Combined Bending and Axial Forces–Braced Frames

Objectives:

1. Review AISC requirements for Design of Members with Combined Forces.
2. Review typical applications of beam–column.
3. Understand and apply AISC column stability requirements.
4. Use Approximate Methods to evaluate second-order P–δ effects.
5. Develop computer models for braced frames and evaluate beam–columns.

Design Requirements

- **Combined Forces (AISC Specifications):**
  - Chapter H: Combined Forces
    - Includes Chapters D through F (Design for Tension, Compression, and Flexure)
  - Chapter C: Stability: Direct Analysis Method
  - Appendix 7: Alternative Stability Analysis Methods
  - Appendix 8: Approximate 2nd Order Analysis
  - Part 6: Design Tables

Combination of multiple states of stress:

- The basic principle for design is an interaction equation which combines forces from axial (Tension or Compression) and bending loads. Shear is checked independently.

- Modes of failure are analyzed independently. This is not completely realistic, but is sufficiently accurate for design purposes.

16.1.H1.1: Doubly and Singly Symmetric Members: Flexure and Compression

For $\dfrac{P_r}{P_c} \geq 0.2\,;$ $\qquad \dfrac{P_r}{P_c} + \dfrac{8}{9}\left(\dfrac{M_{rx}}{M_{cx}} + \dfrac{M_{ry}}{M_{cy}}\right) \leq 1.0$ Equation H1-1a

P_r = required axial compressive strength from 2nd ORDER ANALYSIS (from LRFD load combinations).
P_c = available design axial compressive strength LRFD (strength from Chapter E).

M_r = required flexural strength from 2nd ORDER ANALYSIS (from LRFD load combinations).
M_c = available design flexural strength LRFD (strength from Chapter F).

x = strong axis bending
y = weak axis bending

16.1.H1.1: Doubly and Singly Symmetric Members: Flexure and Compression

For $\frac{P_r}{P_c} < 0.2$;

$$\frac{P_r}{2P_c} + \left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \right) \le 1.0$$

Equation H1-1b

16.1.H1.2: Doubly and Singly Symmetric Members: Flexure and Tension

- The same equations are used for tension and compression.

(H1-1a and H1-1b)

Substitute:

P_r = required axial tensile strength (from LRFD load combinations)

P_c = available design axial tensile strength LRFD (strength from Chapter D)

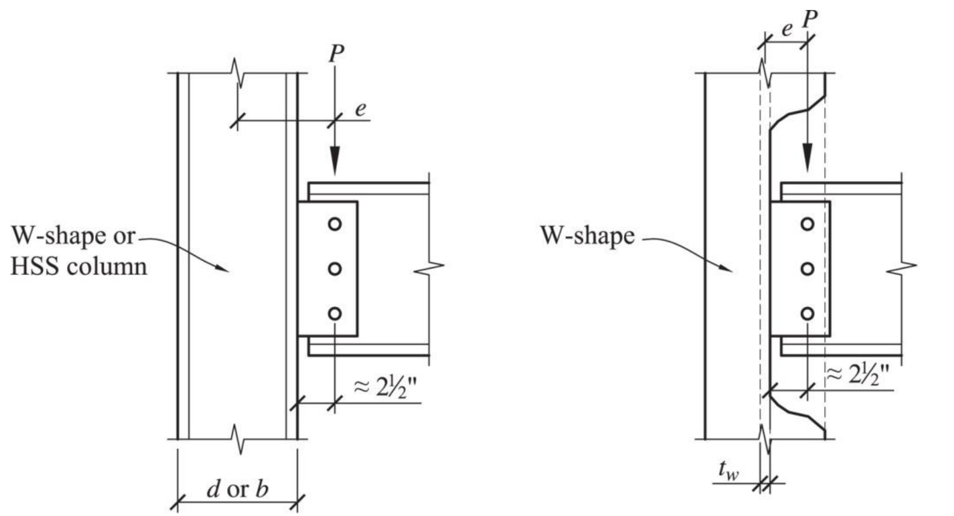
Additionally, for M_c

C_b can be increased by $\sqrt{1+\frac{\alpha P_r}{P_{ey}}}$ per Section H1.2.

