Design for Stability

CE470 Spring 2014

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What is Stability?

- “the capacity of a compression member, element, or frame to remain in position and support load, even if forced slightly out of line or position by an added lateral force” (Galambos, 1998)

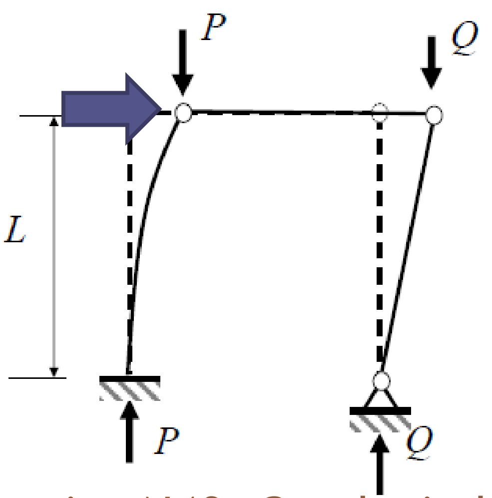


Figure from NASCC: The Steel Conference 2014, Session N40, Geschwindner

5 factors that influence stability

- Member, component, and connection deformations
- Second-order effects (P-Δ and P-δ)
- Geometric imperfections (out-of-plumbness or out-of-straightness)
- Stiffness reductions due to inelasticity (residual stresses)
- Variability in component and system stiffness

“The Evolution of Stability Provisions in the AISC Specification,” C.J. Carter, 2013.

AISC Chapter C: Design for Stability

- Direct Analysis Method of Design
  - Calculation of required strengths – Section C2
  - Calculation of available strengths – Section C3
- Alternative Methods of Design
  - "Effective Length" method and first-order analysis method permitted for structures that satisfy the constraints in Appendix 7
- Use of approximate method of second-order analysis (B1, B2) permitted as an alternative (Appendix 8) to "rigorous" second-order analysis

Appendix 7 - Constraints

$$B_2 = \frac{\Delta_{2nd-order}}{\Delta_{1st-order}} \leq 1.5$$

7.2. EFFECTIVE LENGTH METHOD

1. Limitations

The use of the *effective length* method shall be limited to the following conditions:

(1) The structure supports *gravity loads* primarily through nominally vertical *columns*, walls or frames.

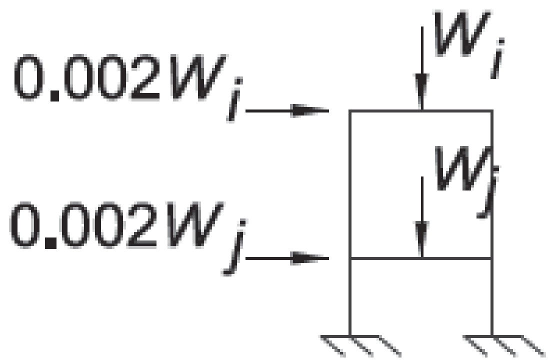
(2) The ratio of maximum second-order *drift* to maximum first-order drift (both determined for *LRFD load combinations* or 1.6 times *ASD load combinations*) in all stories is equal to or less than 1.5.

User Note: The ratio of second-order drift to first-order drift in a story may be taken as the B_2 multiplier, calculated as specified in Appendix 8.

Appendix 7 – Required Strengths

2. Required Strengths

The *required strengths* of components shall be determined from analysis conforming to the requirements of Section C2.1, except that the *stiffness* reduction indicated in Section C2.3 shall not be applied; the nominal stiffnesses of all *structural steel* components shall be used. *Notional loads* shall be applied in the analysis in accordance with Section C2.2b.



Appendix 7 – Available Strengths

(b) In *moment frame* systems and other structural systems in which the flexural stiffnesses of columns are considered to contribute to lateral stability and resistance to lateral loads, the effective length factor, K, or elastic critical *buckling* stress, F_e, of those columns whose flexural stiffnesses are considered to contribute to lateral stability and resistance to lateral loads shall be determined from a *sidesway buckling* analysis of the structure; K shall be taken as 1.0 for columns whose flexural stiffnesses are not considered to contribute to lateral stability and resistance to lateral loads.

