overview of this logic, this two-part lecture will focus on describing how modern structural engineering software includes such factors within the analysis. Part I will cover first-order elastic analysis by the stiffness method, which is the core for almost all of today's structural engineering analysis software.

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Learning Objectives

- Become familiar with the basic principles of structural stability.
- Become familiar with the principle that simplifications in the design process can be granted as more and more known factors are included in the analysis which is the basis of the Direct Analysis Method.
- Gain an understanding of linear and nonlinear analysis by the stiffness method and how it is applied.
- Become familiar with the methods of computer structural analysis.

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

Session 1
Course Introduction and Modern Methods of Structural Analysis, from Linear to Nonlinear – Part I

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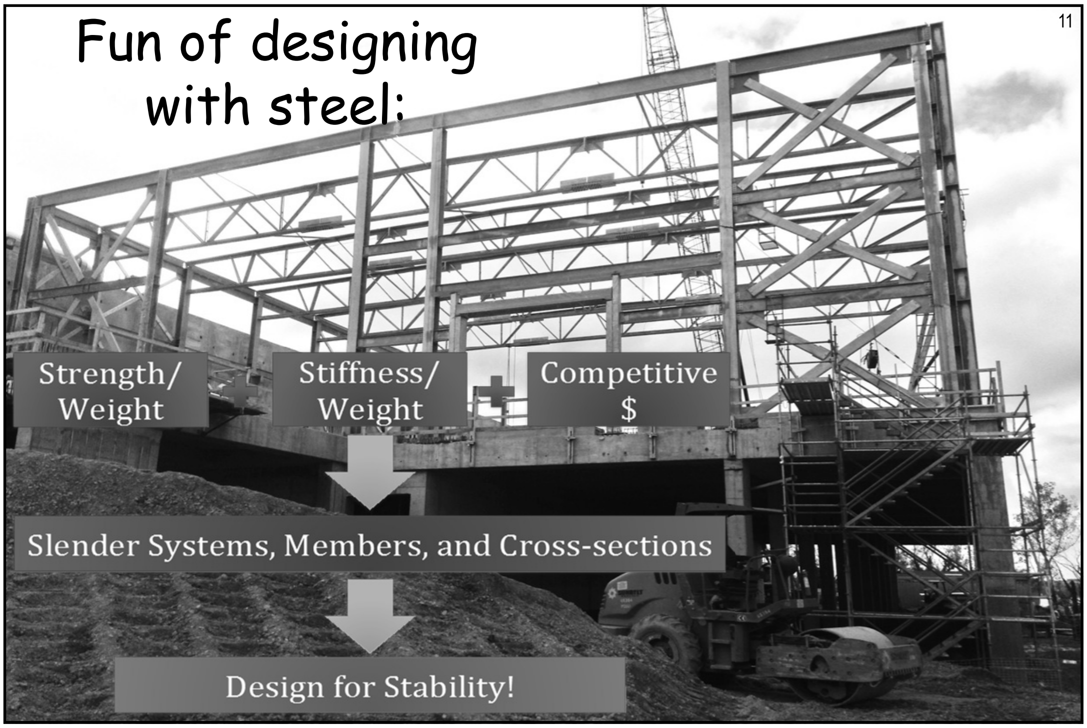
Stability Design of Steel Structures – Applying Modern Methods of Structural Analysis

Course Introduction



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"Buckling" Design Methods:

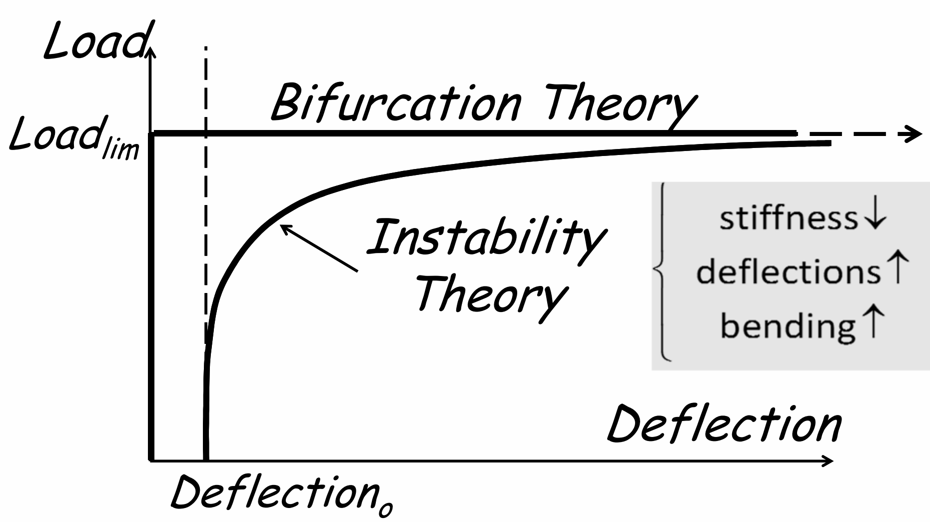

Figure applicable to system, member, and cross-section behavior

General Stability Design Methods:

13

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

"General" Effective Length Method

14

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 (50+ years of use!)

"General" Direct Analysis Method

15

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

General Direct Analysis Method

16

Analys...
- Eq...

Primary effects:
- Applied load and relative stiffness distribution
- Initial imperfections (system and component)
- Yielding accentuated by residual stresses
- All pertinent resulting deformations
- Redistribution of stresses (F/M's) resulting from changes in relative stiffness distribution

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

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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

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AISC's Direct Analysis Method

Analysis for load effects:
- Equilibrium on deformed shape

Based on instability theory (approaching

Design by elastic analysis:
•Poor man's inelastic analysis
- member stiffness reduced by 0.8τ
- include system and member imperfections

•Redistribution of stresses (F/M's) resulting from changes in relative stiffness distribution is not accounted for

Design inelastic analysis:
•loss in stiffness due to yielding is directly modeled
•system and member imperfections are directly modeled
•Redistribution of stresses (F/M's) resulting from changes in relative stiffness distributions is accounted for

- By d
syste
simp
resis
- Desig
~~cross section~~ instabilities

19

AISC's Direct Analysis Method (2005-16)

Elastic Analysis for load effects:

- Equili

Based on instability

Effects modeled:

- Applied load and stiffness distribution of components
- Initial system imperfections (out-of-plumb)
- Yielding accentuated by residual stresses (approximated by reducing member stiffness by 0.8τ)
- All pertinent deformations

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

Simplification granted:

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

DM

20

AISC's Direct Analysis Method (2016)

Elastic An

- Equilib

Effects modeled:

- Applied load and initial stiffness distribution
- 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)
- All pertinent deformations