- Lateral torsional buckling design strength increases due to tension.

Applications: Beam-Columns with Simple Shear connections

Simple shear connection eccentricity



(a) Connection to Column Flange

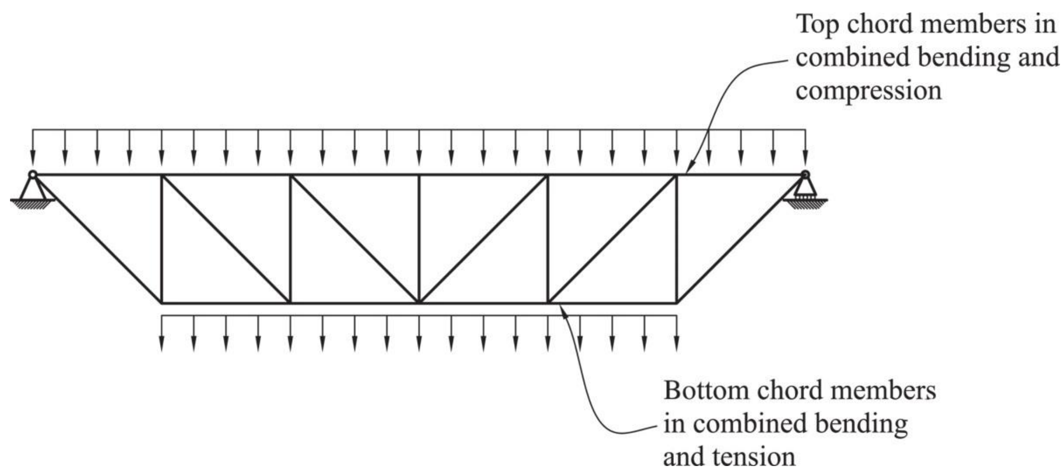
(b) Connection to Column Web

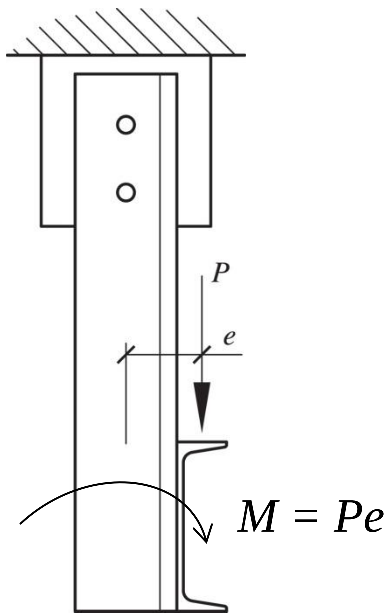
$e = \frac{d}{2} + 2.5"$ For beams framing into column flange

$e = \frac{t_w}{2} + 2.5"$ For beams framing into column web

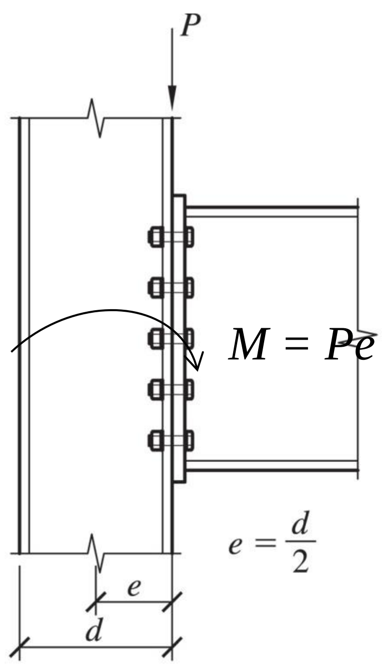
$e = \frac{b}{2} + 2.5"$ For beams framing into face of HSS