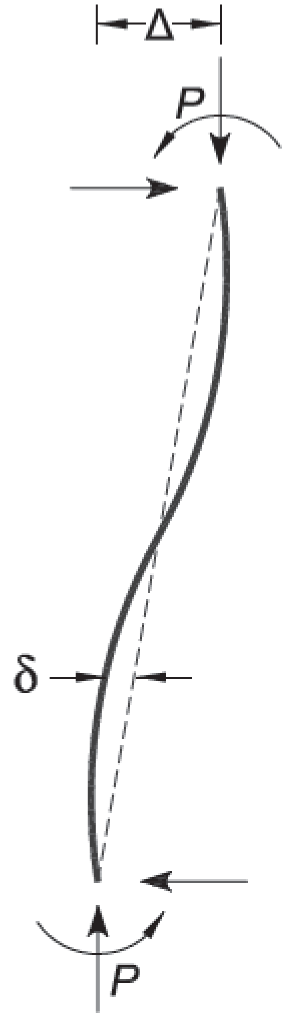
Exception: It is permitted to use $K = 1.0$ in the design of all columns if the ratio of maximum second-order *drift* to maximum first-order drift (both determined for *LRFD load combinations* or 1.6 times *ASD load combinations*) in all stories is equal to or less than 1.1.

User Note: Methods of calculating the effective length factor, K, are discussed in the *Commentary*.

Effective Length Method

- Design process
  - Apply notional loads, $N_i = 0.002\alpha Y_i$ in the gravity only load cases
  - Perform a second-order elastic analysis
  - Determine K-factor from a sidesway buckling analysis
  - Check strength using interaction equations

"B1,B2" OK



P-Δ = Effect of loads acting on the displaced location of joints or nodes in a structure.

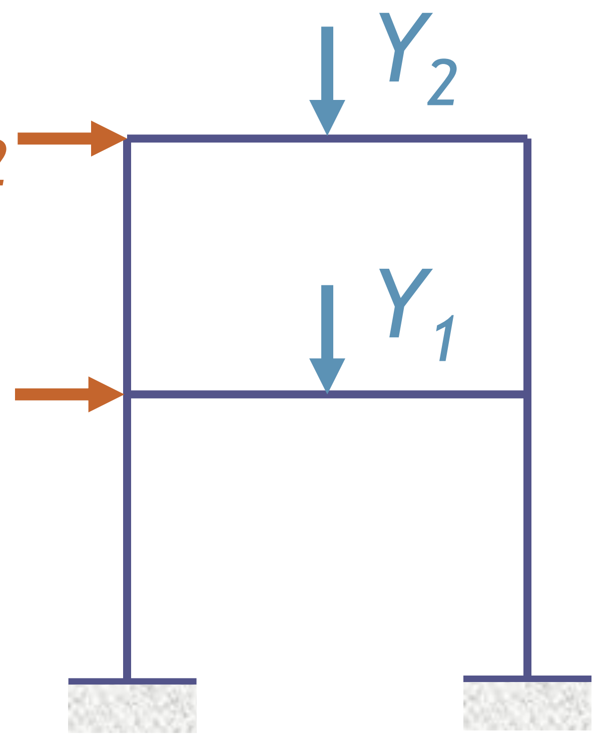
P-δ = Effect of loads acting on the deflected shape of a member between joints or nodes.

