Underlying Concepts in Seismic Design Codes

Chia-Ming Uang
Professor
University of California, San Diego

2009 NASCC: The Steel Conference

Seismic Loadings Codes

- 1985 UBC (*K* Factor)
- 1988 UBC (R_w Factor)
- 1997 UBC (*R* Factor)
- ASCE 7, IBC (*R* Factor)

Steel Materials Codes

- 1985 UBC
- 1988 UBC

<1994 Northridge Earthquake>

- 1997 UBC
- FEMA 350
- Seismic Provisions (AISC 350)
- Prequalified Connections (AISC 358)
- AWS D1.8

Objective of Presentation

- Fundamental Concepts Underlying the Seismic Provisions
- Why and How These Concepts Are Implemented in AISC Seismic Provisions
- not to Elaborate Detailed Design Provisions of any Particular System
- Some Popular Systems Will be Used to Demonstrate the Concepts

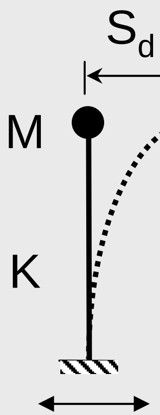
Basic Load Combinations (ASCE 7)

1. $1.4(D + F)$
2. $1.2(D + F + T) + 1.6(L + H) + 0.5(L_r \text{ or } S \text{ or } R)$
3. $1.2D + 1.6(L_r \text{ or } S \text{ or } R) + (L \text{ or } 0.8W)$
4. $1.2D + 1.6W + L + 0.5(L_r \text{ or } S \text{ or } R)$
5. $1.2D + 1.0E + L + 0.2S$
6. $0.9D + 1.6W + 1.6H$
7. $0.9D + 1.0E + 1.6H$

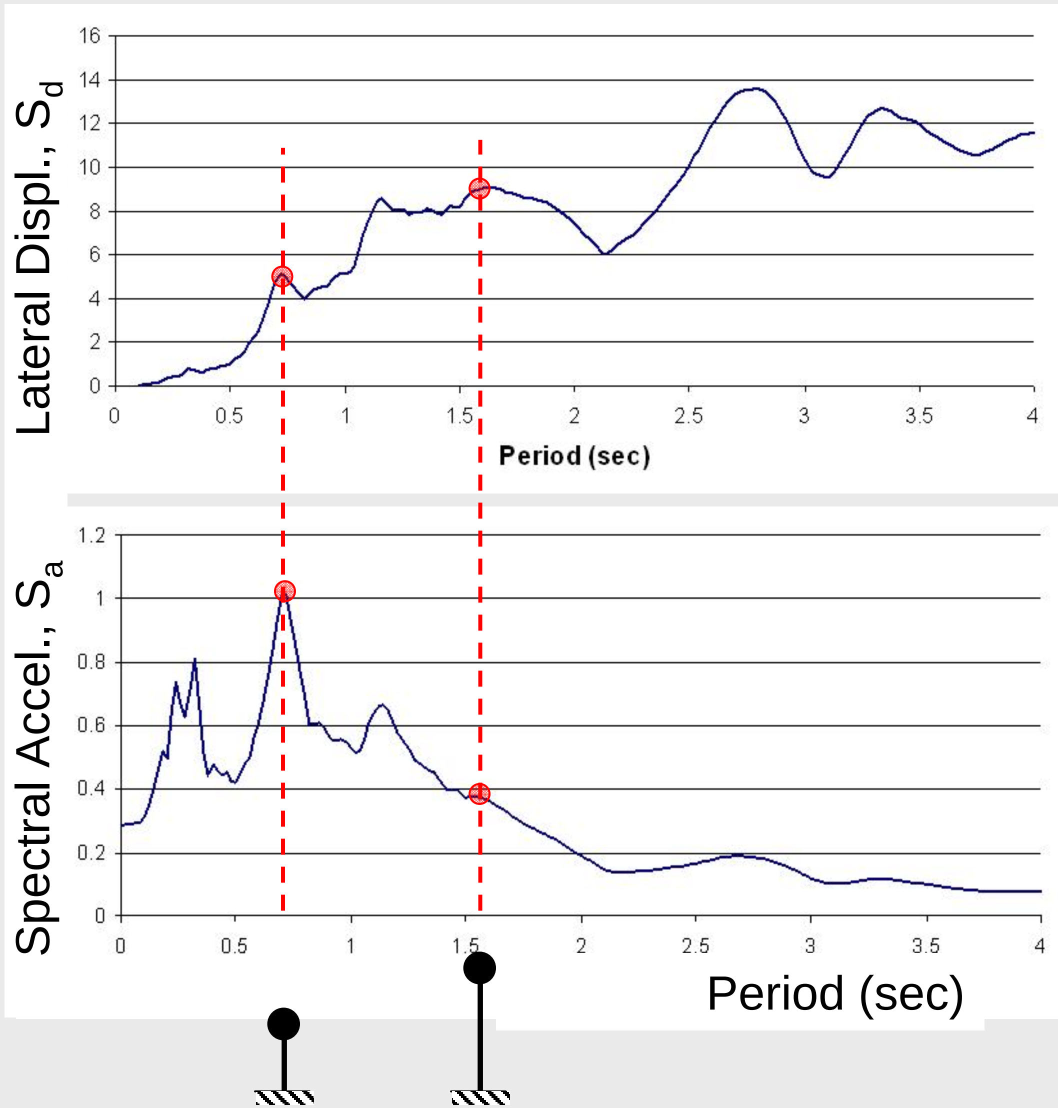
Earthquake “Load”

- Earthquake-Induced Inertia Effect on Structures

Elastic Response Spectra

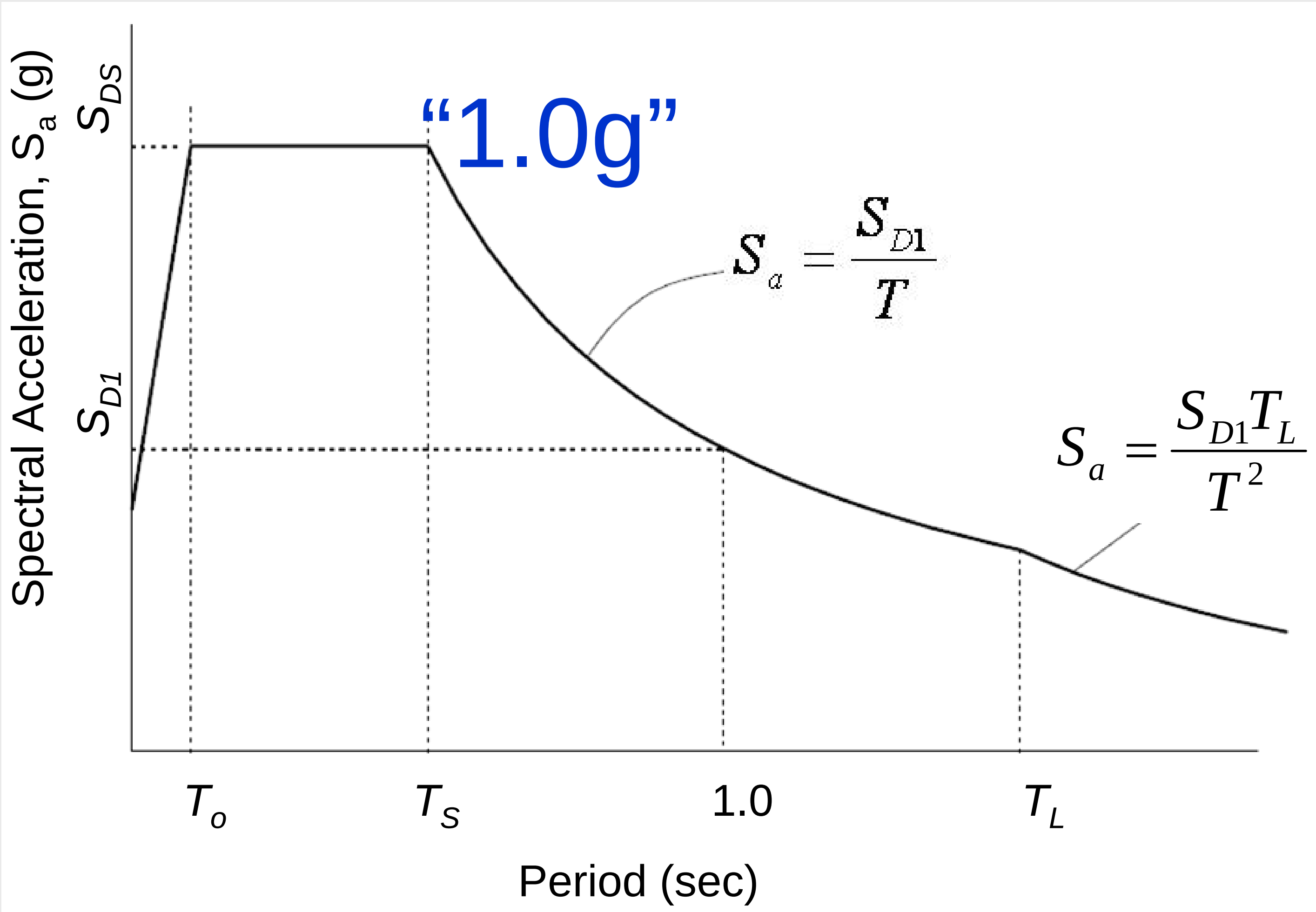


$$S_a = \left(\frac{2\pi}{T}\right)^2 S_d$$

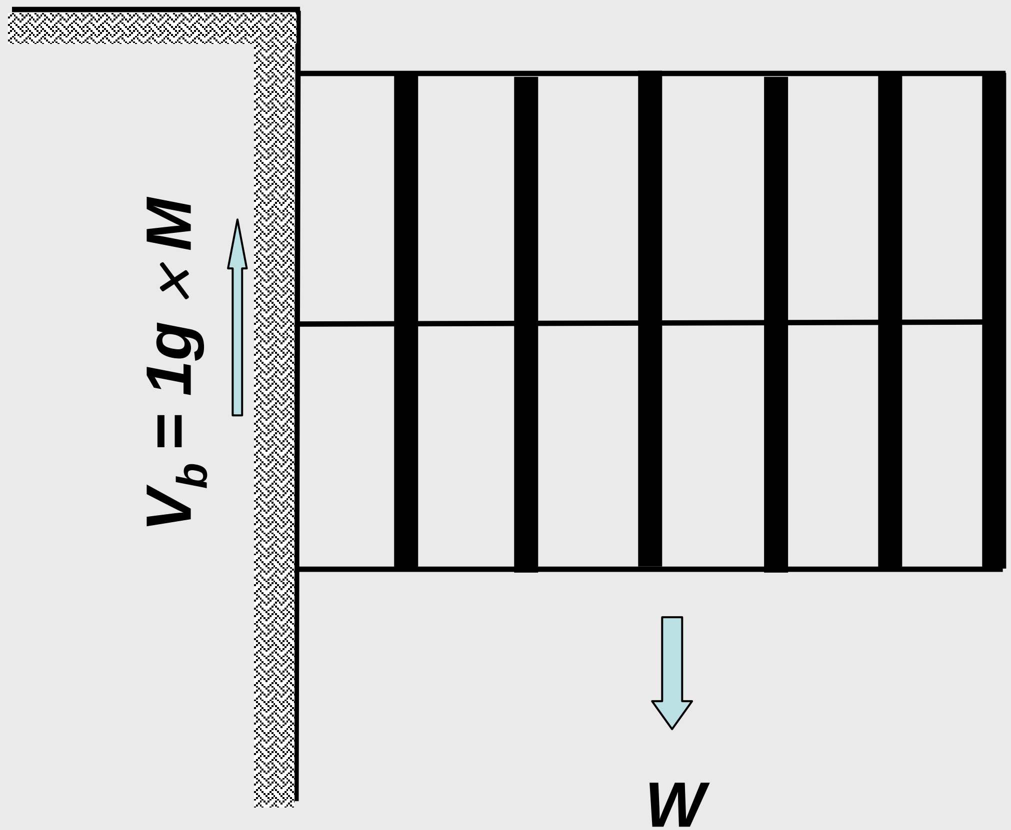


Max. Member Force
$= M \times S_a$

Design Basis Earthquake (ASCE 7)