Applications: Misc. Combined Forces

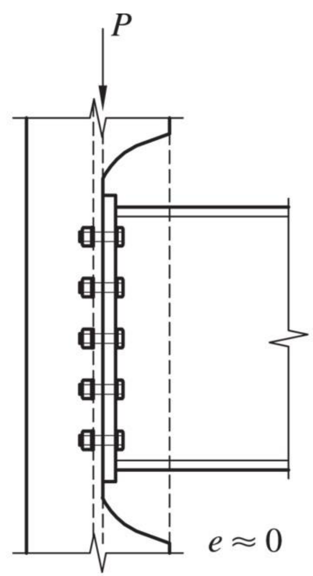




Applications: Misc. Connection Eccentricity

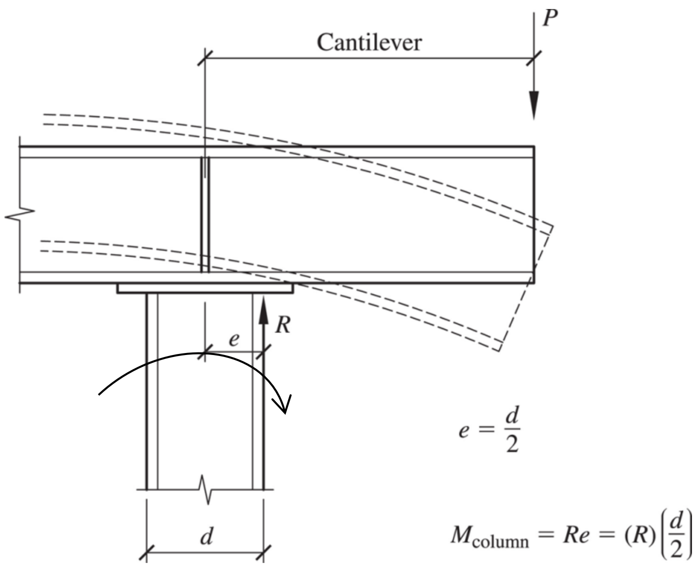


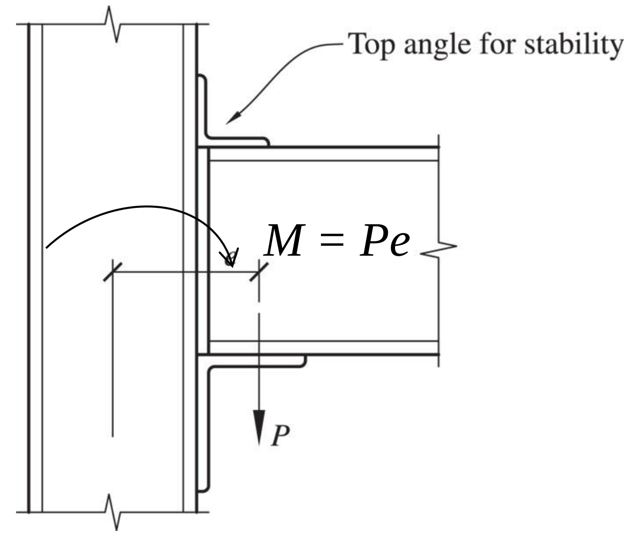
(a) Connection to the Column Flange



(b) Connection to the Column Web

Applications: Misc. Connection Eccentricity





Stability Analysis and Design
Chapter C

C1: General Requirements

The following effects on stability must be considered in the analysis and design of steel structures:

1. All flexural, shear and axial deformations.
2. Second-order, P-Δ and P-δ Amplification
3. Geometric imperfections.
4. Reduced stiffness due to inelasticity.
5. Uncertainties in stiffness and strength.

Stability Analysis and Design
Chapter C

Chapter C1 General Requirements:

C1.1 Direct Analysis Method is the prescribed method and is applicable to any structure.

C1.2 Alternative Methods described in Appendix 7 (Effective Length and First-Order) may be used provided specified constraints are satisfied.

Note: Direct Analysis is REQUIRED if $\Delta_{2nd\ Order}/\Delta_{1st\ Order} > 1.5$ ($B_2 > 1.5$) (See Section Appendix 7.2.1)

DIRECT ANALYSIS METHOD

Key Features:

- Does not distinguish between different LLRS (e.g. braced or moment frames) .
- Additional lateral "Notional" loads to account for geometric imperfections.
- Reduced stiffness of structure is utilized to account for inelasticity and uncertainty of second-order effects.
- No *K* values required. K=1.0 (all columns)
  No alignment charts!