Fig. C-C2.1. P-Δ *and* P-δ *effects in beam-columns.*

Notional Loads

$N_2 = 0.002\alpha Y_2$

$N_1 = 0.002\alpha Y_1$

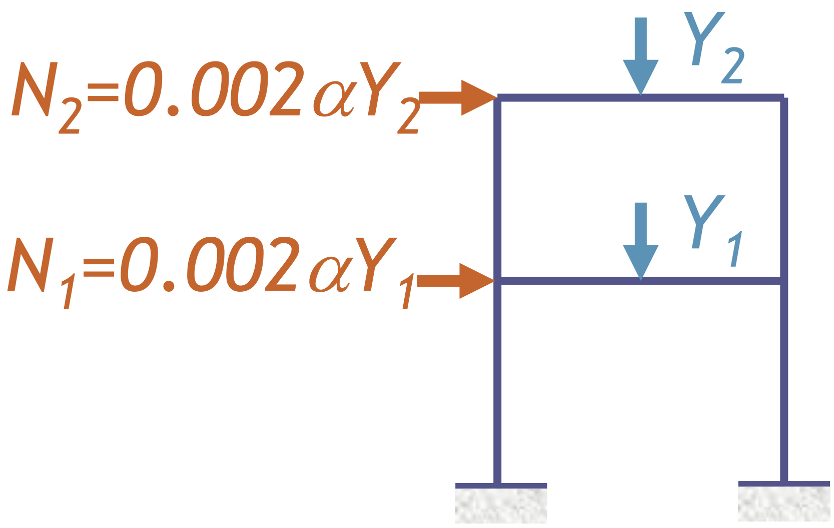


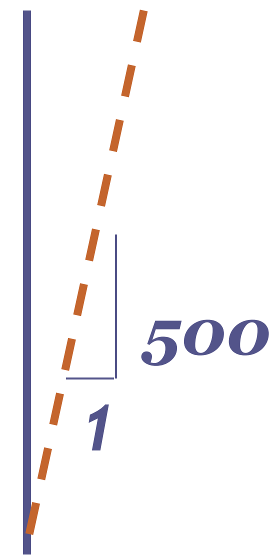
$N_i = 0.002\alpha Y_i$

$\alpha = 1.0$ (LRFD)

AISC Code of Standard Practice (Section 16.3)

Notional Loads

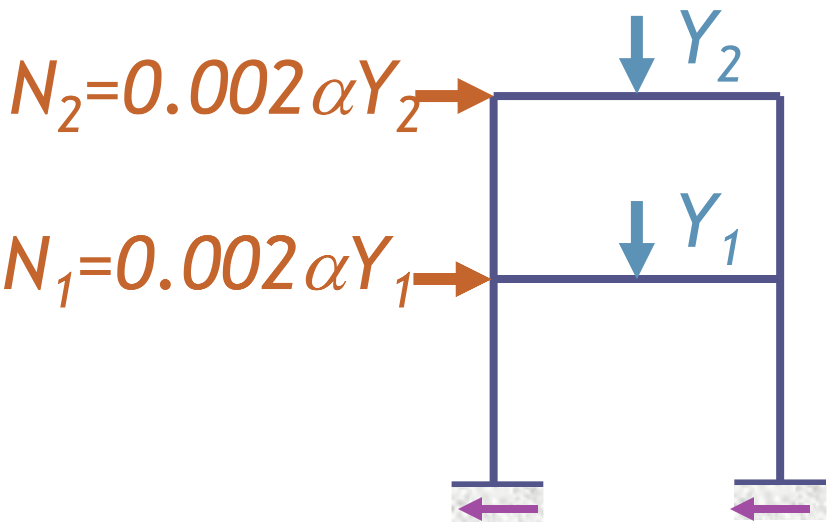




Member “out-of-plumbness”