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

Simplification granted:

- Compressive strength P_n taken as cross-section axial strength

DM-DMMI

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AISC's Direct Analysis Method (2005-16)

Inelastic Analysis for load effects:

• Eq

Effects modeled:

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

s↓
ns↑
g↑

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

DM-Inelastic

Simplifications granted:

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

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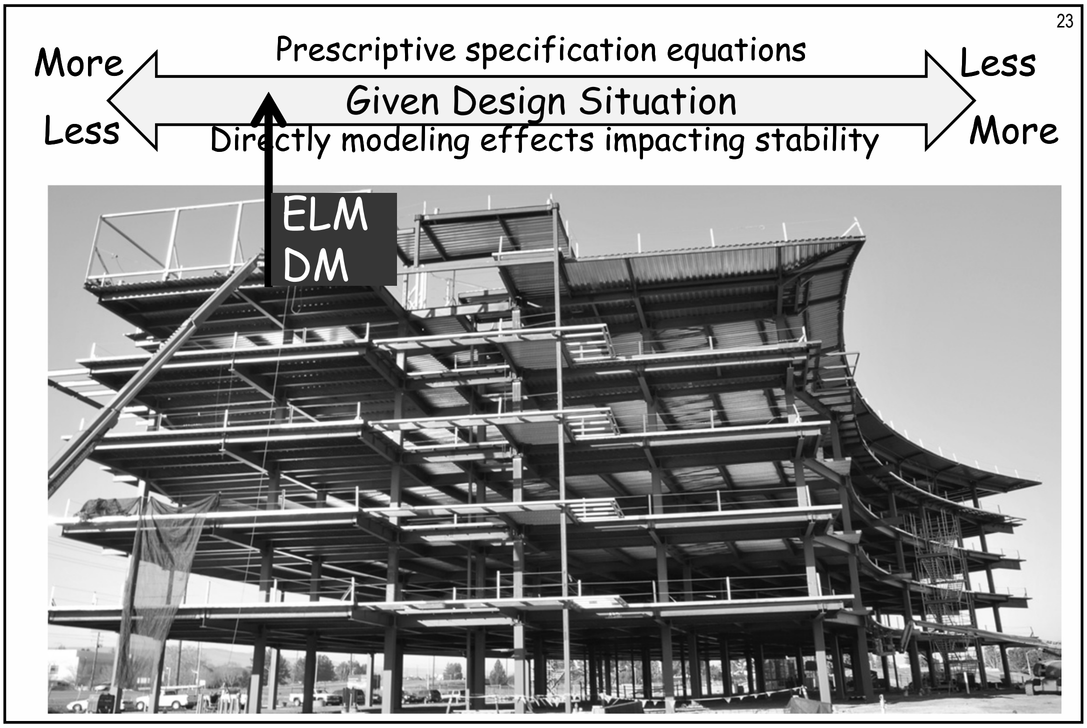
Additional thoughts…

- 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?*

	Prescriptive specification equations	
More	Given Design Situation	Less
Less	Directly modeling effects impacting stability	More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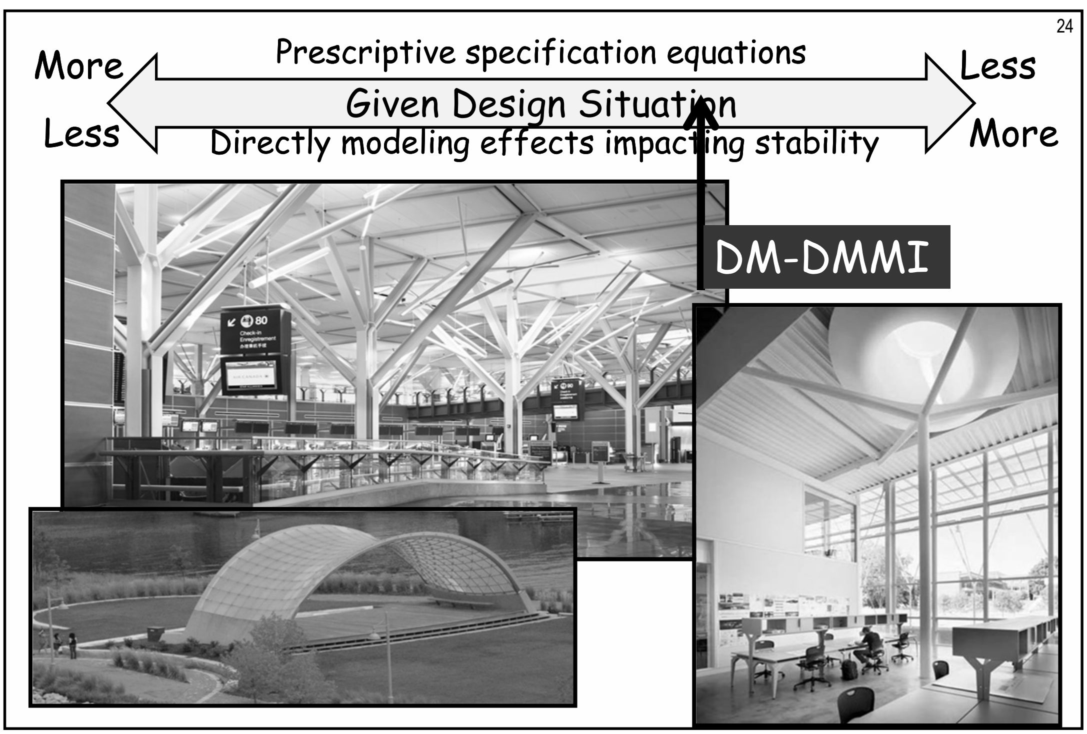
Prescriptive specification equations
More
Less
Given Design Situation
Less
More
Directly modeling effects impacting stability
ELM
DM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Prescriptive specification equations
More
Less
Given Design Situation
Less
More
Directly modeling effects impacting stability
DM-DMMI