Stability Analysis and Design
Direct Analysis Method

Chapter C2: Calculation of <u>Required</u> Strengths

C2.1 General Analysis Requirements:

C2.1(1): Use reduce stiffnesses for all elements that contribute to stability.

C2.1(2): Second-order analysis is required. Approximate method in Appendix is acceptable.

C2.1(3): Include all loads that influence stability, including leaning columns and other elements not part of the *Lateral Force Resisting System (LFRS).*

C2.1(4): Use LRFD factored load combinations for Second-order analysis. For ASD, multiply load combinations by 1.6 and divide results by 1.6 to obtain required strengths of components.

Stability Analysis and Design
Direct Analysis Method

C2.2 Consideration of Imperfections:

C2.2(b): Use Notional Loads to represent geometric imperfections.

$$N_i = 0.002\alpha Y_i \qquad \textbf{(Eq. C2-1)}$$

where,

N_i = horizontal "notional" load applied at level *i*

Y_i = gravity load applied at level *i*

$\alpha = 1.0$ *(LRFD)*

.002 = 1/500 out-of-plumbness

Note: Notional loads are applied to all load combinations and in each direction separately unless second order to first order drift ratio is ≤ 1.7. Then, apply notional loads only to gravity load combinations

Stability Analysis and Design
Direct Analysis Method

C2.3 Adjustments to stiffness:

C2.3(1): Apply a factor of 0.8 to all member stiffnesses (.8EI) contributing to stability. Suggest apply to <u>all</u> primary members.

C2.3(2): Apply additional factor, τ_b, to all members (typically columns) whose flexural stiffness contributes to stability.

Stability Analysis and Design
Direct Analysis Method

Reduce Stiffness *EI per Section C2.3:**

$$EI^* = 0.8\,\tau_b EI.$$

E = modulus of elasticity
I = moment of inertia about axis of bending
t_b = reduction factor for inelastic action

Note: Required for all members that contribute to lateral stability of the structure (safe to include for all members).

Stability Analysis and Design
Direct Analysis Method

Reduce Stiffness, EA^* per Section C2.3:

$$EA^* = 0.8EA$$

E = modulus of elasticity
A = cross sectional member area

Required for all members that contribute to lateral stability of the structure (safe to include for all members).

Stability Analysis and Design
Direct Analysis Method

Reduce Flexural Stiffness *EI per Section C2.3:**

τ_b = Reduction Factor for Inelastic Action

$$\tau_b = 1.0 \quad \text{for} \quad \frac{\alpha P_r}{P_y} \le 0.5 \qquad \textbf{Eq. C2-2a}$$

$$\tau_b = 4\left[\frac{\alpha P_r}{P_y}\left(1 - \frac{\alpha P_r}{P_y}\right)\right] \quad \text{for} \quad \frac{\alpha P_r}{P_y} > 0.5 \qquad \textbf{Eq. C2-2b}$$

P_r = required axial compressive strength
P_y = F_yA = member yield strength
a = 1.0 (LRFD), 1.6 (ASD)

Note: If an additional notional load of $N_i = .001\alpha Y_i$ is applied at all levels in all load combinations (even if Section C2.2b(4) applies), $\tau_b = 1$ per Section C2.3(3).

Column Stability Analysis :
Chapter C2: Required Strengths

Direct Analysis Method (DAM)

1. Replace *EI** with $.8\,\tau_b\,EI$ and *EA** by *0.8EA in all members.* *K=1* all columns.

2. Conduct first and second-order analysis with reduced stiffnesses. Computer or Approximate Methods (Appendix 8)

3. Add notional loads at each level to all load combinations to account for geometric imperfections. Note: exceptions C2b(4).