AISC C2.2b

Notional Loads



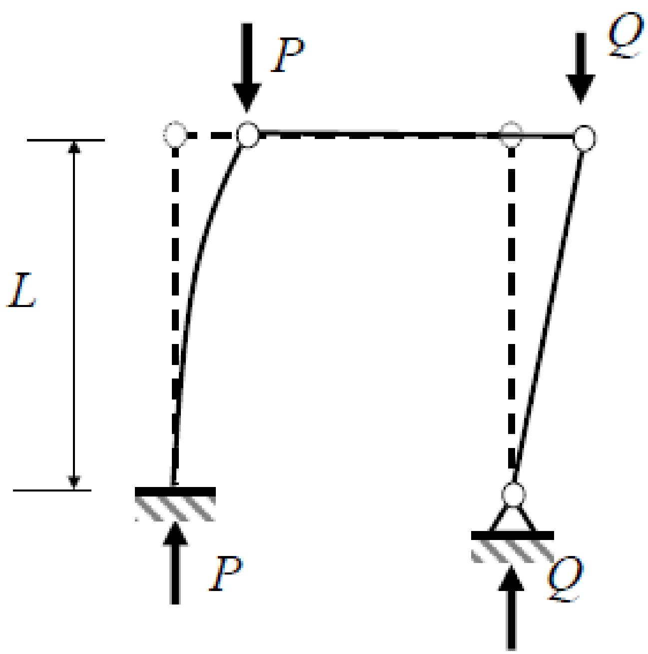
User Note: The notional loads can lead to additional (generally small) fictitious base shears in the structure. The correct horizontal reactions at the foundation may be obtained by applying an additional horizontal force at the base of the structure, equal and opposite in direction to the sum of all notional loads, distributed among vertical load-carrying elements in the same proportion as the gravity load supported by those elements. The notional loads can also lead to additional overturning effects, which are not fictitious.

Direct Analysis Method - Advantages

- No K-factor calculations (K = 1.0)
  - Good! K often difficult to predict; alignment charts utilize many assumptions
- Internal forces more accurately represented
  - At ultimate capacity (e.g., inelasticity)
- Method applies logically & consistently to all framing systems
  - Braced frames, moment frames, trusses, etc.
- More economical in some cases