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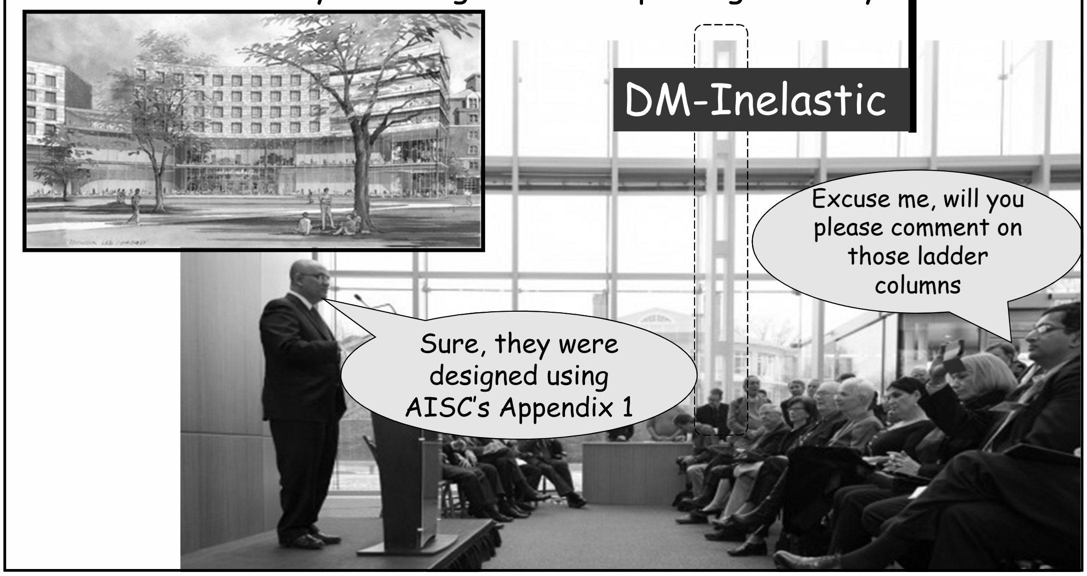
More — Prescriptive specification equations — Less

Given Design Situation

Less — Directly modeling effects impacting stability — More



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More — Prescriptive specification equations — Less

Given Design Situation

Less — Directly modeling effects impacting stability — More

AISC's *Direct Analysis Method* is intended to provide a wide range of design opportunities to the structural engineer…

2005 DM appears, Elastic analysis, $P_n(KL=L)$, App. 7

2010 DM upgraded and extended

Elastic analysis, $P_n(KL=L)$, upgraded to Ch. C

Extended to include inelasticity, fully revised App. 1

2016 DM, extended to include DMMI

to permit direct modeling of member imperfections; rigorous elastic analysis, $P_n = P_{ns}$ (cross section strength)

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Effective Length Method (ELM)

2nd-order elastic analysis with:
$E = E_o$
no initial imperfections or stiffness reduction

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

AISC column curve based on KL with $K \geq 1.0$

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Direct Analysis Method (DM)

2nd-order elastic analysis with:
$E = 0.8\,\tau\,E_o$
initial frame out-of-plumbness
$\Delta_o = H/500$

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

AISC column curve based on KL with $K = 1.0$

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Direct Modeling of Member Imperfections Method (DM-DMMI)

2nd-order elastic analysis with:

$E = 0.8\,\tau\,E_o$

initial frame out-of-plumbness

$\Delta_o = H/500$

initial member out-of-straightness

$\delta_o = L/1000$

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

Cross-section strength,

$P_n = P_{ns} = A_e F_y$

30

The big tradeoff!

M_u increasing:

- ELM
- DM (Δ_o,0.8τ)
- DM-DMMI (Δ_o,0.8τ,δ_o)

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

P_n increasing:

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

Methods often give very similar designs

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

Session 1

Modern Methods of Structural Analysis, from Linear to Nonlinear – Part I

32

Role of the analysis:

- forces, moments and deflections --> design equations
- insight into the behavior of a structure
  --> better the understanding, better the design

Limit States Design:

Prior to limit of resistance, significant nonlinear response, including
- geometrical effects (P-Δ, P-δ)
- material effects (yielding, cracking, crushing)
- combined effects

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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

Research

Education

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Linear to Nonlinear Analysis

- Hand methods
  - Second-order effects
    - i.e. Moment Amplification Factors (B1 and B2 factors)
  - Material nonlinear effects
    - i.e. plastic analysis (upper and lower bound theories)
- Computer Methods (focus of this lecture)
  - Lots of variations
    - all use same basic concepts (most important to today)
    - one approach will be presented (basis for MASTAN2)
- Please keep in mind
  - All methods are approximate
  - Not a substitute, but a complement to good engineering

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Overview of Lectures

- Session 1
  - Brief Introduction (done!)
  - Computer Structural Analysis (Review?)
- Session 2
  - Basis for Material Nonlinear Models
  - Incorporating Geometric Nonlinear Behavior
  - Critical Load Analysis
  - Overview of MASTAN2 software
  - Summary and Concluding Remarks

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How does the computer get these results?

- State-of-the-Art Crystal Ball? Not quite.
- By applying 2 requirements and 1 translator
  - Two Requirements:
    - Equilibrium (equations in terms of F's and M's, 1 per d.o.f.)
    - Compatibility (equations in terms of Δ's and θ's, 1 per d.o.f.)
  - Translator "apples to oranges"
    - Constitutive Relationship (i.e. Hooke's Law, $\sigma = E \epsilon$)
    - Generalized to Force-to-Displacement (i.e. $F=k\Delta$)
    - Re-write equilibrium eqs. in terms of unknown displacements
- # of Equil. Eqs. = # of Unknown Displacements

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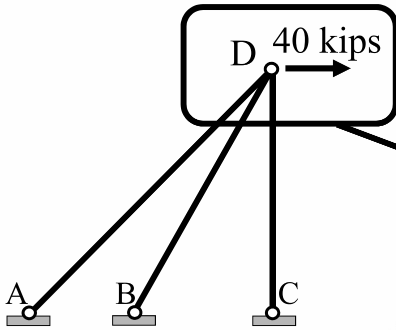
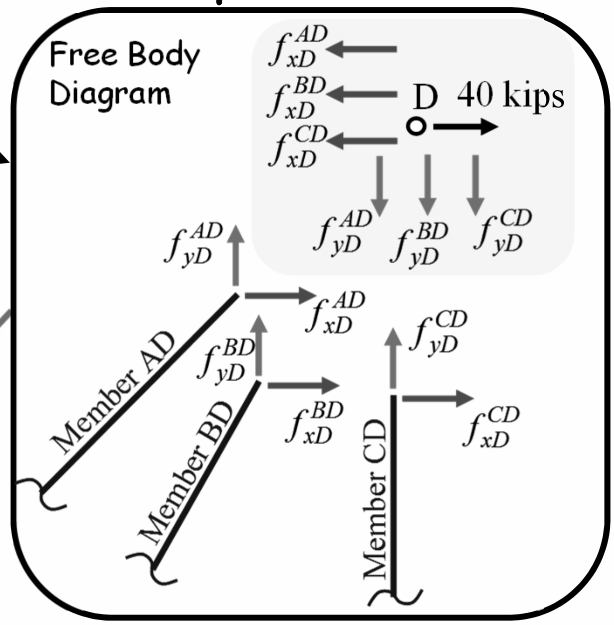
Equilibrium Equations