4. Include leaning columns effects for unbraced frames.

Column Stability Analysis :
Chapter C2: Required Strengths

Effective Length Method (ELM): Appendix 7

1. No reduction in elastic stiffness, use *EI* and *EA.* Use alignment charts to determine K.

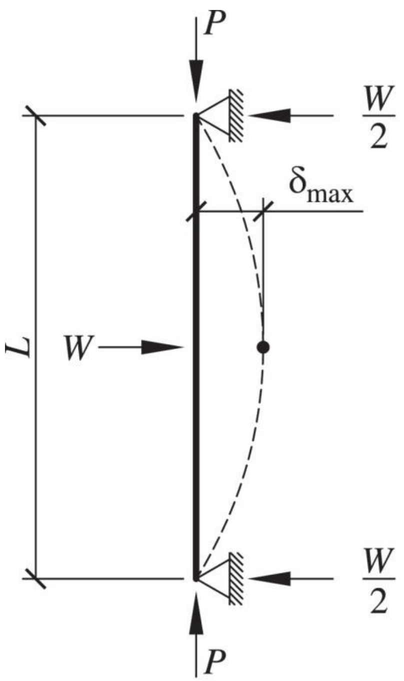
2. Conduct first and second-order analysis. Computer or Approximate Methods (Appendix 8)

3. Add notional loads to account for geometric imperfections to gravity only load combinations.

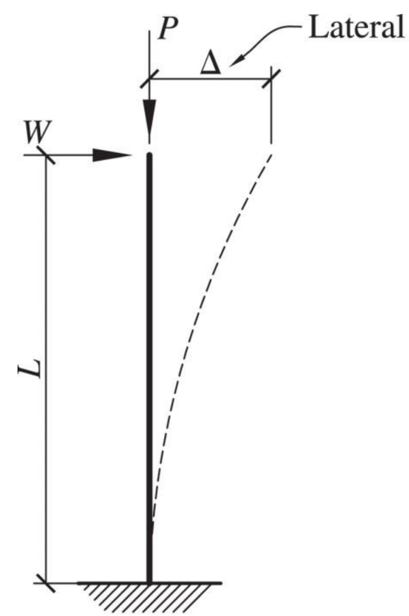
4. Include leaning columns effects for unbraced frames.

Appendix 8: Approximate Second-Order Analysis

Second-Order Effects:



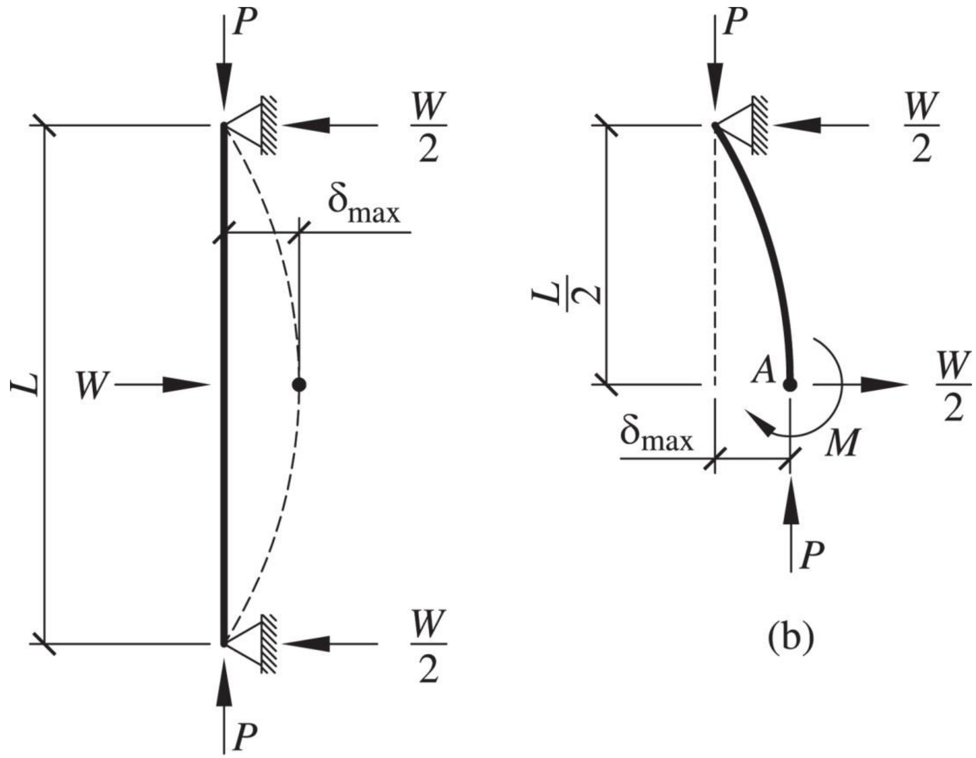
Braced Frame
pin-pin



Unbraced Frame
Fixed-Free

Appendix 8: Approximate Second-Order Analysis

Second-Order Effects:



Braced Frame

Appendix 8: Approximate Second-Order Analysis

Amplified First Order Moments–Braced Frame

$$M_r = B_1 M_{nt} + B_2 M_{lt} \qquad \text{Eq. A-8-1}$$

M_r = second order required flexural strength
B_1 = amplification factor to account for second order effects caused by displacements along member length (P-δ effects).
M_{nt} = first order moment, assuming no lateral translation of frame (from load combinations).
B_2 = amplification factor to account for second order effects caused by displacements of member ends (P-Δ effects).
M_{lt} = first order moment caused by lateral translation of frame (from load combinations).

Appendix 8: Approximate Second-Order Analysis

Amplified First Order Axial Forces-Braced Frame:

$$P_r = P_{nt} + B_2 P_{lt} \qquad \text{Eq A-8-2}$$

P_r = second order required axial strength.
P_{nt} = first order axial force, assuming no lateral translation of frame (from load combinations).
B_2 = amplification factor to account for second order effects caused by displacements of member ends (P-Δ effects).
P_{lt} = first order axial force caused by lateral translation of frame (from load combinations).

Amplified Moment Factor

Braced Frame: No Translation

$$B_1 = \left(\frac{C_m}{1 - \alpha \dfrac{P_r}{P_{e1}}} \right) \geq 1 \qquad \text{Eq. A-8-3}$$

$$P_{e1} = \frac{\pi^2 EI^*}{(K_1 L^2)} \qquad \text{Eq. A-8-5}$$

K_1 = 1 (DAM) or less since there is no end translation (ELM)

* Use $.8\ \tau_b EI$ for DAM and EI for ELM

α=1.0 for LRFD design $\qquad$ α=1.6 for ASD design

Amplified First Order Analysis

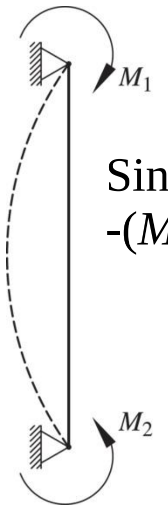
Braced Frame: No Translation

For cases where member has end moment only (no transverse loads between brace points are applied):

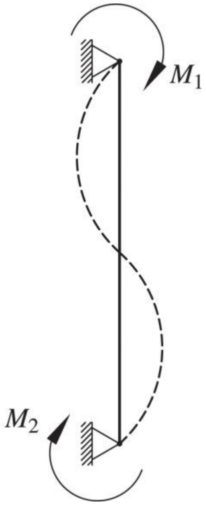
$C_m = 0.6 - 0.4(M_1/M_2)$ Equation A-8-4

M_1 = smaller first order end moment

M_2 = larger first order end moment



Single Curvature:
$-(M_1/M_2)$



Reverse Curvature:
$+(M_1/M_2)$

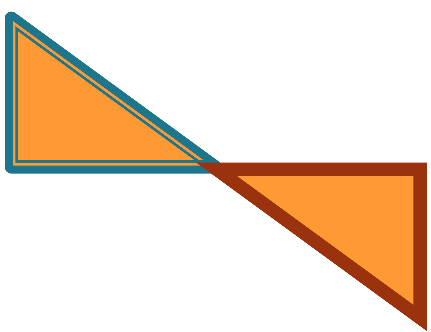
Amplified First Order Analysis
Modification Coefficient, C_m

$$M_1 / M_2 = -1$$

$$C_m = 0.6 - 0.4(-1) = 1.0$$

(largest possible value)

$$M_1 / M_2 = 0 \qquad C_m = 0.6 - 0.4(0) = 0.6$$



$$M_1 / M_2 = +1 \qquad C_m = 0.6 - 0.4(+1) = 0.2$$

(smallest possible value)