Just one example for K …

Buckling with Gravity Only Columns



$$K_n = K_o\sqrt{1+\frac{Q}{P}}$$

No load on gravity only column

$Q = 0,\ K = 2.0$

Equal loads on restraining and gravity only column

$Q/P = 1,\ K = 2.8$

Other combinations

$Q/P = 2,\ K = 3.46$

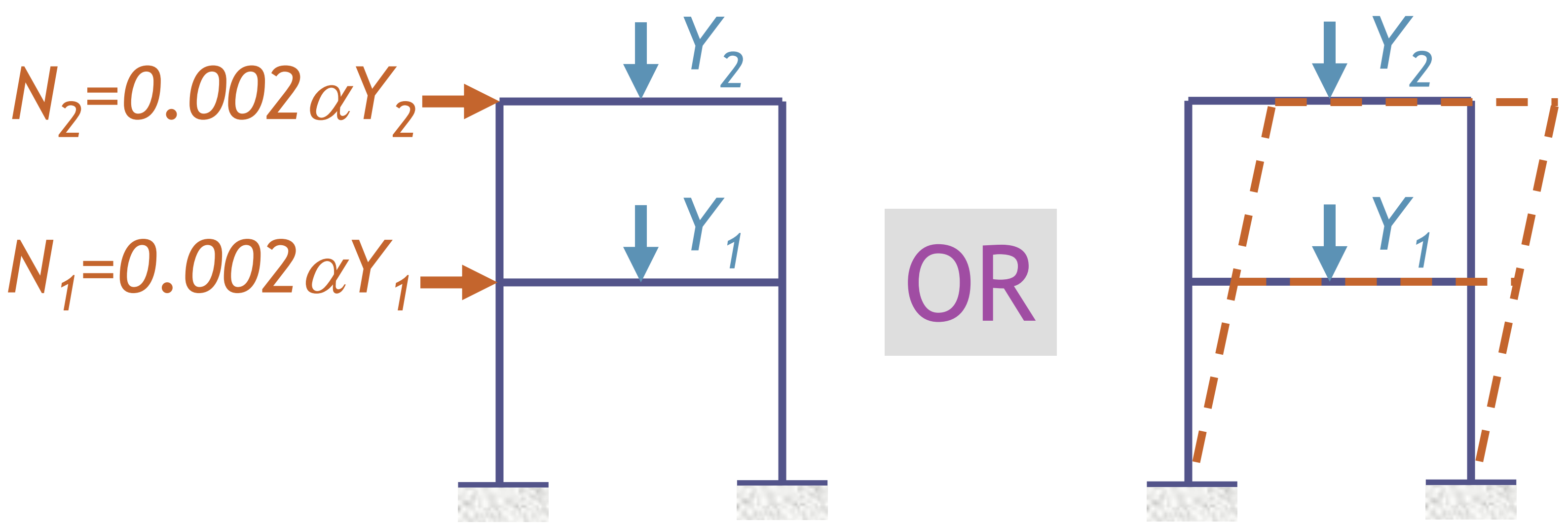
$Q/P = 10,\ K = 6.63$

What would you do if there were no load P?

N40.73

NASCC: The Steel Conference, Toronto, March, 2014
There's always a solution in steel!

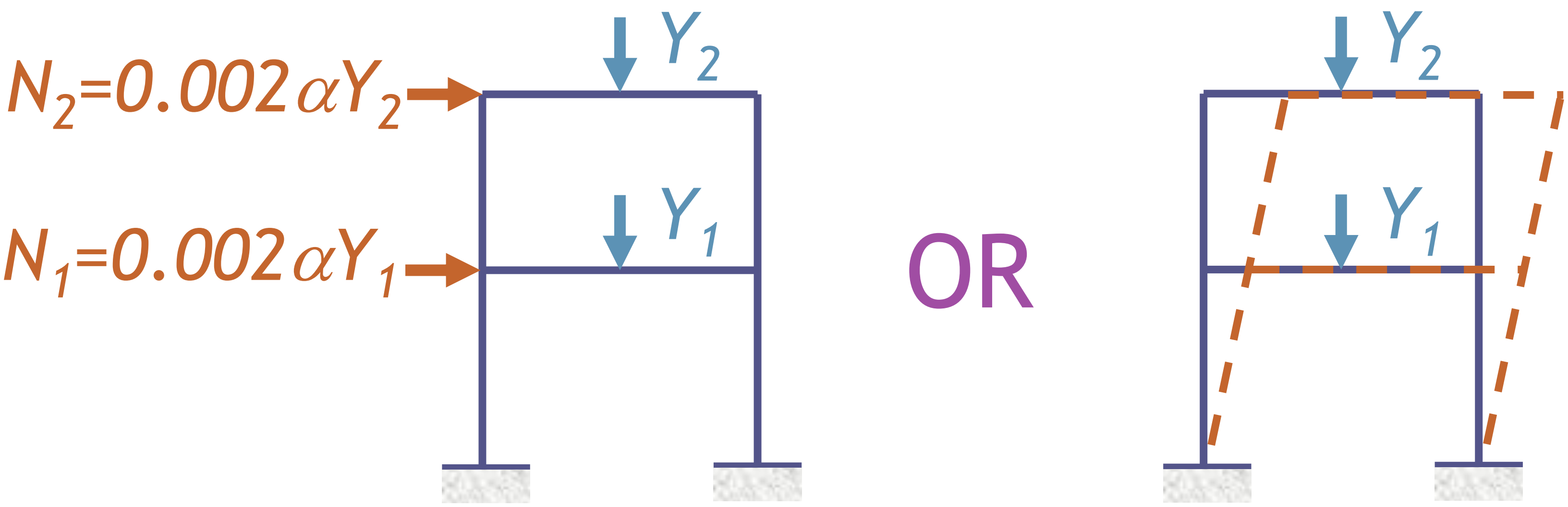
Direct Analysis Method



Notional Loads

Direct Modeling of Imperfections

Adjustments to Stiffness



Reduced stiffnesses 0.8EA and $0.8\tau_b EI$
(including in B_1-B_2 amplification, if used)