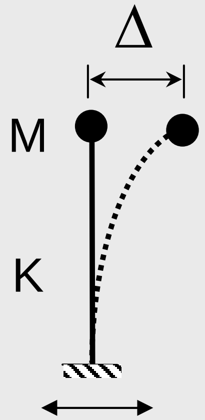
“1g” Building

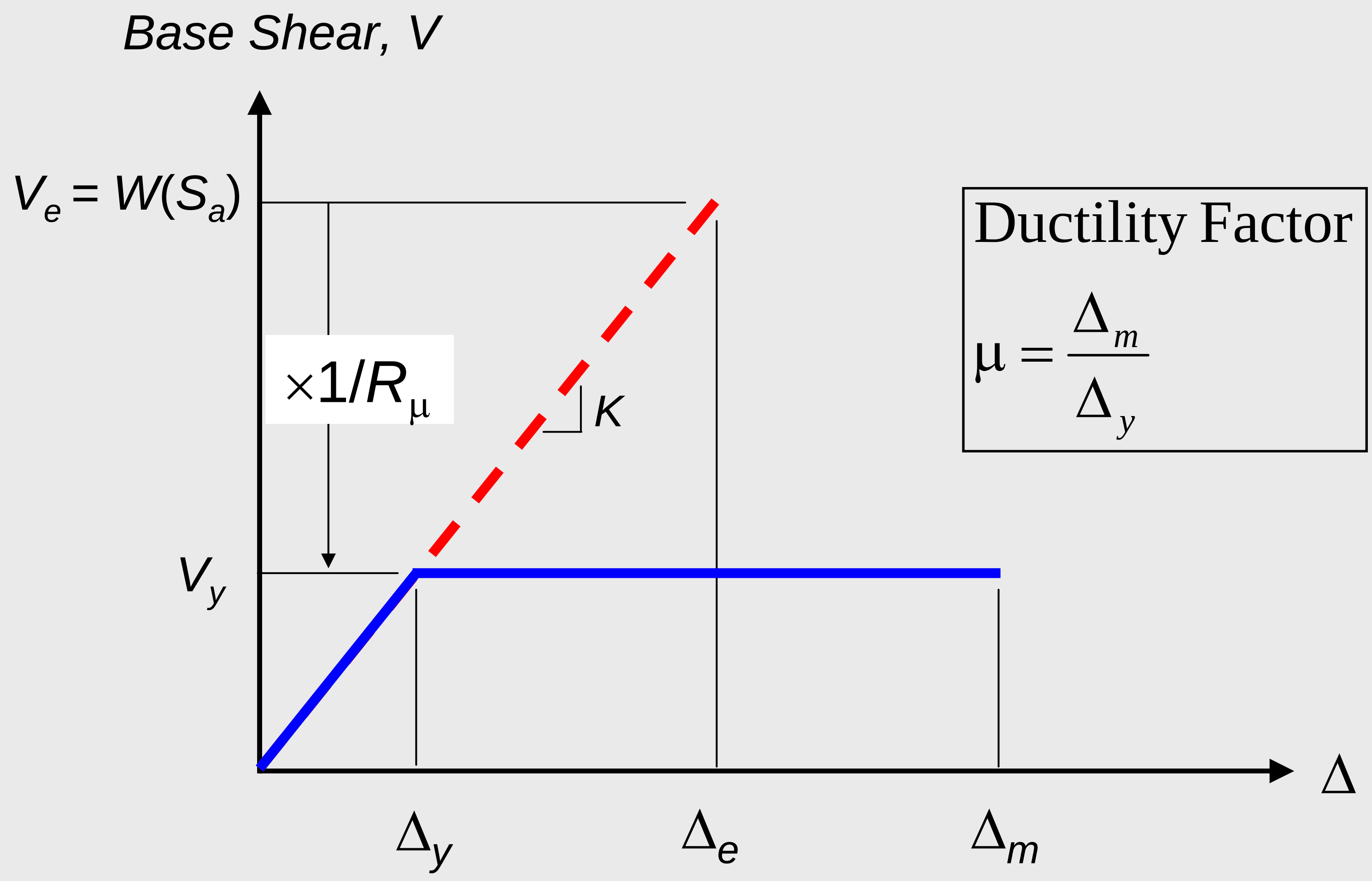


Resort to DUCTILITY

(or Trade Ductility for Strength)

Ductility Factor

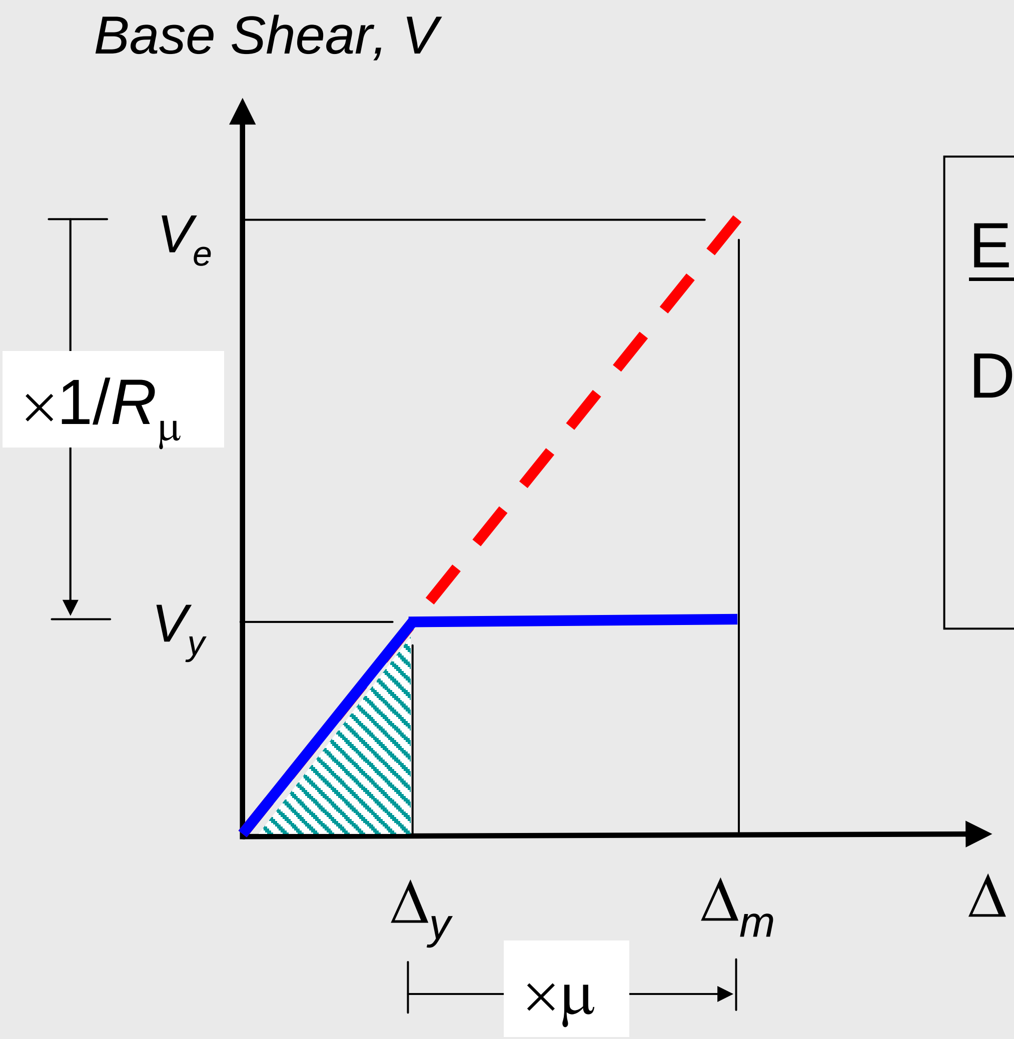




Ductility Factor

$$\mu = \frac{\Delta_m}{\Delta_y}$$

Newmark-Hall Ductility Reduction Rule



<u>Equal Displacement Rule</u>

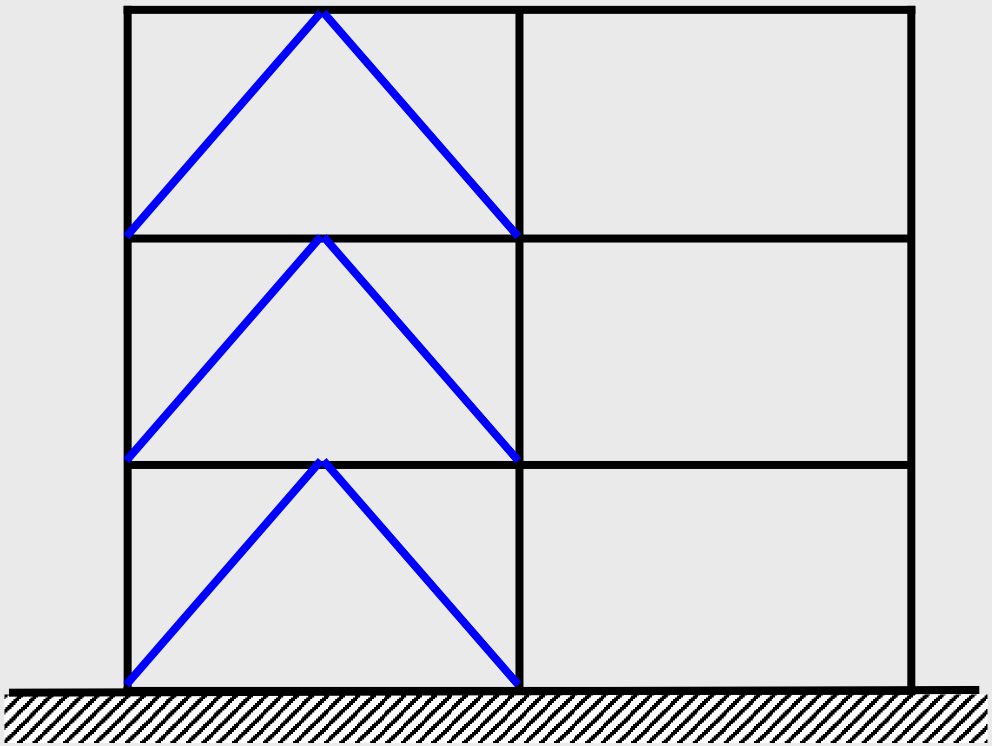
Ductility Reduction Factor:

$$R_\mu = \mu$$

Seismic Design Concept 1–Ductility Design

- A Reduced Design Seismic Force Can Be Used IF Sufficient Ductility Is Built into the Structure
- But Only a Certain Elements Are Strategically Designated to Serve as Structural Fuse, i.e., Deformation-Controlled Elements (DCE)