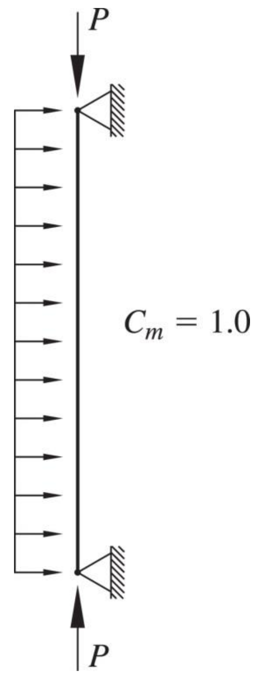
Amplified First Order Analysis

Braced Frame: No Translation

For cases where loads are present transverse to the member:

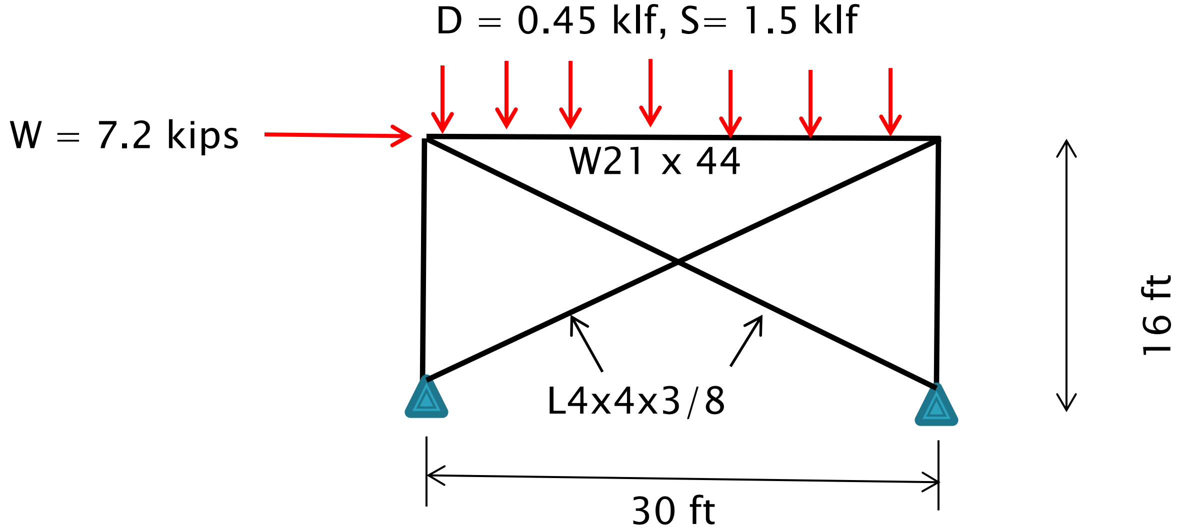
$$C_m = 1 - \psi \frac{\alpha P_r}{P_{e1}}$$ Eq. C-A-8-2