Adjustments to Stiffness

(a) When $\alpha P_r/P_y \leq 0.5$

$$\tau_b = 1.0 \qquad \text{(C2-2a)}$$

(b) When $\alpha P_r/P_y > 0.5$

$$\tau_b = 4(\alpha P_r/P_y)[1-(\alpha P_r/P_y)] \qquad \text{(C2-2b)}$$

where

α = 1.0 (LRFD); α = 1.6 (ASD)

P_r = required axial compressive strength using *LRFD* or *ASD load combinations*, kips (N)

P_y = axial *yield strength* (= $F_y A_g$), kips (N)

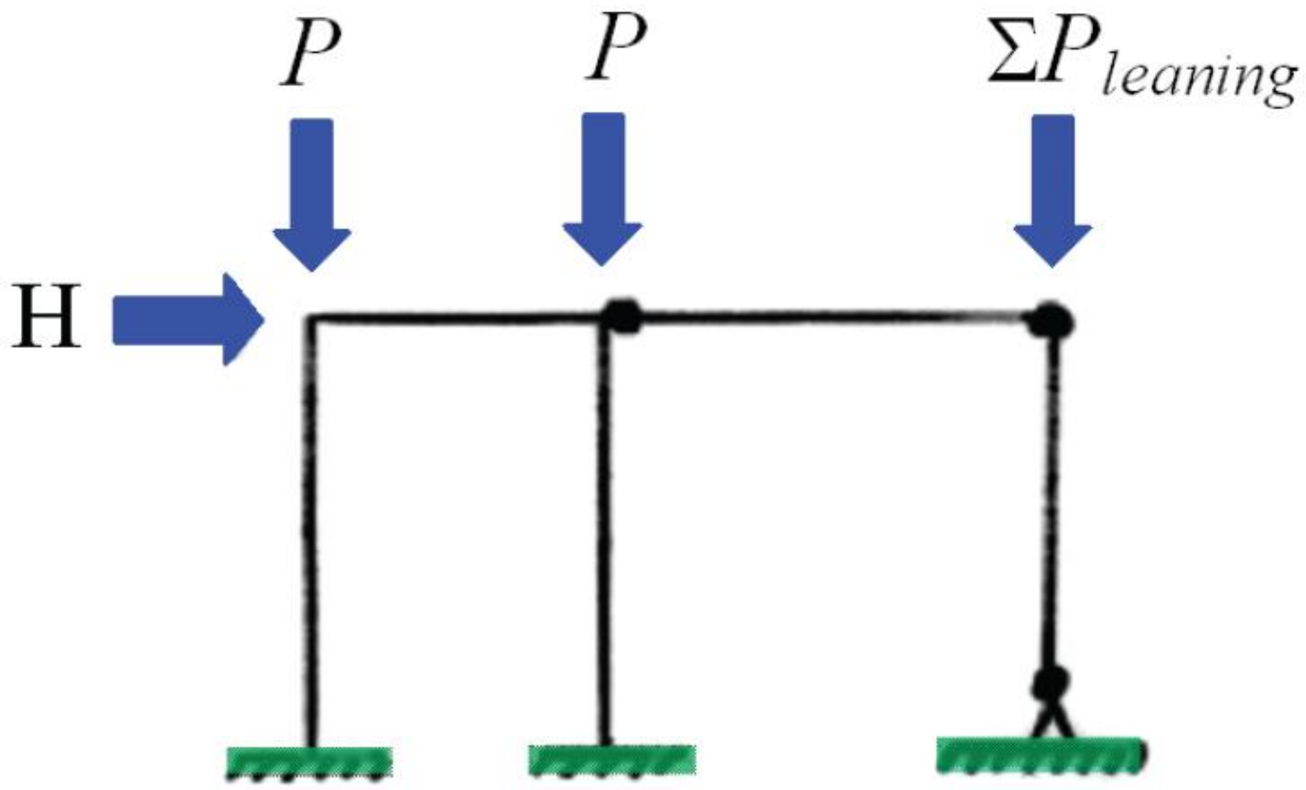


Figure 3. 2D frame model that captures leaning column effects.