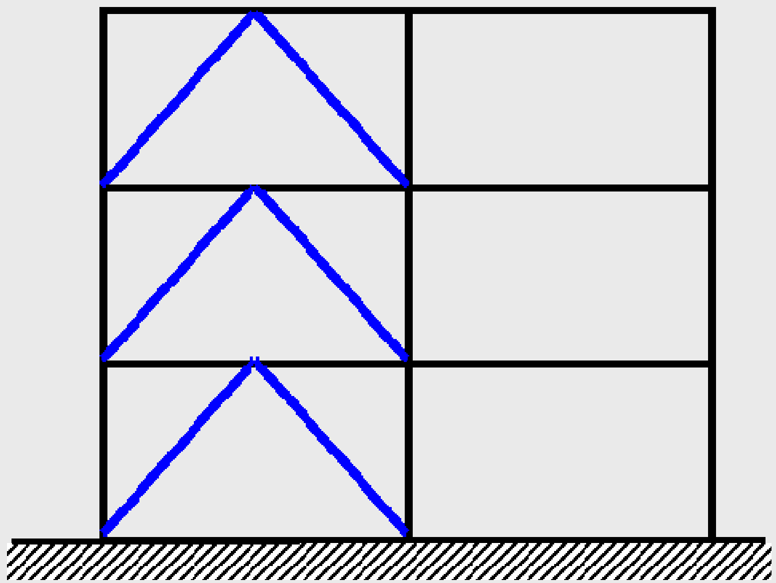
Example



- Diagonal Braces as Structural Fuse
- Braces to Buckle Out of Plane
- To Achieve This, More Effort Is Needed to Make It Happen!

Seismic Design Concept 2–"Capacity Design"

- Remaining Part of the Structure Is Designed to Remain Elastic, i.e., Designed These Elements as Force-Controlled Elements (FCE).



Two Key Concepts in AISC Seismic Provisions

Ductility Design Provisions

+

Capacity Design Provisions

Seismic Provisions for Structural Steel Buildings

Including Supplement No. 1

Seismic Provisions for Structural Steel Buildings dated **March 9, 2005**
and Supplement No. 1 dated **November 16, 2005**

Ductility vs. Capacity Design

	Ductility Design (Deformation-Controlled Elements)	**Capacity Design** (Force-Controlled Elements)
Research Effort	More	
Design Effort	Easier (Straightforward)	Requires Understanding/Judgment

User Note: Section 14 (OCBF) should be used for the design of tension-only bracing.

13.2. Members

13.2a. Slenderness

Bracing members shall have $Kl/r \le 4\sqrt{E/F_y}$.

Exception: Braces with $4\sqrt{E/F_y} < Kl/r \le 200$ are permitted in frames in which the *available strength* of the column is at least equal to the maximum load transferred to the column considering R_y (LRFD) or $(1/1.5)R_y$ (ASD), as appropriate, times the *nominal strengths* of the connecting brace elements of the building. Column forces need not exceed those determined by inelastic analysis, nor the maximum *load effects* that can be developed by the system.

13.2b. Required Strength

Where the effective net area of bracing members is less than the gross area, the *required tensile strength* of the brace based upon the limit state of fracture in the net section shall be greater than the lesser of the following:

(a) The *expected yield strength*, in tension, of the bracing member, determined as $R_yF_yA_g$ (LRFD) or $R_yF_yA_g/1.5$ (ASD), as appropriate.

(b) The maximum load effect, indicated by analysis that can be transferred to the brace by the system.

User Note: This provision applies to bracing members where the section is reduced. A typical case is a slotted HSS brace at the gusset plate connection.

13.2c. Lateral Force Distribution

Along any line of bracing, braces shall be deployed in alternate directions such that, for either direction of force parallel to the bracing, at least 30 percent but no more than 70 percent of the total horizontal force along that line is resisted by braces in tension, unless the available strength of each brace in compression is larger than the *required strength* resulting from the application of the appropriate load combinations stipulated by the *applicable building code* including the *amplified seismic load*. For the purposes of this provision, a line of bracing is defined as a single line or parallel lines with a plan offset of 10 percent or less of the building dimension perpendicular to the line of bracing.

13.2d. Width-Thickness Limitations

Column and brace members shall meet the requirements of Section 8.2b.

User Note: HSS walls may be stiffened to comply with this requirement.

13.2e. Built-up Members

The spacing of stitches shall be such that the slenderness ratio l/r of individual elements between the stitches does not exceed 0.4 times the governing slenderness ratio of the built-up member.

The sum of the *available shear strengths* of the stitches shall equal or exceed the available tensile strength of each element. The spacing of stitches shall be uniform. Not less than two stitches shall be used in a built-up member. Bolted stitches shall not be located within the middle one-fourth of the clear brace length.

Exception: Where the buckling of braces about their critical bucking axis does not cause shear in the stitches, the spacing of the stitches shall be such that the slenderness ratio l/r of the individual elements between the stitches does not exceed 0.75 times the governing slenderness ratio of the built-up member.

13.3. Required Strength of Bracing Connections

13.3a. Required Tensile Strength

The *required tensile strength* of bracing connections (including beam-to-column connections if part of the bracing system) shall be the lesser of the following:

(a) The *expected yield strength*, in tension, of the bracing member, determined as $R_yF_yA_g$ (LRFD) or $R_yF_yA_g/1.5$ (ASD), as appropriate.

(b) The maximum *load effect*, indicated by analysis that can be transferred to the brace by the system.

13.3b. Required Flexural Strength

The *required flexural strength* of bracing connections shall be equal to $1.1R_yM_p$ (LRFD) or $(1.1/1.5)R_yM_p$ (ASD), as appropriate, of the brace about the critical buckling axis.

Exception: Brace connections that meet the requirements of Section 13.3a and can accommodate the inelastic rotations associated with brace post-buckling deformations need not meet this requirement.

User Note: Accommodation of inelastic rotation is typically accomplished by means of a single gusset plate with the brace terminating before the line of restraint. The detailing requirements for such a connection are described in the commentary.

13.3c. Required Compressive Strength

Bracing connections shall be designed for a *required compressive strength* based on buckling limit states that is at least equal to $1.1R_yP_n$ (LRFD) or $(1.1/1.5)R_yP_n$ (ASD), as appropriate, where P_n is the *nominal compressive strength* of the brace.

13.4. Special Bracing Configuration Requirements

13.4a. V-Type and Inverted-V-Type Bracing

V-type and inverted V-type SCBF shall meet the following requirements:

(1) The *required strength* of beams intersected by braces, their connections, and supporting members shall be determined based on the load combinations of the *applicable building code* assuming that the braces provide no support for dead and live loads. For load combinations that include earthquake effects, the earthquake effect, E, on the beam shall be determined as follows:

(a) The forces in all braces in tension shall be assumed to be equal to $R_yF_yA_g$.

(b) The forces in all adjoining braces in compression shall be assumed to be equal to $0.3P_n$.

(2) Beams shall be continuous between columns. Both flanges of beams shall be laterally braced, with a maximum spacing of $L_b = L_{pd}$, as specified by Equation A-1-7 and A-1-8 of Appendix 1 of the *Specification*. Lateral braces shall meet the provisions of Equations A-6-7 and A-6-8 of Appendix 6 of the *Specification*, where $M_r = M_u = R_yZF_y$ (LRFD) or $M_r = M_a = R_yZF_y/1.5$ (ASD), as appropriate, of the beam and $C_d = 1.0$.

As a minimum, one set of lateral braces is required at the point of intersection of the V-type (or inverted V-type) bracing, unless the beam has sufficient out-of-plane strength and stiffness to ensure stability between adjacent brace points.

User Note: One method of demonstrating sufficient out-of-plane strength and stiffness of the beam is to apply the bracing force defined in Equation A-6-7 of Appendix 6 of the *Specification* to each flange so as to form a torsional couple; this loading should be in conjunction with the flexural forces defined in item (1) above. The stiffness of the beam (and its restraints) with respect to this torsional loading should be sufficient to satisfy Equation A-6-8.

13.4b. K-Type Bracing

K-type braced frames are not permitted for SCBF.

13.5. Column Splices

In addition to meeting the requirements in Section 8.4, column splices in SCBF shall be designed to develop 50 percent of the lesser available flexural strength of the connected members. The *required shear strength* shall be $\Sigma M_{pc}/H$ (LRFD) or $\Sigma M_{pc}/1.5H$ (ASD), as appropriate, where ΣM_{pc} is the sum of the nominal plastic flexural strengths of the columns above and below the splice.