x-d.o.f. u_D : $\sum F_x = 0$

$$40 = f_{xD}^{AD} + f_{xD}^{BD} + f_{xD}^{CD}$$

y-d.o.f. v_D : $\sum F_y = 0$

$$0 = f_{yD}^{AD} + f_{yD}^{BD} + f_{yD}^{CD}$$

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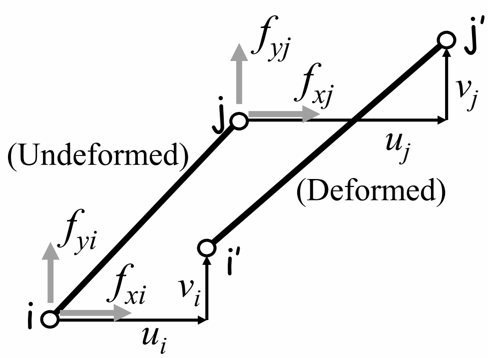
Translator: Forces → Displacements



$$f_{xi} = k_{11}u_i + k_{12}v_i + k_{13}u_j + k_{14}v_j$$

$$f_{yi} = k_{21}u_i + k_{22}v_i + k_{23}u_j + k_{24}v_j$$

$$f_{xj} = k_{31}u_i + k_{32}v_i + k_{33}u_j + k_{34}v_j$$

$$f_{yj} = k_{41}u_i + k_{42}v_i + k_{43}u_j + k_{44}v_j$$

<u>Big Question</u>:
Where do these known stiffness coefficients k's come from?

<u>Little Answer</u>:
Function of member's material and geometric properties, including its orientation.

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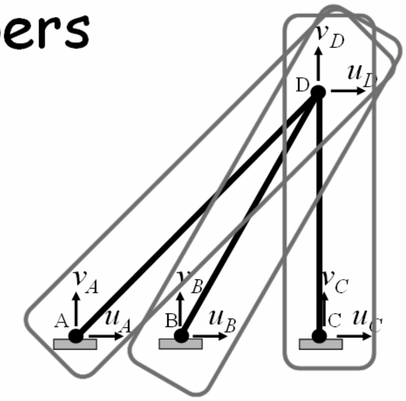
F → Δ for all members



Member AD:

$$f_{xA}^{AD} = k_{11}^{AD}u_A^{AD} + k_{12}^{AD}v_A^{AD} + k_{13}^{AD}u_D^{AD} + k_{14}^{AD}v_D^{AD}$$
$$f_{yA}^{AD} = k_{21}^{AD}u_A^{AD} + k_{22}^{AD}v_A^{AD} + k_{23}^{AD}u_D^{AD} + k_{24}^{AD}v_D^{AD}$$
$$f_{xD}^{AD} = k_{31}^{AD}u_A^{AD} + k_{32}^{AD}v_A^{AD} + k_{33}^{AD}u_D^{AD} + k_{34}^{AD}v_D^{AD}$$
$$f_{yD}^{AD} = k_{41}^{AD}u_A^{AD} + k_{42}^{AD}v_A^{AD} + k_{43}^{AD}u_D^{AD} + k_{44}^{AD}v_D^{AD}$$

Member BD:

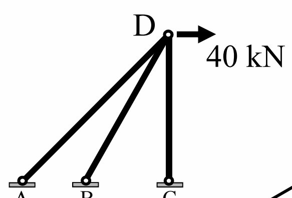
$$f_{xB}^{BD} = k_{11}^{BD}u_B^{BD} + k_{12}^{BD}v_B^{BD} + k_{13}^{BD}u_D^{BD} + k_{14}^{BD}v_D^{BD}$$
$$f_{yB}^{BD} = k_{21}^{BD}u_B^{BD} + k_{22}^{BD}v_B^{BD} + k_{23}^{BD}u_D^{BD} + k_{24}^{BD}v_D^{BD}$$
$$f_{xD}^{BD} = k_{31}^{BD}u_B^{BD} + k_{32}^{BD}v_B^{BD} + k_{33}^{BD}u_D^{BD} + k_{34}^{BD}v_D^{BD}$$
$$f_{yD}^{BD} = k_{41}^{BD}u_B^{BD} + k_{42}^{BD}v_B^{BD} + k_{43}^{BD}u_D^{BD} + k_{44}^{BD}v_D^{BD}$$

Member CD:

$$f_{xC}^{CD} = k_{11}^{CD}u_C^{CD} + k_{12}^{CD}v_C^{CD} + k_{13}^{CD}u_D^{CD} + k_{14}^{CD}v_D^{CD}$$
$$f_{yC}^{CD} = k_{21}^{CD}u_C^{CD} + k_{22}^{CD}v_C^{CD} + k_{23}^{CD}u_D^{CD} + k_{24}^{CD}v_D^{CD}$$
$$f_{xD}^{CD} = k_{31}^{CD}u_C^{CD} + k_{32}^{CD}v_C^{CD} + k_{33}^{CD}u_D^{CD} + k_{34}^{CD}v_D^{CD}$$
$$f_{yD}^{CD} = k_{41}^{CD}u_C^{CD} + k_{42}^{CD}v_C^{CD} + k_{43}^{CD}u_D^{CD} + k_{44}^{CD}v_D^{CD}$$

40

Substituting into Equil. Eqs.



Member AD:

$$f_{xD}^{AD} = k_{31}^{AD}u_A^{AD} + k_{32}^{AD}v_A^{AD} + k_{33}^{AD}u_D^{AD} + k_{34}^{AD}v_D^{AD}$$

Member BD:

$$f_{xD}^{BD} = k_{31}^{BD}u_B^{BD} + k_{32}^{BD}v_B^{BD} + k_{33}^{BD}u_D^{BD} + k_{34}^{BD}v_D^{BD}$$

Member CD:

$$f_{xD}^{CD} = k_{31}^{CD}u_C^{CD} + k_{32}^{CD}v_C^{CD} + k_{33}^{CD}u_D^{CD} + k_{34}^{CD}v_D^{CD}$$

x-d.o.f. u_D : $\sum F_x = 0$

$$40 = f_{xD}^{AD} + f_{xD}^{BD} + f_{xD}^{CD}$$

u_D : $\sum F_x = 0$

$$40 = \left(k_{31}^{AD}u_A^{AD} + k_{32}^{AD}v_A^{AD} + k_{33}^{AD}u_D^{AD} + k_{34}^{AD}v_D^{AD}\right) + \left(k_{31}^{BD}u_B^{BD} + k_{32}^{BD}v_B^{BD} + k_{33}^{BD}u_D^{BD} + k_{34}^{BD}v_D^{BD}\right) + \left(k_{31}^{CD}u_C^{CD} + k_{32}^{CD}v_C^{CD} + k_{33}^{CD}u_D^{CD} + k_{34}^{CD}v_D^{CD}\right)$$

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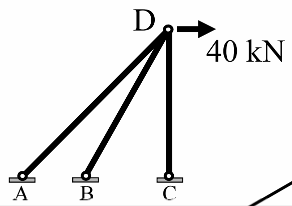
Substituting into Equil. Eqs. (cont.)