"Stability Analysis: It's not as Hard as you Think," C.M. Hewitt, 2008.

5 factors that influence stability
Effective Length Method

- Member, component, and connection deformations – addressed directly in analysis
- Second-order effects (P-Δ and P-δ) – rigorous second-order analysis or first-order with B1-B2
- Geometric imperfections (out-of-plumbness [notional loads] or out-of-straightness [column design equations for effect on member strength])

"The Evolution of Stability Provisions in the AISC Specification," C.J. Carter, 2013.

5 factors that influence stability

Effective Length Method, cont'd.

- Stiffness reductions due to inelasticity (residual stresses) -- column design equations for effect on member strength
- Variability in component and system stiffness – in resistance and safety factors!

But K must be calculated and used to account for effects on structure stiffness of member out-of-straightness, residual stresses, and variability in component and system stiffness.

"The Evolution of Stability Provisions in the AISC Specification," C.J. Carter, 2013.

5 factors that influence stability

Direct Analysis Method

- Member, component, and connection deformations – addressed directly in analysis
- Second-order effects (P-Δ and P-δ) – rigorous second-order analysis or first-order with B1-B2
- Geometric imperfections (out-of-plumbness [notional loads *or direct modeling*] or out-of-straightness [column design equations; *and reduced stiffness for effect on structure stiffness*])

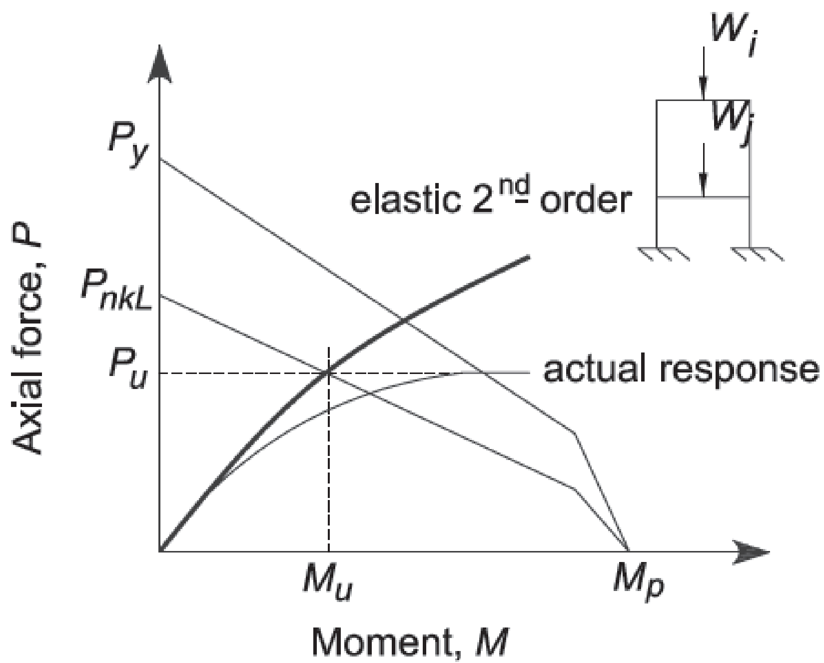
"The Evolution of Stability Provisions in the AISC Specification," C.J. Carter, 2013.

5 factors that influence stability
Direct Analysis Method, cont'd.