13.6. Protected Zone

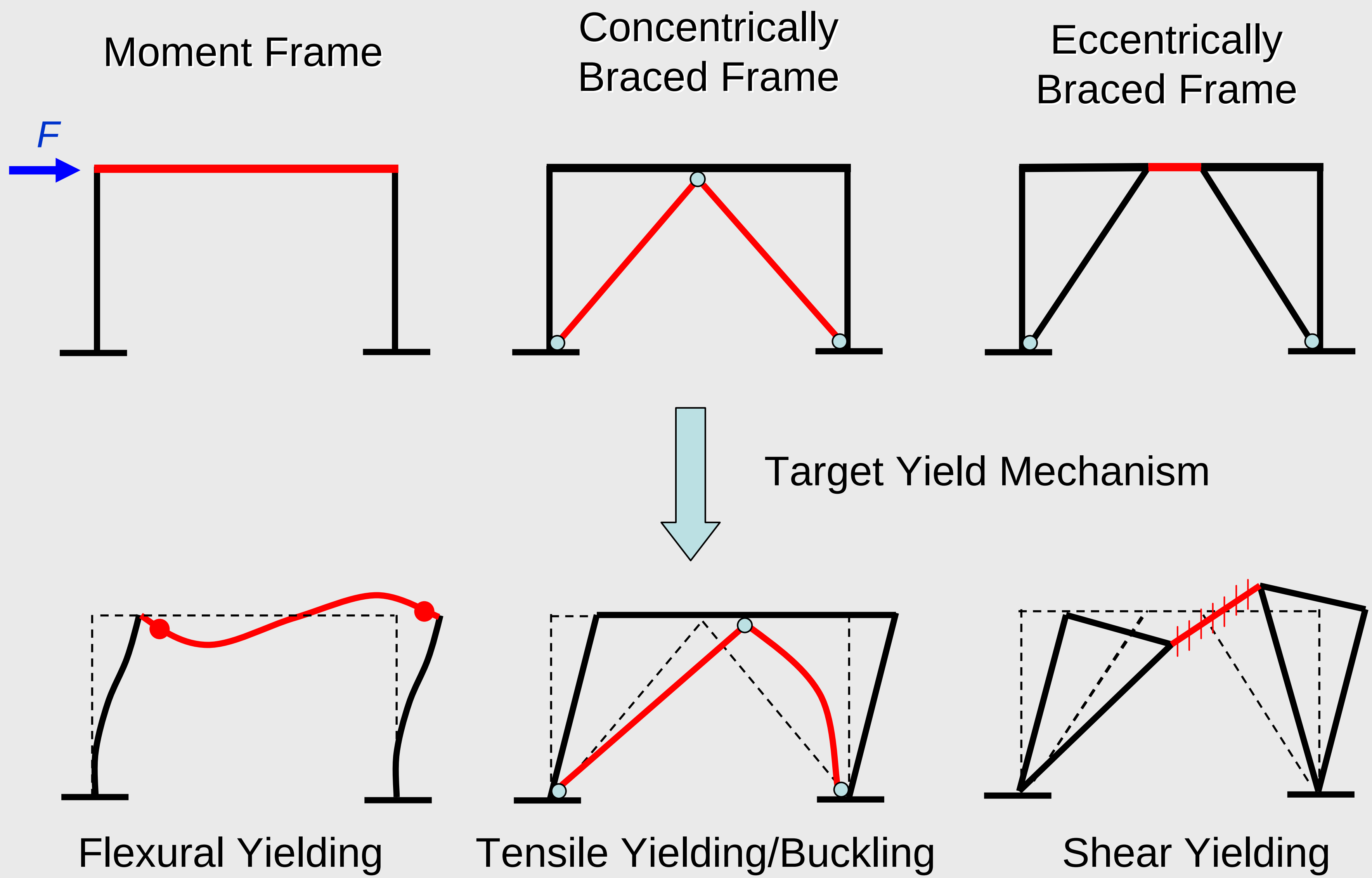
The *protected zone* of bracing members in SCBF shall include the center one-quarter of the brace length, and a zone adjacent to each connection equal to the brace depth in the plane of buckling. The protected zone of SCBF shall include

AISC Seismic Provisions

- Moment Frames (Sections 9, 10, 11)
- Special Truss Moment Frames (Section 12)
- Concentrically Braced Frames (Sections 13,14)
- Eccentrically Braced Frames (Section 15)
- Buckling-Restrained Braced Frames (Section 16)
- Special Plate-Shear Walls (Section 17)

Ductility Design Concept

Target Yield Mechanism



Ductility Requirements

Code Implementation Example 1:

Special Moment Frame (SMF) Design

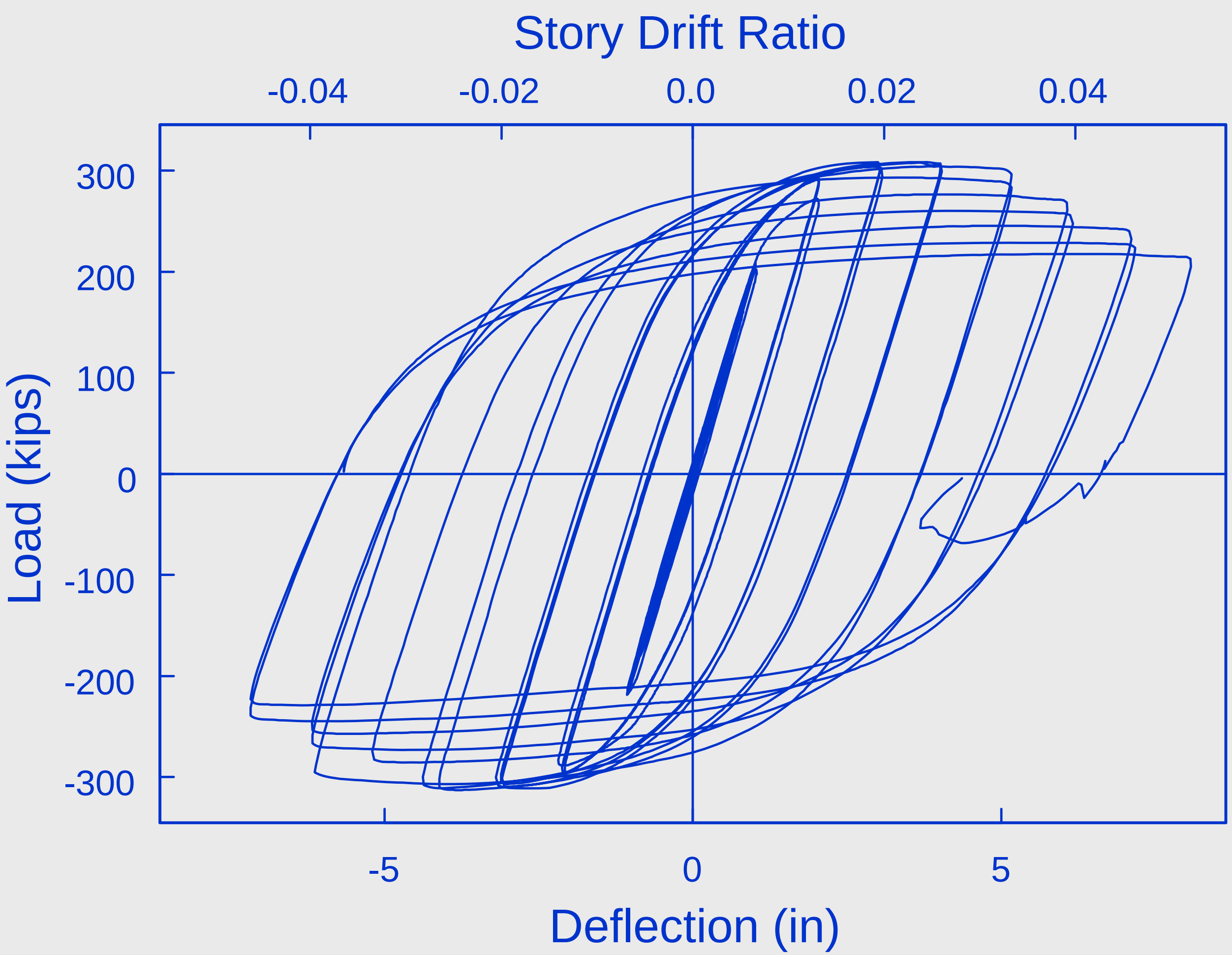
(Courtesy:
M.D. Engelhardt)

Steel Moment Connections

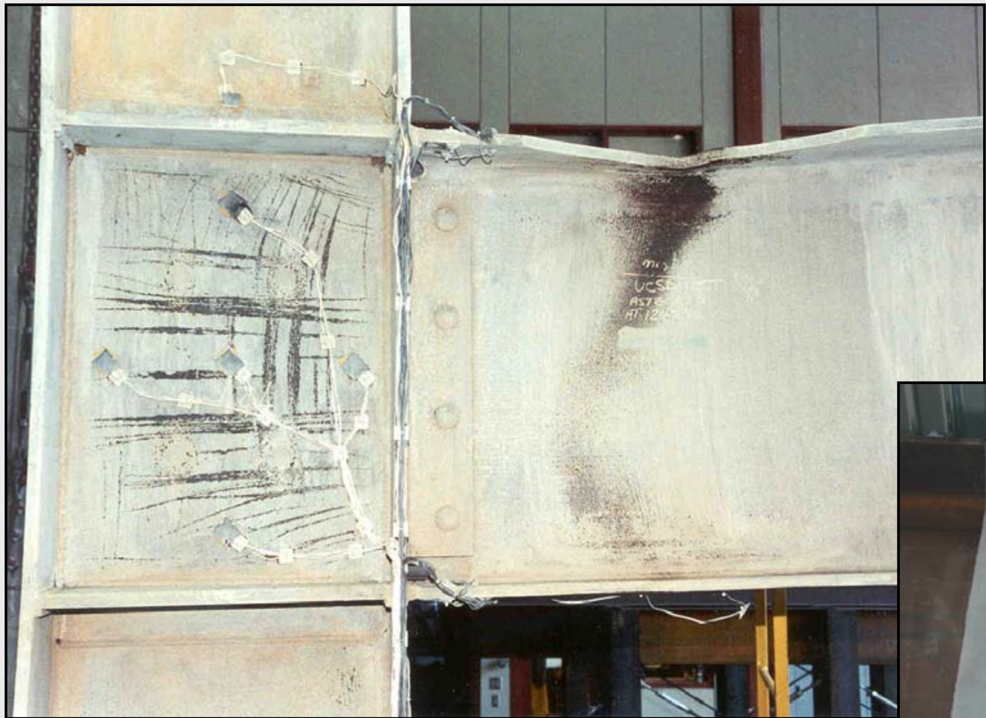
RBS Moment Connection

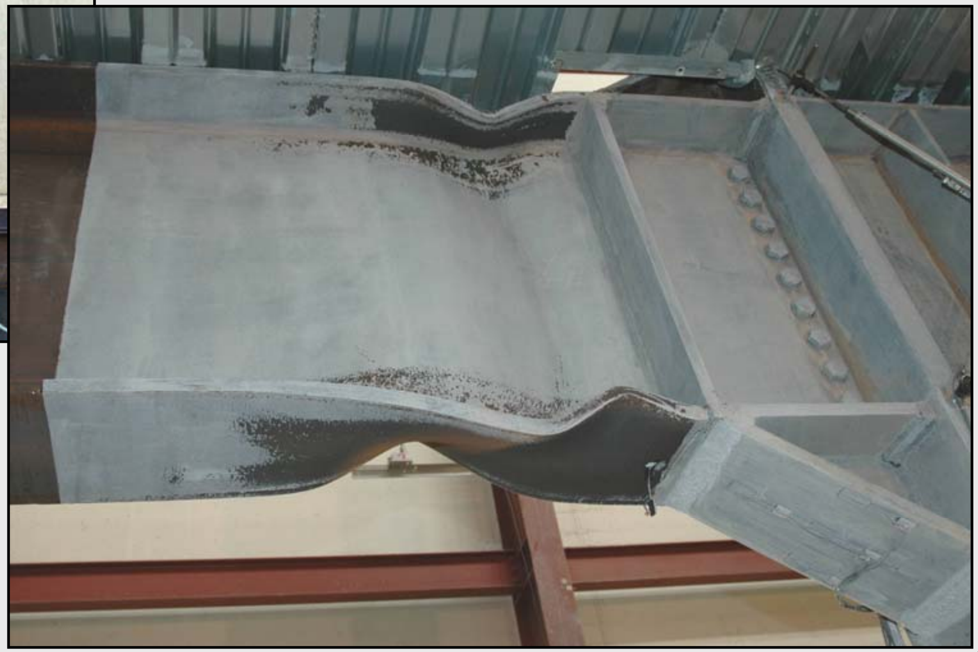
RBS Moment Connection

RBS Moment Connection Response



Local Buckling Control





Local Buckling Control

TABLE I-8-1
Limiting Width-Thickness Ratios for Compression Elements

	Description of Element	Width-Thickness Ratio	Limiting Width-Thickness Ratios λ_{ps} (seismically compact)
...ned Elements	Flexure in flanges of rolled or built-up I-shaped sections [a], [c], [e], [g], [h]	b/t	$0.30\sqrt{E/F_y}$
	Uniform compression in flanges of rolled or built-up I-shaped sections [b], [h]	b/t	$0.30\sqrt{E/F_y}$
	Uniform compression in flanges of rolled or built-up I-shaped sections [d]	b/t	$0.38\sqrt{E/F_y}$
	Uniform compression in flanges of channels, outstanding legs of pairs of angles in continuous contact, and braces [c], [g]	b/t	$0.30\sqrt{E/F_y}$