Member AD:

$$f_{yD}^{AD} = k_{41}^{AD}u_A^{AD} + k_{42}^{AD}v_A^{AD} + k_{43}^{AD}u_D^{AD} + k_{44}^{AD}v_D^{AD}$$

Member BD:

$$f_{yD}^{BD} = k_{41}^{BD}u_B^{BD} + k_{42}^{BD}v_B^{BD} + k_{43}^{BD}u_D^{BD} + k_{44}^{BD}v_D^{BD}$$

Member CD:

$$f_{yD}^{CD} = k_{41}^{CD}u_C^{CD} + k_{42}^{CD}v_C^{CD} + k_{43}^{CD}u_D^{CD} + k_{44}^{CD}v_D^{CD}$$

y-d.o.f. v_D : $\sum F_y = 0$

$$0 = f_{yD}^{AD} + f_{yD}^{BD} + f_{yD}^{CD}$$

v_D : $\sum F_y = 0$

$$0 = \left(k_{41}^{AD}u_A^{AD} + k_{42}^{AD}v_A^{AD} + k_{43}^{AD}u_D^{AD} + k_{44}^{AD}v_D^{AD}\right) + \left(k_{41}^{BD}u_B^{BD} + k_{42}^{BD}v_B^{BD} + k_{43}^{BD}u_D^{BD} + k_{44}^{BD}v_D^{BD}\right) + \left(k_{41}^{CD}u_C^{CD} + k_{42}^{CD}v_C^{CD} + k_{43}^{CD}u_D^{CD} + k_{44}^{CD}v_D^{CD}\right)$$

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So, where are we at?

- We have two equilibrium equations (1 per d.o.f.) in terms of a lot of displacements:

$$u_D: \quad 40 = \left(k_{31}^{AD}u_A^{AD} + k_{32}^{AD}v_A^{AD} + k_{33}^{AD}u_D^{AD} + k_{34}^{AD}v_D^{AD}\right) + \left(k_{31}^{BD}u_B^{BD} + k_{32}^{BD}v_B^{BD} + k_{33}^{BD}u_D^{BD} + k_{34}^{BD}v_D^{BD}\right) + \left(k_{31}^{CD}u_C^{CD} + k_{32}^{CD}v_C^{CD} + k_{33}^{CD}u_D^{CD} + k_{34}^{CD}v_D^{CD}\right)$$

$$v_D: \quad 0 = \left(k_{41}^{AD}u_A^{AD} + k_{42}^{AD}v_A^{AD} + k_{43}^{AD}u_D^{AD} + k_{44}^{AD}v_D^{AD}\right) + \left(k_{41}^{BD}u_B^{BD} + k_{42}^{BD}v_B^{BD} + k_{43}^{BD}u_D^{BD} + k_{44}^{BD}v_D^{BD}\right) + \left(k_{41}^{CD}u_C^{CD} + k_{42}^{CD}v_C^{CD} + k_{43}^{CD}u_D^{CD} + k_{44}^{CD}v_D^{CD}\right)$$

What card haven't we played yet?

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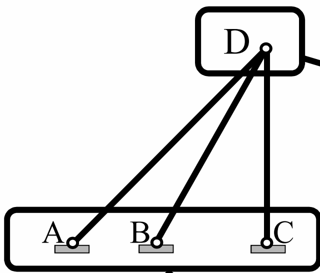
Compatibility Eqs. (consistent deflections)



Member-to-Support

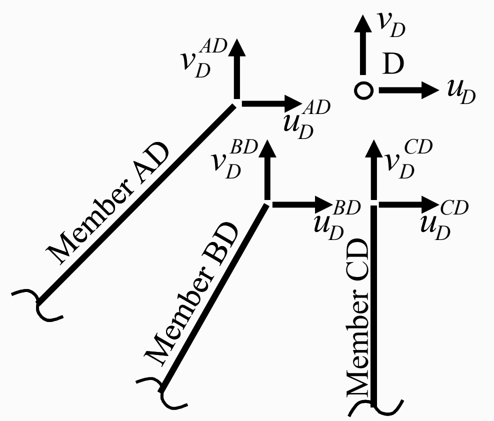
$$u_A = u_A^{AD} = 0 \qquad u_C = u_C^{CD} = 0$$

$$v_A = v_A^{AD} = 0 \qquad v_C = v_C^{CD} = 0$$

$$u_B = u_B^{BD} = 0$$

$$v_B = v_B^{BD} = 0$$

Member-to-Member



$$u_D = u_D^{AD} = u_D^{BD} = u_D^{CD}$$

$$v_D = v_D^{AD} = v_D^{BD} = v_D^{CD}$$

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Time for some serious simplifying

- Applying Compatibility to Equil. Eqs.:

$$u_D: \quad 40 = \left(k_{31}^{AD}u_A^{AD} + k_{32}^{AD}v_A^{AD} + k_{33}^{AD}u_D^{AD} + k_{34}^{AD}v_D^{AD}\right) + \left(k_{31}^{BD}u_B^{BD} + k_{32}^{BD}v_B^{BD} + k_{33}^{BD}u_D^{BD} + k_{34}^{BD}v_D^{BD}\right) + \left(k_{31}^{CD}u_C^{CD} + k_{32}^{CD}v_C^{CD} + k_{33}^{CD}u_D^{CD} + k_{34}^{CD}v_D^{CD}\right)$$

$$v_D: \quad 0 = \left(k_{41}^{AD}u_A^{AD} + k_{42}^{AD}v_A^{AD} + k_{43}^{AD}u_D^{AD} + k_{44}^{AD}v_D^{AD}\right) + \left(k_{41}^{BD}u_B^{BD} + k_{42}^{BD}v_B^{BD} + k_{43}^{BD}u_D^{BD} + k_{44}^{BD}v_D^{BD}\right) + \left(k_{41}^{CD}u_C^{CD} + k_{42}^{CD}v_C^{CD} + k_{43}^{CD}u_D^{CD} + k_{44}^{CD}v_D^{CD}\right)$$