ψ from Table C-A-8.1



Example 1–Braced Frame

Given: Braced Frame



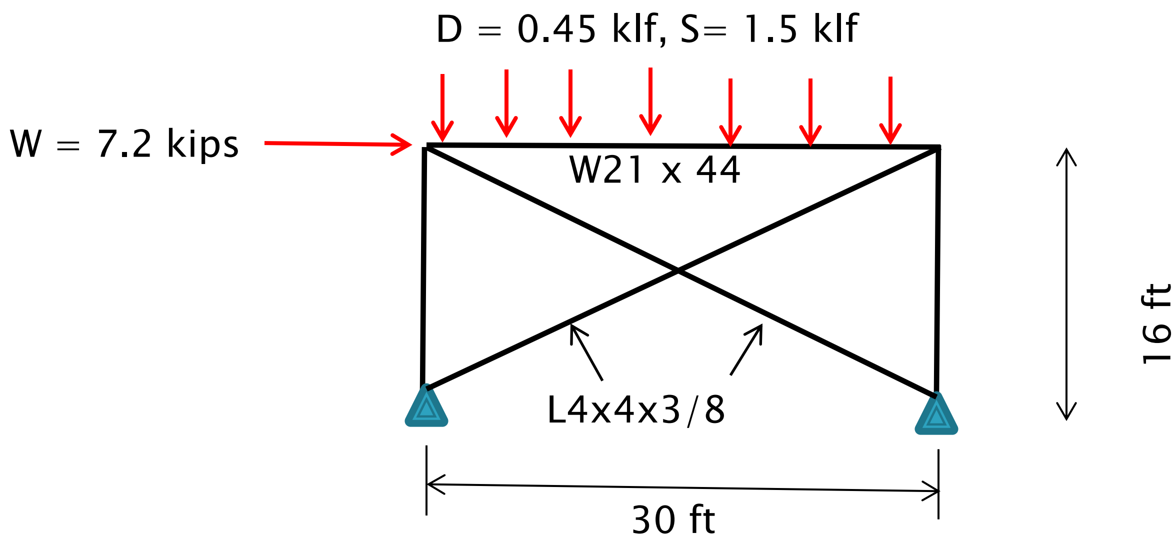
Find:

1. Evaluate W10x33 Columns.

Method: LRFD, ELM, include *l/500* out-of-plumbness, 3 in. connection eccentricity. Appendix 8

Example 2–Braced Frame

Given: Braced Frame



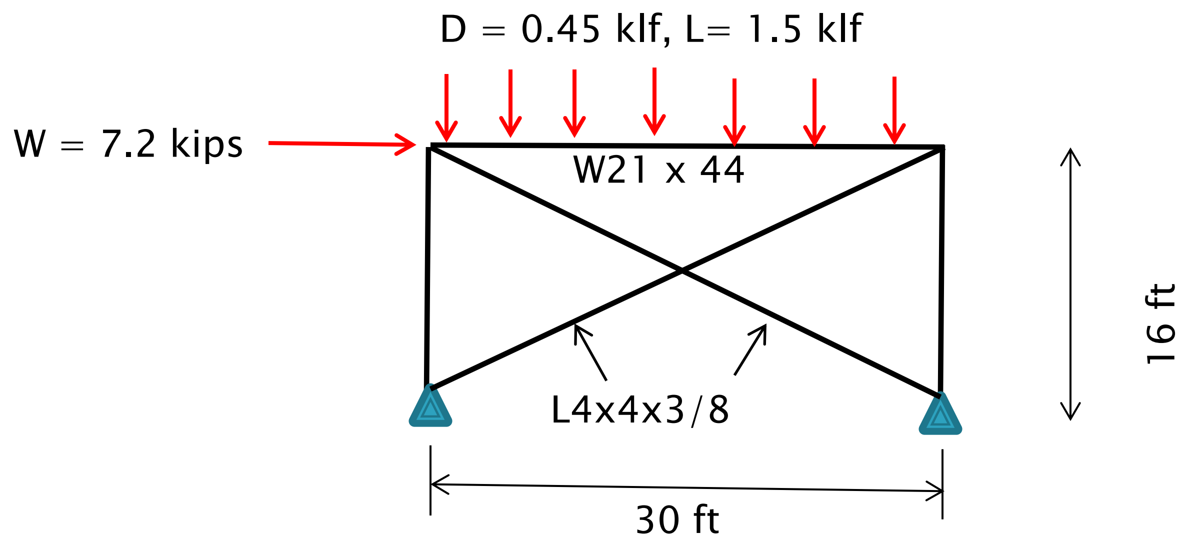
Find:

1. Design Column, LRFD.

Method: ELM, include *l/500* out-of-plumbness, 3 in. connection eccentricity. Appendix 8

Example 3–Braced Frame

Given:



Find:

1. Design Column.

Method: LRFD, DAM–Ch C, include *l/500* out-of-plumbness, 3 in. connection eccentricity. Appendix 8

HW#4– Handout

Due 10/6/14