Lateral-Torsional Buckling

AISC SP §9.8:

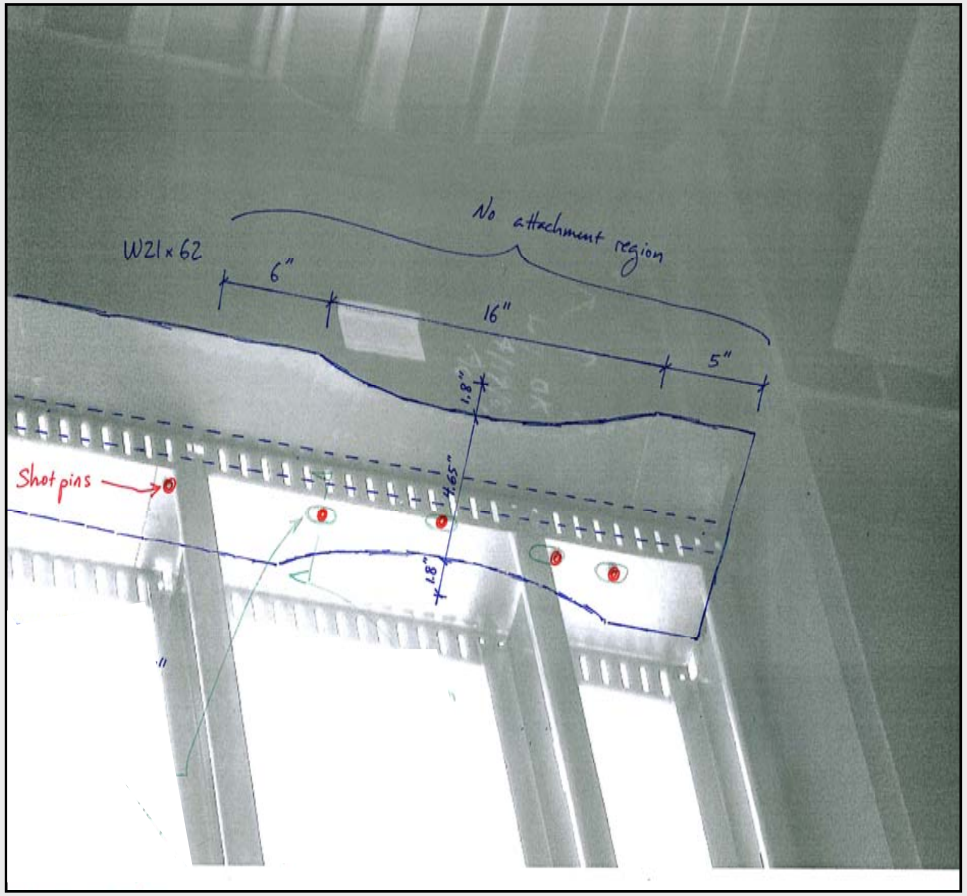
$$L_b = 0.086 r_y E / F_y$$

Panel Zone

AISC SP §9.3:

$$t = (d_z + w_z)/90$$

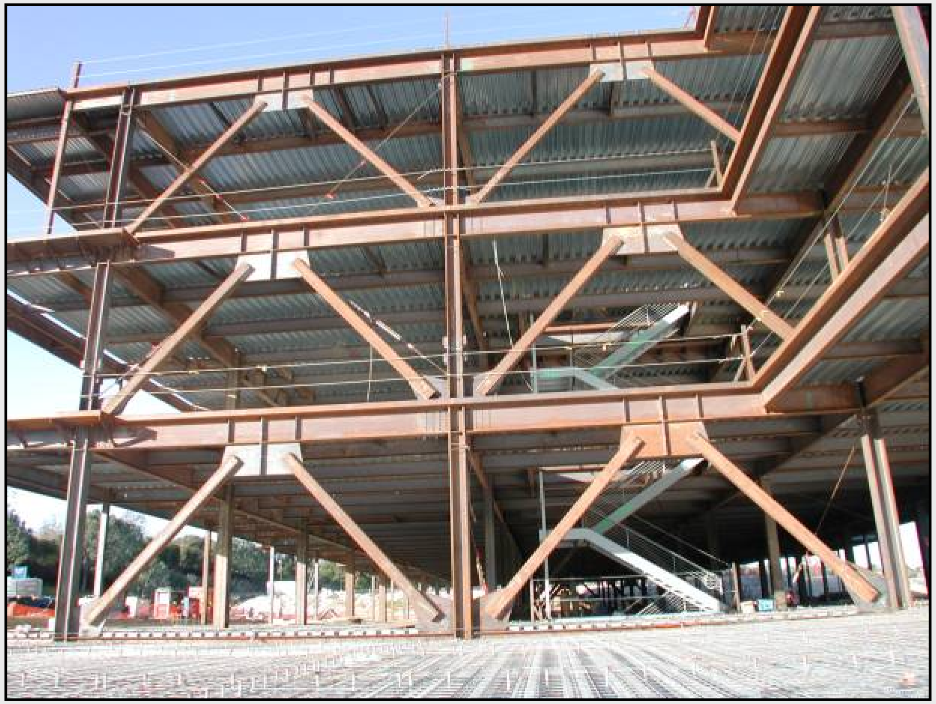
Protected Zone
(AISC SP §9.3)



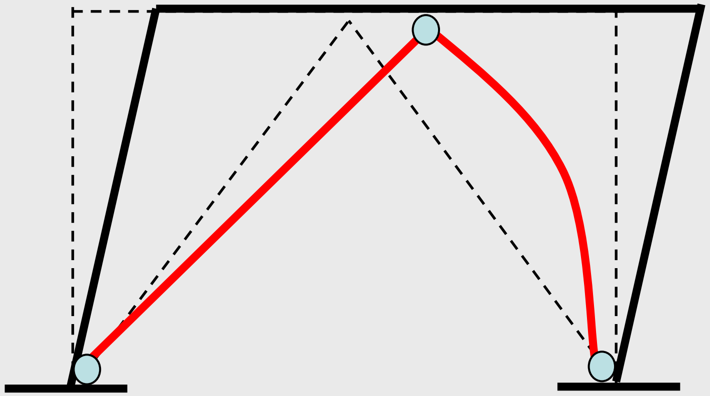
Ductility Requirements

Code Implementation Example 2:

Special Concentrically Braced Frame (SCBF) Design



Target Yield Mechanism

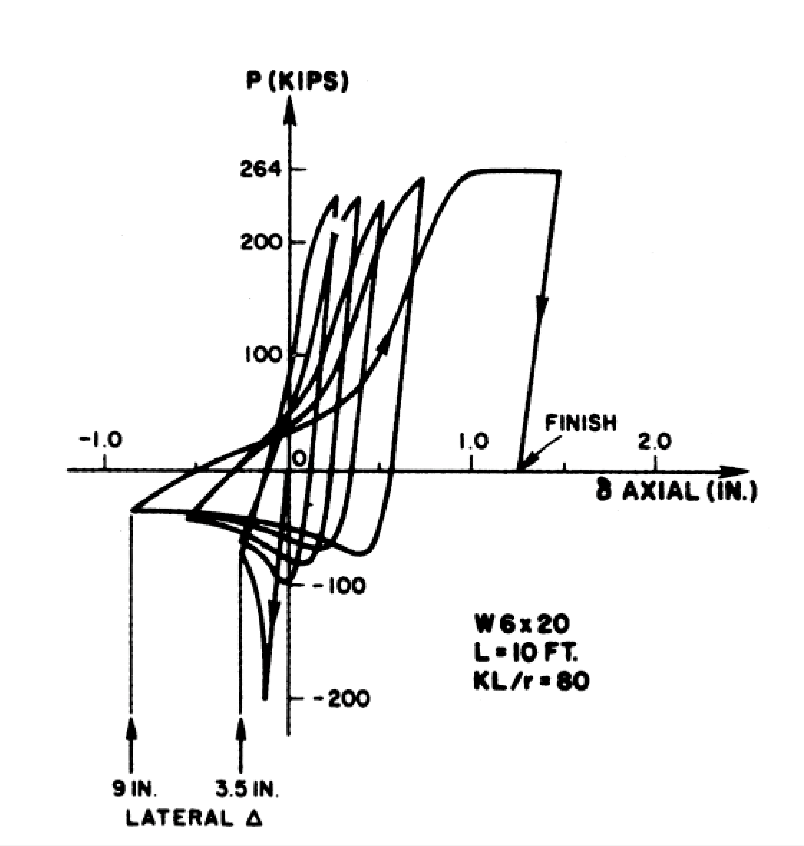


(Courtesy: K.C. Tsai, NCREE)

Bracing Ductility Requirements

- Bracing Buckling (SP §13.2a)

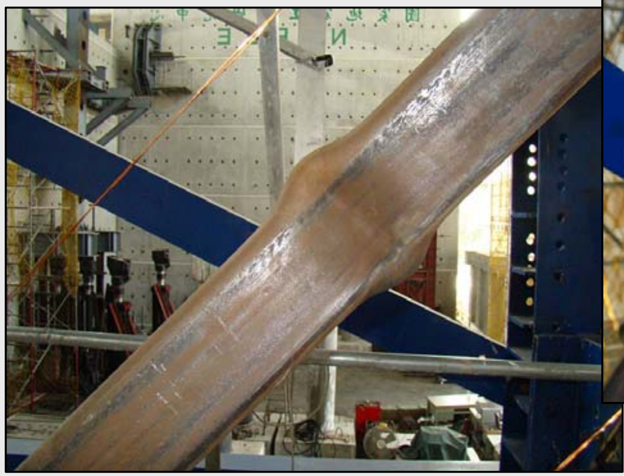
$$\left(\frac{KL}{r}\right)_{\max} = 4\sqrt{\frac{E_s}{F_y}}$$



Bracing Ductility Requirements

- Local Buckling (SP §8.2b): Seismically Compact

Stiffen			$1.12\sqrt{\frac{\ }{F_y}}(2.33-C_a)\geq 1.49\sqrt{\frac{\ }{F_y}}$
	Round HSS in axial and/or flexural compression [c], [g]	D/t	$0.044\, E/F_y$
	Rectangular HSS in axial and/or flexural compression [c], [g]	b/t or h/t_w	$0.64\sqrt{E/F_y}$