All = 0

All = u_D

All = v_D

Which simplifies to…

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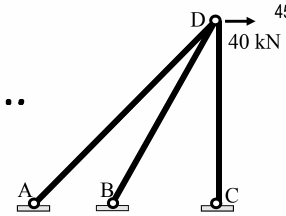
After simplifying…



$$u_D: \quad 40 = \left(k_{33}^{AD} + k_{33}^{BD} + k_{33}^{CD}\right)u_D^{?} + \left(k_{34}^{AD} + k_{34}^{BD} + k_{34}^{CD}\right)v_D^{?}$$

$$v_D: \quad 0 = \left(k_{43}^{AD} + k_{43}^{BD} + k_{43}^{CD}\right)u_D^{?} + \left(k_{44}^{AD} + k_{44}^{BD} + k_{44}^{CD}\right)v_D^{?}$$

Since k's are known, we have
2 Equations and 2 Unknowns

Solve for Unknown Displacements

$$u_D = \# \qquad \text{and} \qquad v_D = \#\#$$

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With all displacements, solve for member forces…

$$u_A = u_A^{AD} = 0$$
$$v_A = v_A^{AD} = 0$$

$$u_B = u_B^{BD} = 0$$
$$v_B = v_B^{BD} = 0$$

$$u_C = u_C^{CD} = 0$$
$$v_C = v_C^{CD} = 0$$

$$u_D = u_D^{AD} = u_D^{BD} = u_D^{CD} = \#$$
$$v_D = v_D^{AD} = v_D^{BD} = v_D^{CD} = \#\#$$

Member AD:

$$f_{xA}^{AD} = k_{11}^{AD}u_A^{AD} + k_{12}^{AD}v_A^{AD} + k_{13}^{AD}u_D^{AD} + k_{14}^{AD}v_D^{AD}$$
$$f_{yA}^{AD} = k_{21}^{AD}u_A^{AD} + k_{22}^{AD}v_A^{AD} + k_{23}^{AD}u_D^{AD} + k_{24}^{AD}v_D^{AD}$$
$$f_{xD}^{AD} = k_{31}^{AD}u_A^{AD} + k_{32}^{AD}v_A^{AD} + k_{33}^{AD}u_D^{AD} + k_{34}^{AD}v_D^{AD}$$
$$f_{yD}^{AD} = k_{41}^{AD}u_A^{AD} + k_{42}^{AD}v_A^{AD} + k_{43}^{AD}u_D^{AD} + k_{44}^{AD}v_D^{AD}$$

Member BD:

$$f_{xB}^{BD} = k_{11}^{BD}u_B^{BD} + k_{12}^{BD}v_B^{BD} + k_{13}^{BD}u_D^{BD} + k_{14}^{BD}v_D^{BD}$$
$$f_{yB}^{BD} = k_{21}^{BD}u_B^{BD} + k_{22}^{BD}v_B^{BD} + k_{23}^{BD}u_D^{BD} + k_{24}^{BD}v_D^{BD}$$
$$f_{xD}^{BD} = k_{31}^{BD}u_B^{BD} + k_{32}^{BD}v_B^{BD} + k_{33}^{BD}u_D^{BD} + k_{34}^{BD}v_D^{BD}$$
$$f_{yD}^{BD} = k_{41}^{BD}u_B^{BD} + k_{42}^{BD}v_B^{BD} + k_{43}^{BD}u_D^{BD} + k_{44}^{BD}v_D^{BD}$$

Member CD:

$$f_{xC}^{CD} = k_{11}^{CD}u_C^{CD} + k_{12}^{CD}v_C^{CD} + k_{13}^{CD}u_D^{CD} + k_{14}^{CD}v_D^{CD}$$
$$f_{yC}^{CD} = k_{21}^{CD}u_C^{CD} + k_{22}^{CD}v_C^{CD} + k_{23}^{CD}u_D^{CD} + k_{24}^{CD}v_D^{CD}$$
$$f_{xD}^{CD} = k_{31}^{CD}u_C^{CD} + k_{32}^{CD}v_C^{CD} + k_{33}^{CD}u_D^{CD} + k_{34}^{CD}v_D^{CD}$$
$$f_{yD}^{CD} = k_{41}^{CD}u_C^{CD} + k_{42}^{CD}v_C^{CD} + k_{43}^{CD}u_D^{CD} + k_{44}^{CD}v_D^{CD}$$

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Summary of Computer Approach

- For each d.o.f., write an equilibrium equation:

$$F_{external} = \Sigma f_{member} \quad \text{(Equil. Eqs.)}$$

- Re-write (translate) each member force in terms of its end displacements (Stiffness Eqs.)

$$f_{member} = \Sigma k_{member} \Delta_{member\ end}$$

- Substitute Stiffness Eqs. into above Equil. Eqs.
- Simplify Equil. Eqs. by applying member-to-member and member-to-support compatibility conditions
- Solve n Equil. Eqs. for the n unknown displacements
- Use Stiffness Eqs. to calculate member forces
- Apply Equil. Eqs. to solve for reactions

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Lot's of Questions

- So, this is how most commercial programs such as SAP2000, RISA, STAAD, Strand7, etc. get the answer?
  - Yes! Known as "Direct Stiffness Method"
- So, all such programs will give the same answer?
  - Yes, as long as it is a static 1^{st}-order elastic analysis.
- Wait a minute…Is this the basic analysis procedure for the "finite element method"?
  - Yes! Bit more tricky to get k's, σ's, and ϵ's

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Two Big Questions

- Where do those stiffness coefficients come from?
  - You mean the ones that relate member end forces to member end displacements?
  - Yeah, those k's ! <More to come on this>
- What happens when we go static nonlinear or even dynamic?
  - Same basic procedure, but apply loads in increments and perform a series of analyses. Then, sum incremental results.

    < Much more to come on this! >

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Important Points

- The only opportunity for most computer analysis software to model the actual behavior of the structure is through the member stiffness terms.
- So, to include
  - first-order effects
  - second-order effects
  - material nonlinear behavior

  Must modify member stiffness!!!
- Let's review member stiffness

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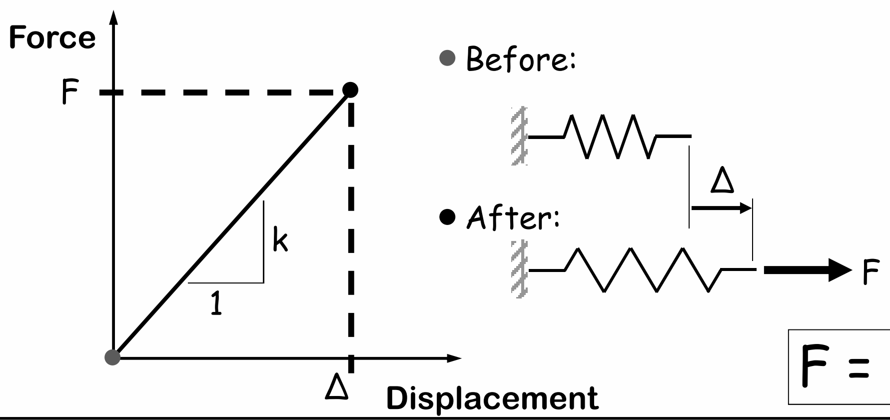
Stiffness Coefficients, k's