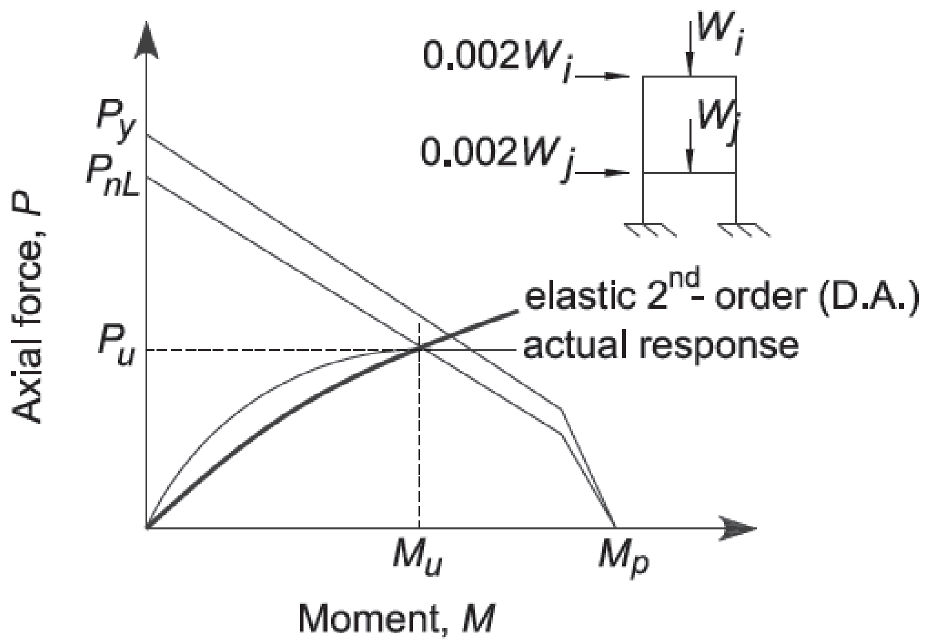
- Stiffness reductions due to inelasticity (residual stresses) -- column design equations; *and reduced stiffness for effect on structure stiffness*
- Variability in component and system stiffness – in resistance and safety factors!

"The Evolution of Stability Provisions in the AISC Specification," C.J. Carter, 2013.

AISC C-C2.3

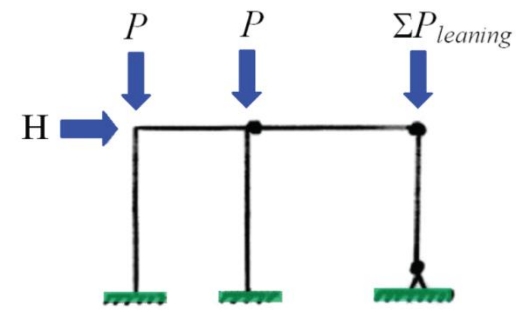


(a) Effective length method



(b) Direct analysis method

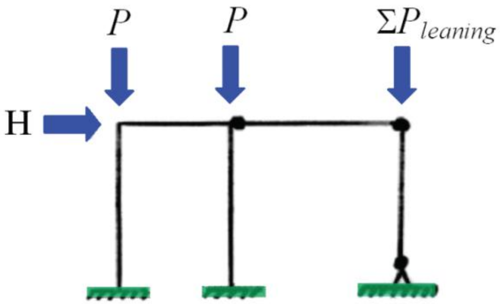
Direct Analysis Method "Step-by-Step"



- Create a model of the lateral force resisting frame, including the leaning columns.
- Reduce the stiffnesses (modify E) of the lateral framing members in your model.
- Apply notional loads or directly model the imperfections
- Conduct a second-order analysis ("rigorous" or B1-B2 amplification on first-order)

"Stability Analysis: It's not as Hard as you Think," C.M. Hewitt, 2008.

“Step-by-Step” cont’d.



- Design members using the AISC Specification and K=1.0.
  - If using structural analysis program to do this, reset E to 29,000 ksi.
- Check lateral drift limits for wind and seismic.

“Stability Analysis: It’s not as Hard as you Think,” C.M. Hewitt, 2008.