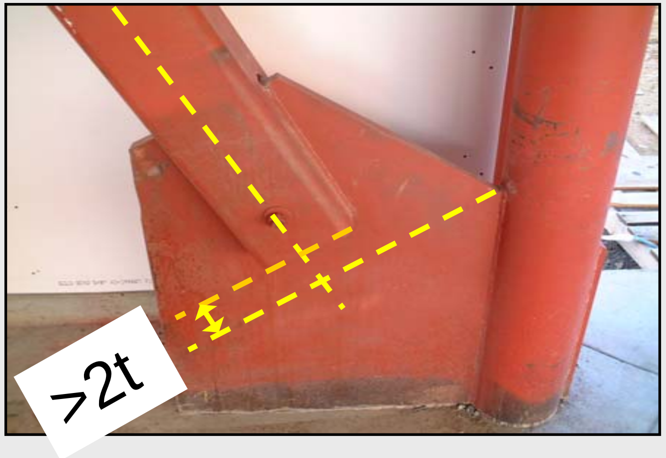


(Courtesy: K.C. Tsai)

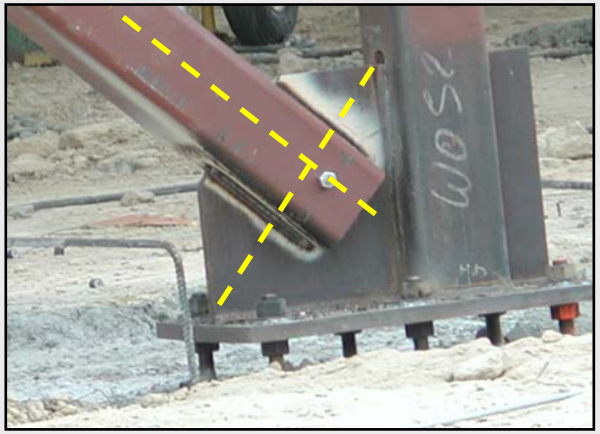
Gusset "2t" Requirement

(Courtesy: K.C. Tsai)