- Let's start with high school physics
  - Extension Spring Experiment



$F = k\,\Delta$

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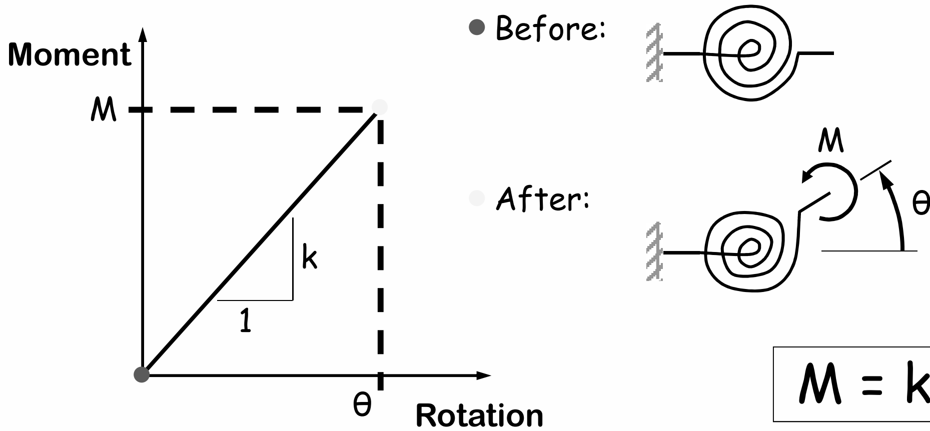
Stiffness Coefficients, k's (cont.)

- More "advanced" high school physics lab
  - Rotational Spring Experiment



$M = k\,\theta$

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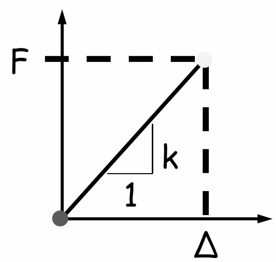
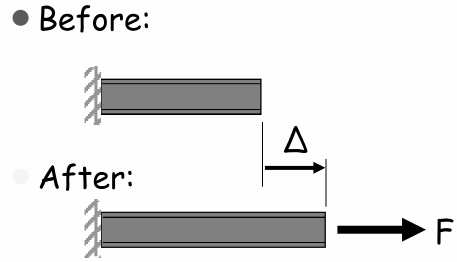
How about real structural members?

- Axial force member





- Stiffness k function of:
  - **Geometry**: Area and Length (A↑,k↑ & L↑, k↓)
  - **Material**: Elastic Modulus (E↑,k↑)

$$F = k(A,L,E)\ \Delta$$

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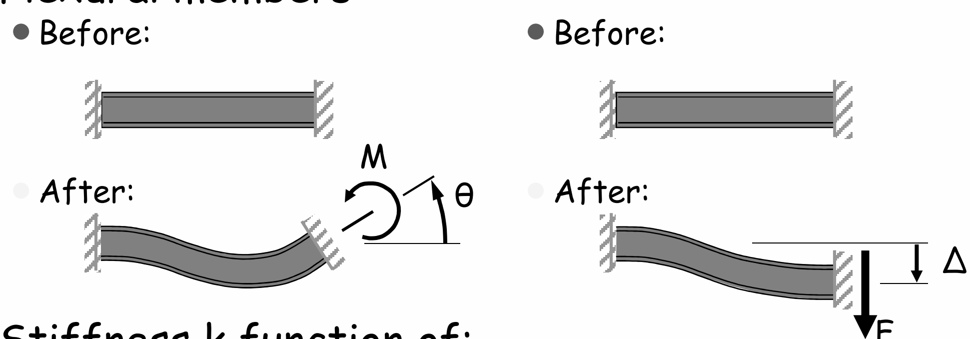
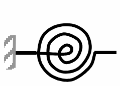
How about real members? (cont.)

- Flexural members



- Stiffness k function of:
  - **Geometry**: Moment of Inertia & Length (I↑,k↑& L↑, k↓)
  - **Material**: Elastic Modulus (E↑,k↑)



$$M = k(I,L,E)\ \theta$$

$$F = k(I,L,E)\ \Delta$$

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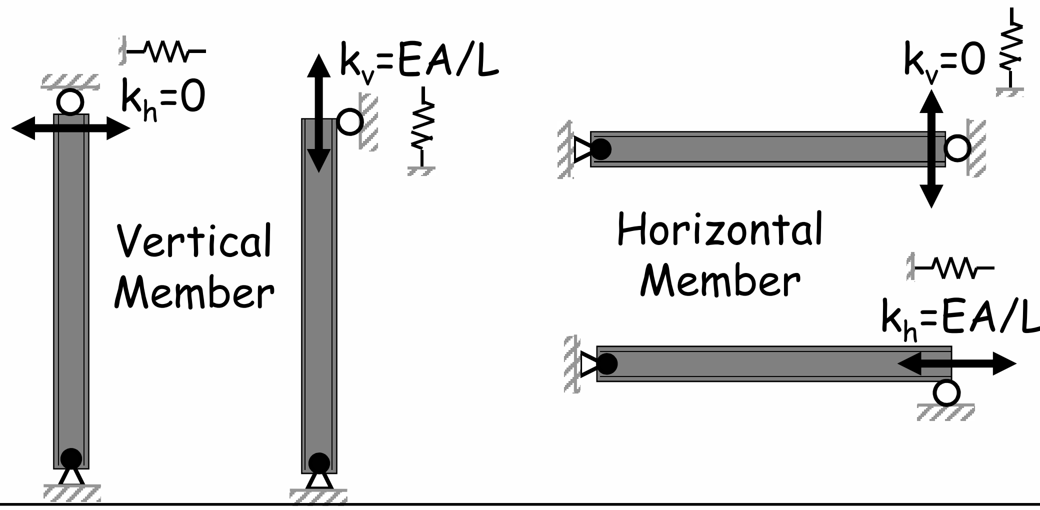
Other factor impacting stiffness

- Orientation of member
  - consider axial force member:



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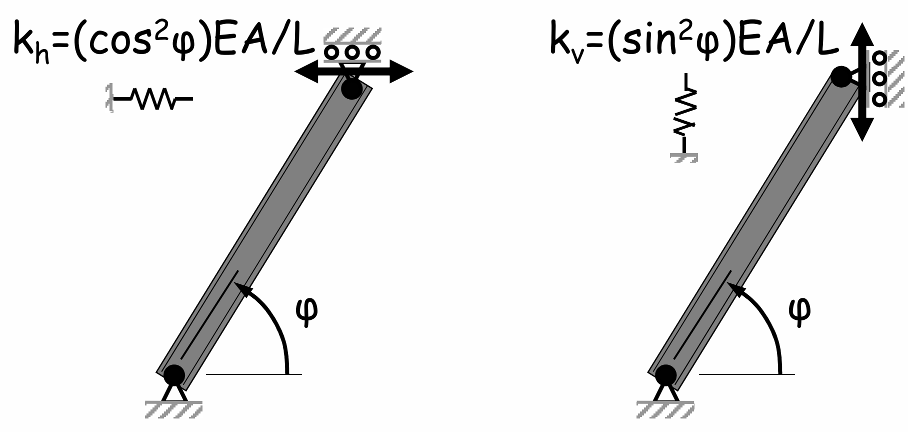
Orientation of axial force member



Important Point: Less vertical a member, the less stiffness to resist vertical loads.

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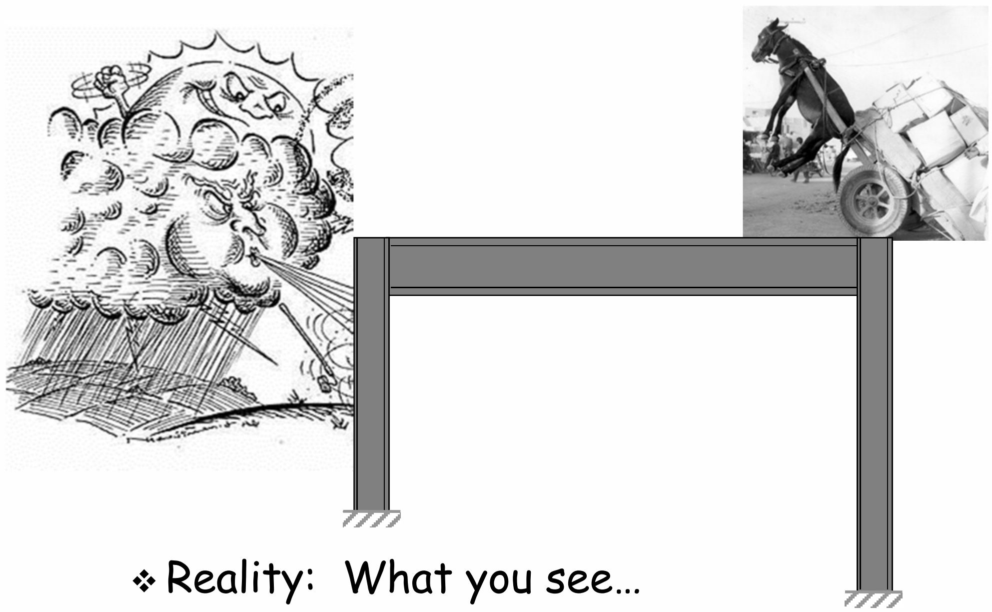
Summary: Three Perspectives



- Reality: What you see…

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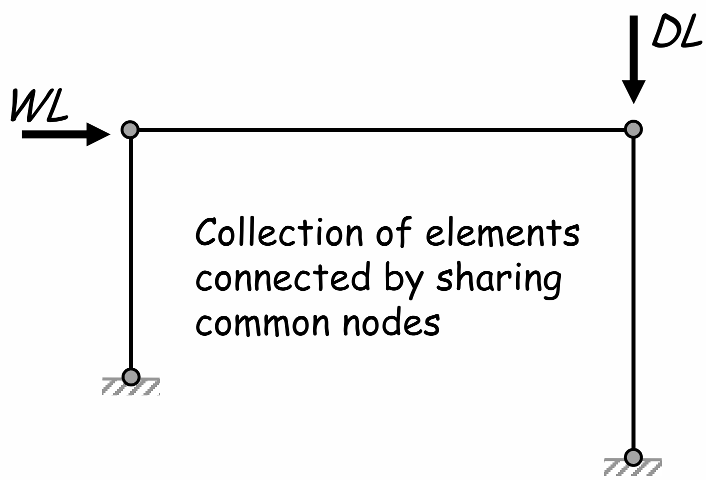
Three Perspectives (cont.)

- What you see on your computer screen:



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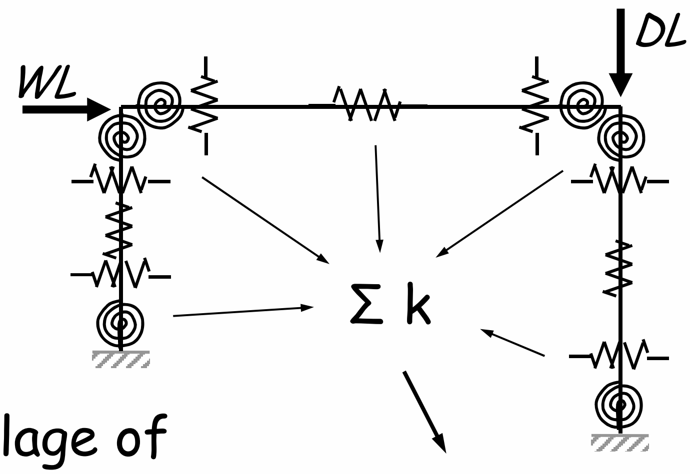
Three Perspectives

- What your computer actually sees:



Assemblage of equivalent springs $\{F\} = [K]\{\Delta\}$

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Analysis Review: Key Points

- Reviewed the "Direct Stiffness Method"
  - Equilibrium → Translator F(Δ) → Compatibility
- Response of structure controlled by stiffness of members (a.k.a. springs)
- First-order elastic stiffness of member function of:
  - Material Property (E)
  - Geometric Properties (A, I, L, and orientation)
- Time to go nonlinear…

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Up Next…

- Session 2: February 2 –
  Modern Methods of Structural Analysis, from Linear to Nonlinear – Part II
  by R.D. Ziemian, PE, PhD
- Time to go nonlinear! Using the approach provided in Lecture 1, the participants will receive a basic introduction to nonlinear methods of structural analysis. This session will give an overview of how material nonlinear behavior and/or second-order effects can be included in modern structural analysis software.

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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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Within 2 business days…

- New reporting site (URL will be provided in the forthcoming email).
- Username: Same as AISC website username.
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One certificate will be issued at the conclusion of all 8 sessions.

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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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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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