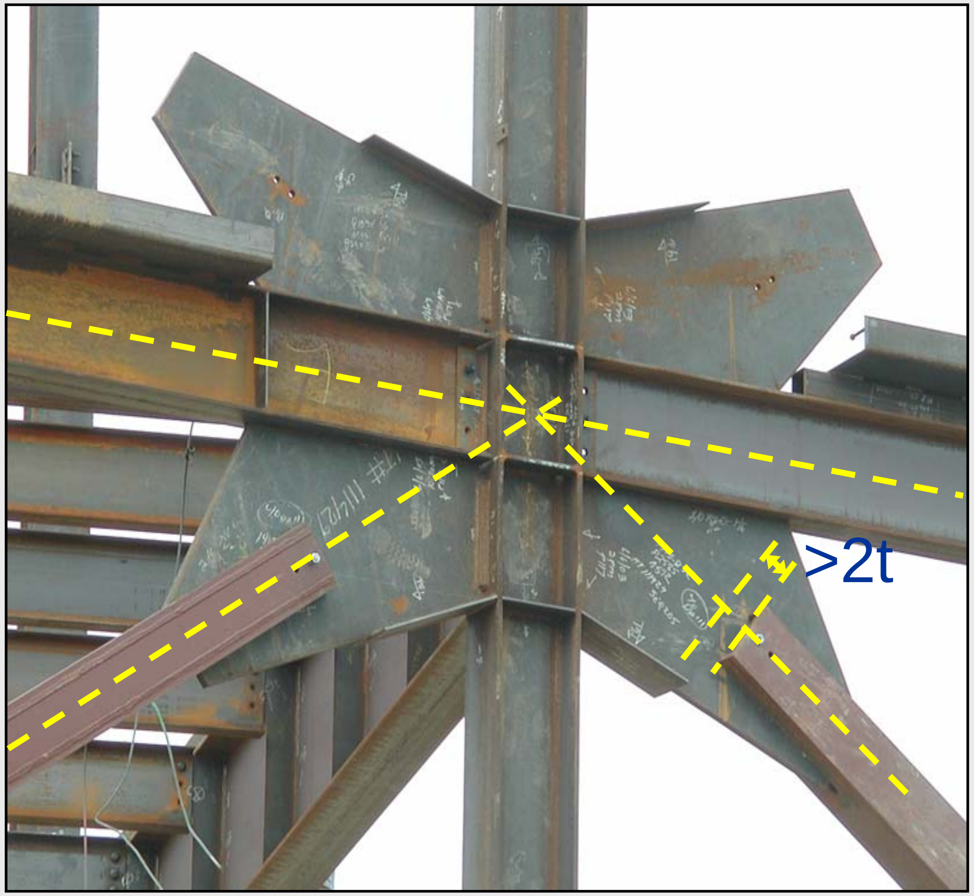
SCBF



OCBF



Gusset “2t” Requirement

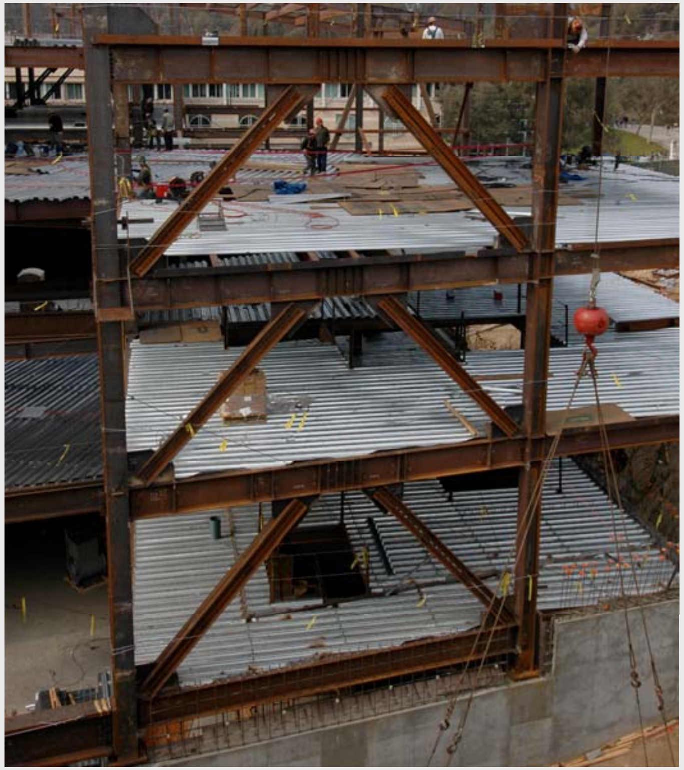


Gusset “2t” Requirement

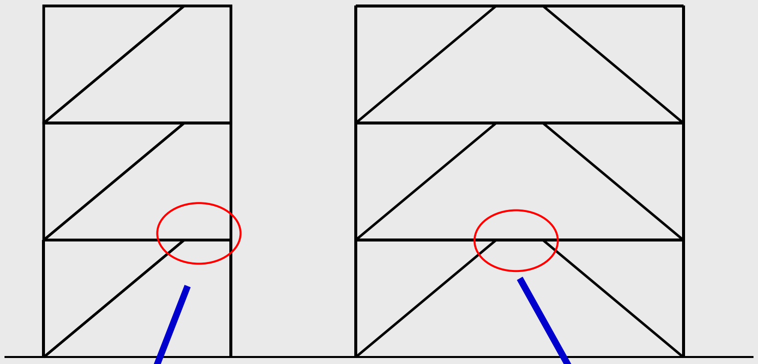
Ductility Requirements

<u>Code Implementation Example 3:</u>

Eccentrically Braced Frame (EBF) Design

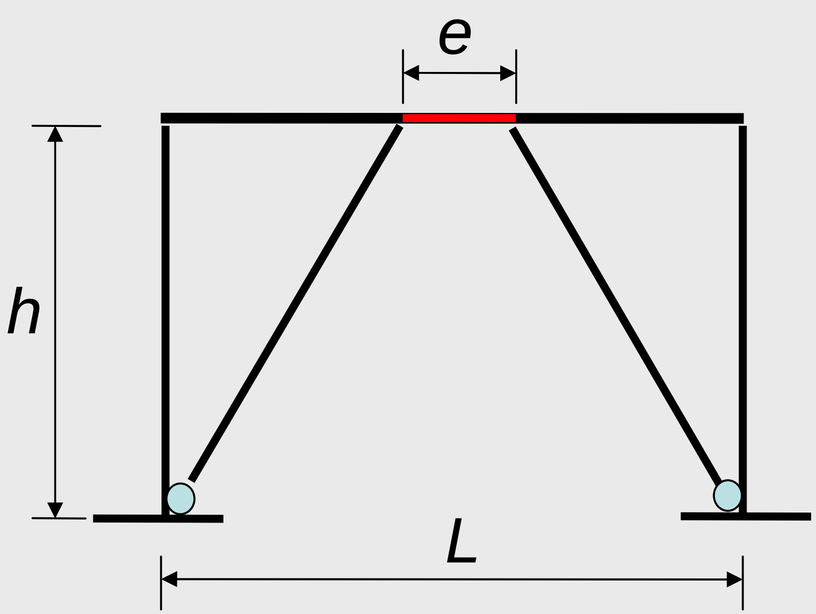


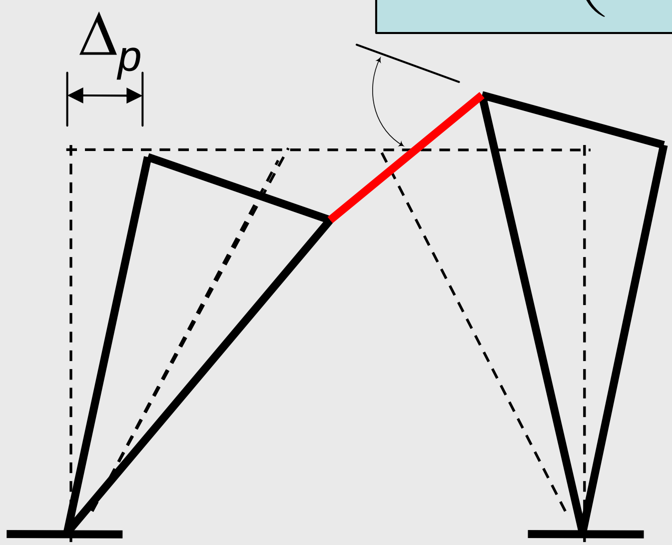
EBF Configuration



Structural Fuse:
Links

Link Ductility Requirement





$$\gamma_p = \frac{L}{e}\left(\frac{\Delta_p}{h}\right)$$

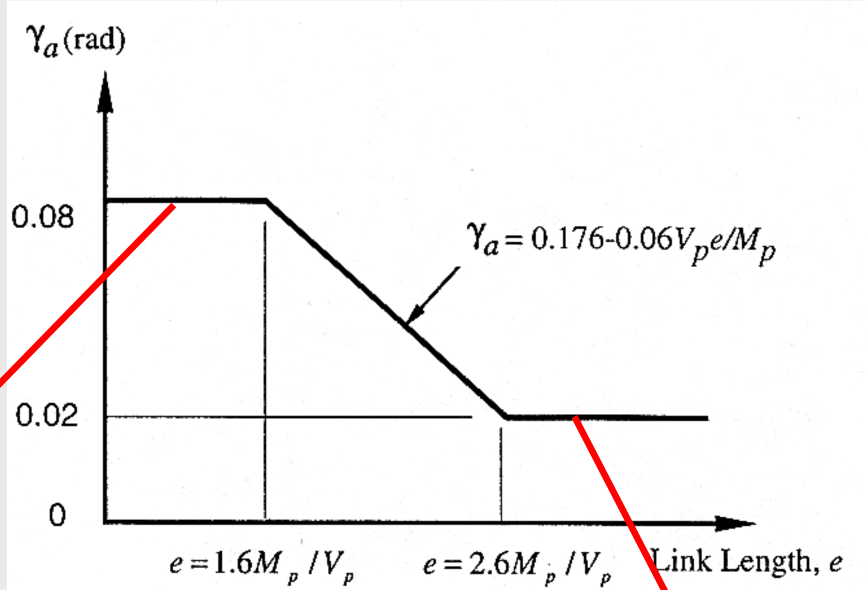
Plastic Deformation Demand

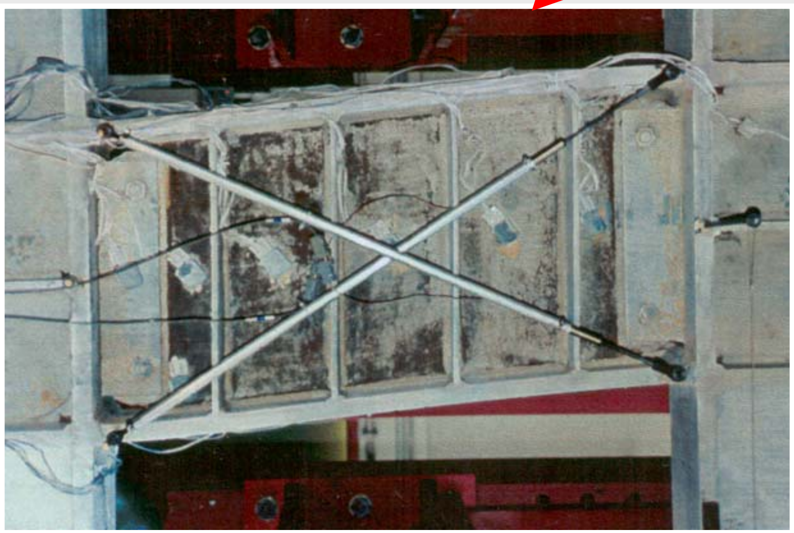
Link Ductility Requirements

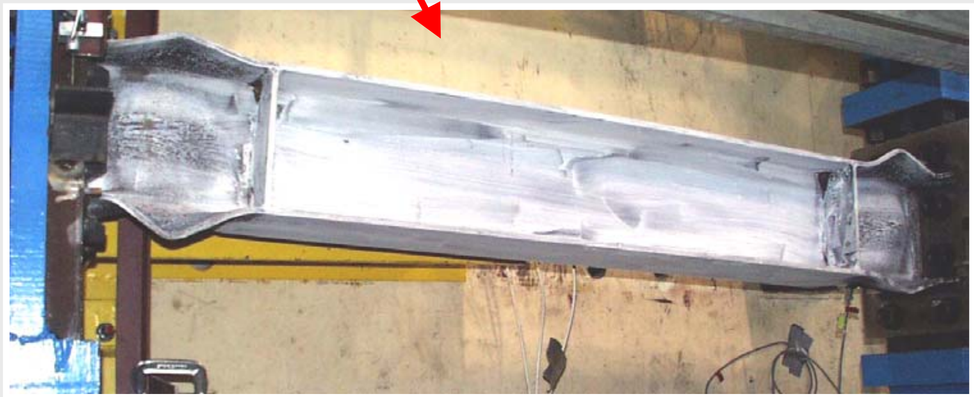
- Link Deformation Capacity Depends on
  - (Seismically) Compactness
  - Length
  - Link Stiffeners

Link Length Effect

(AISC SP §15.2c)







(Courtesy: M.D. Engelhardt)

Link Web Stiffeners

(AISC SP §15.2c)

Links Worked!
(2001 Nisqually Earthquake)

(Courtesy A. Filiatrault)

EBF: Lateral Bracing

(AISC SP §15.5)

Ductility Requirements

<u>Code Implementation for</u>
<u>Other Lateral Force-Resisting Systems</u>

- Special Truss Moment Frames
- Buckling-Restrained Braced Frames
- Special Plate Shear Walls
- Composite Systems

Capacity Design Concept

Ductility vs. Capacity Design

	Ductility Design (Deformation-Controlled Elements)	**Capacity Design** (Force-Controlled Elements)
Research Effort	More	
Design Effort	Easier (Straightforward)	Requires Understanding/Judgment

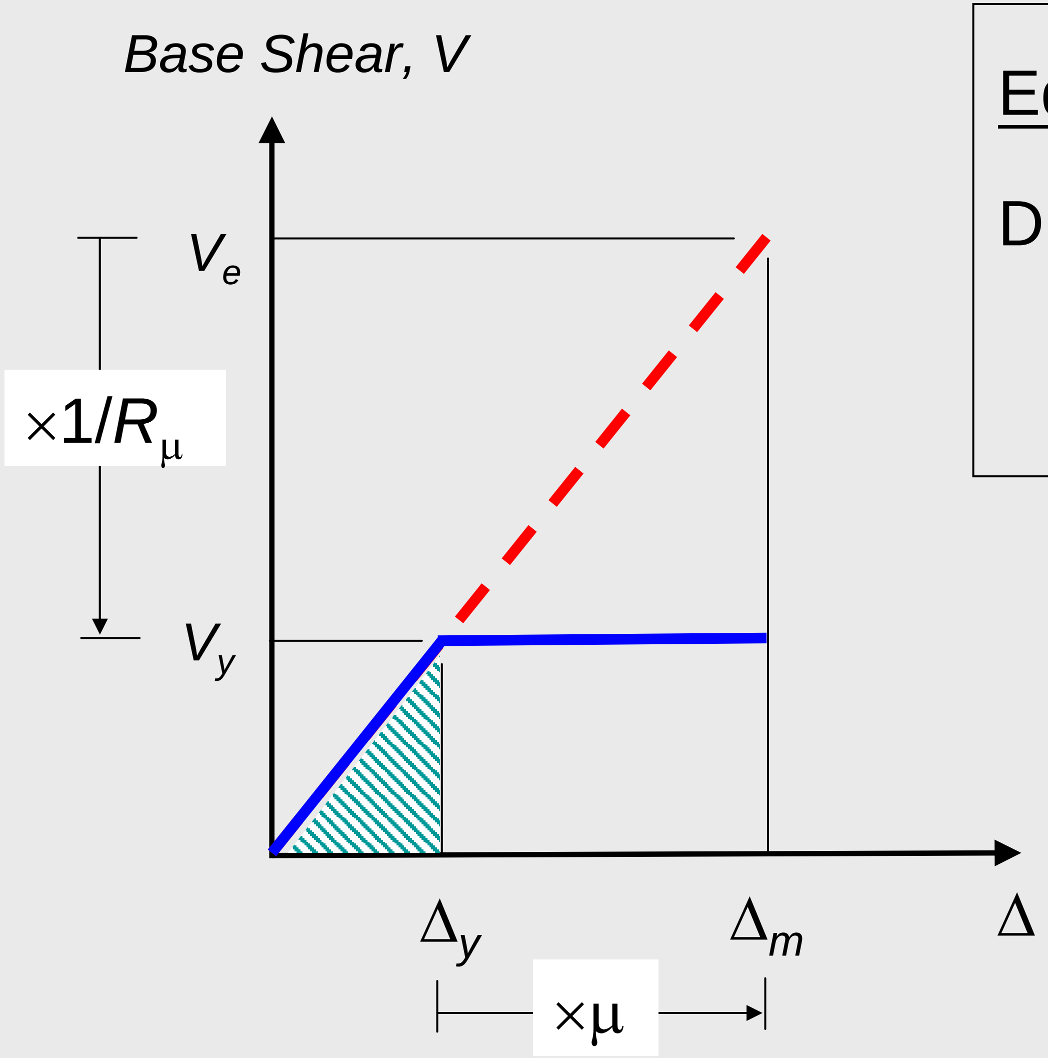
ASCE 7 Seismic Performance Factors

3 Mysterious Factors: R, C_d, and Ω_o

TABLE 12.2-1 DESIGN COEFFICIENTS AND FACTORS FOR SEISMIC FORCE–RESISTING

Seismic Force–Resisting System	ASCE 7 Section where Detailing Requirements are Specified	Response Modification Coefficient, R^a	System Overstrength Factor, $\Omega_0{}^g$	Deflection Amplification Factor, $C_d{}^b$
A. BEARING WALL SYSTEMS				
1. Special reinforced concrete shear walls	14.2 and 14.2.3.6	5	$2\frac{1}{2}$	5
2. Ordinary reinforced concrete shear walls	14.2 and 14.2.3.4	4	$2\frac{1}{2}$	4
3. Detailed plain concrete shear walls	14.2 and 14.2.3.2	2	$2\frac{1}{2}$	2
4. Ordinary plain concrete shear walls	14.2 and 14.2.3.1	$1\frac{1}{2}$	$2\frac{1}{2}$	$1\frac{1}{2}$
5. Intermediate precast shear walls	14.2 and 14.2.3.5	4	$2\frac{1}{2}$	4

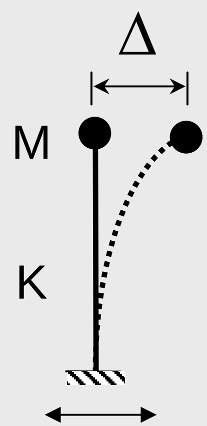
Newmark-Hall Ductility Reduction Rule



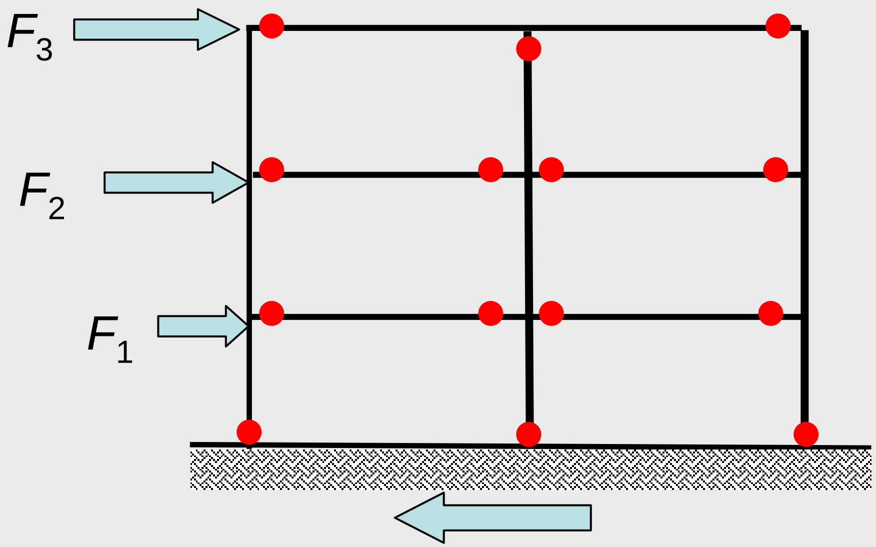
<u>Equal Displacement Rule</u>

Ductility Reduction Factor:

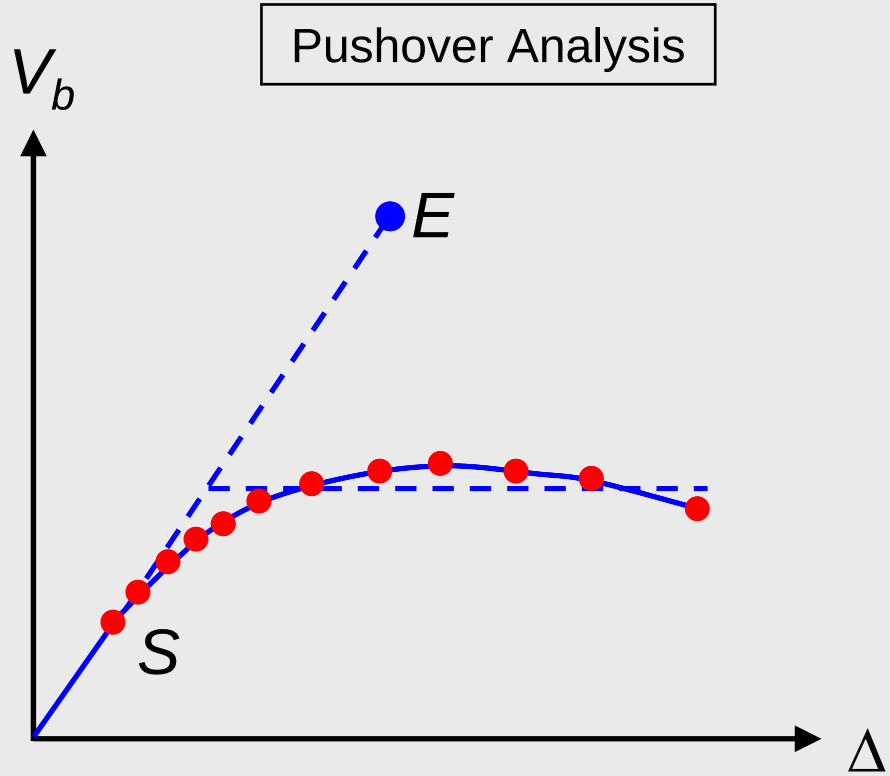
$$R_\mu = \mu$$



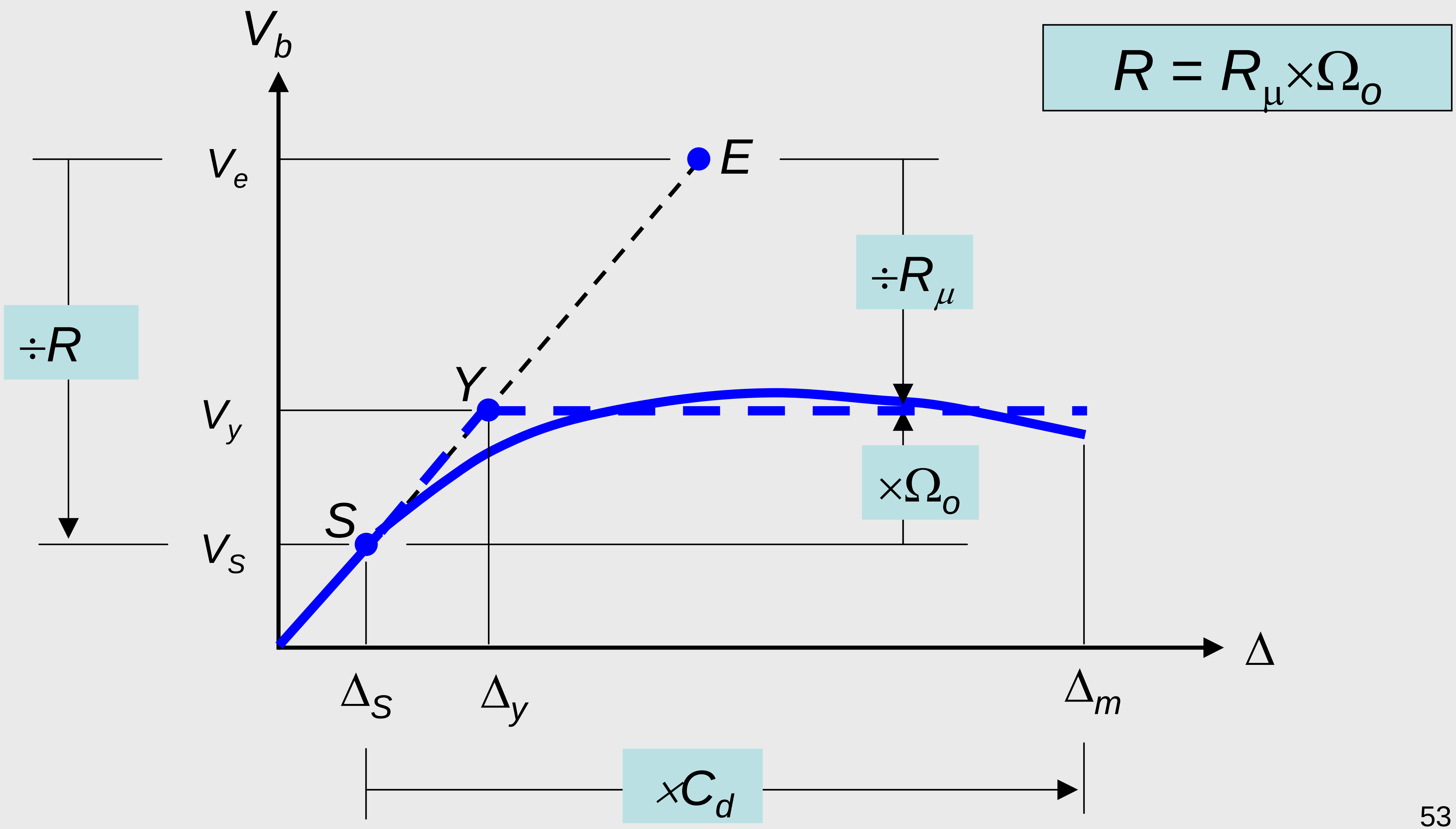
Multistory Frames



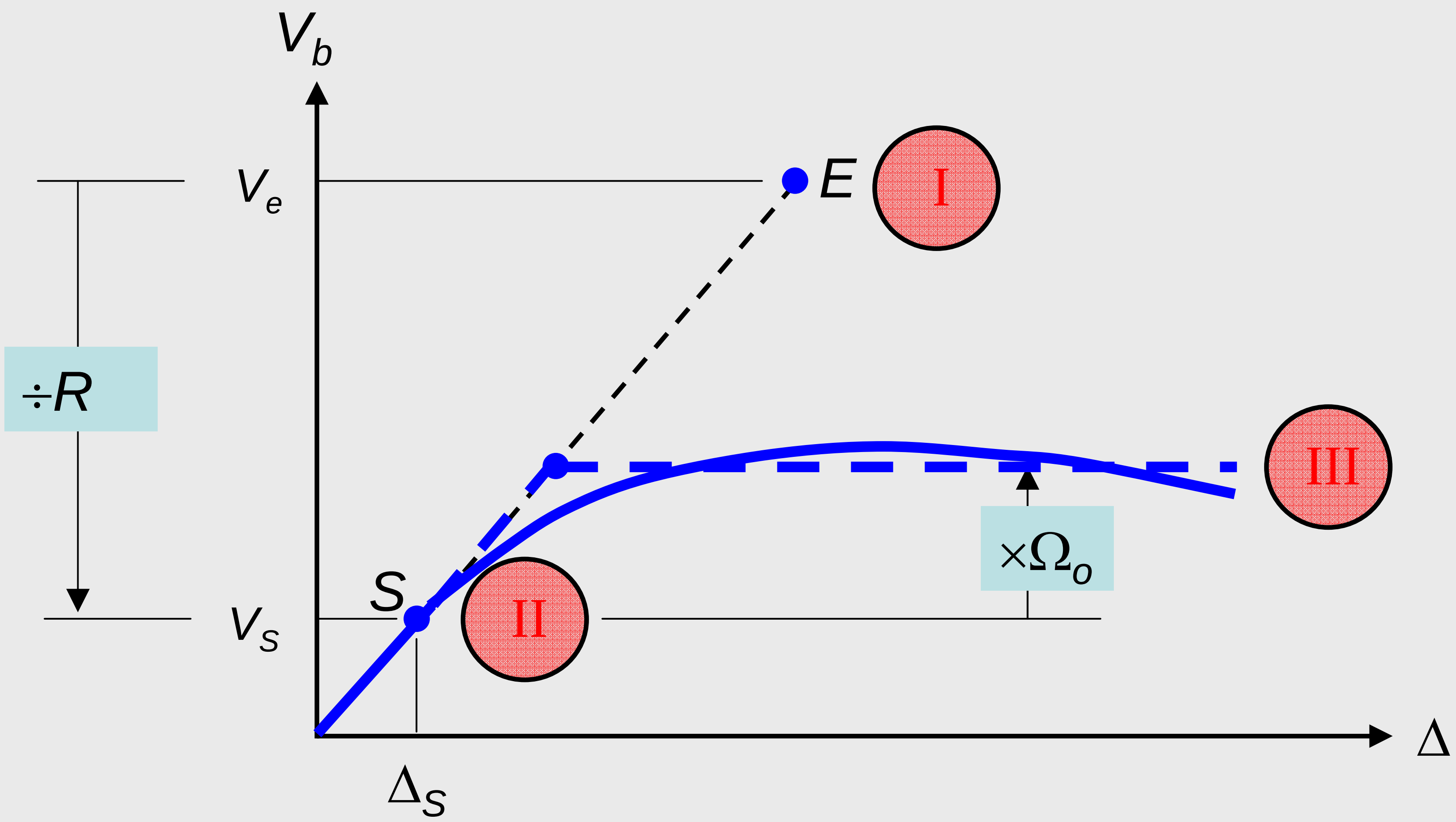
$$V_b = \sum F_i$$



Multistory Frames



Capacity Design Seismic Forces



Seismic Load Combinations (IBC)

- §16.5.2.1 Basic Seismic Load Combination:

  $1.2D + f_1 L + f_2 S + 1.0E$

  Seismic Force Level II Force for Deformation-Controlled Elements (Ductility Design Needed)

- §1605.4 Special Seismic Load Combination:

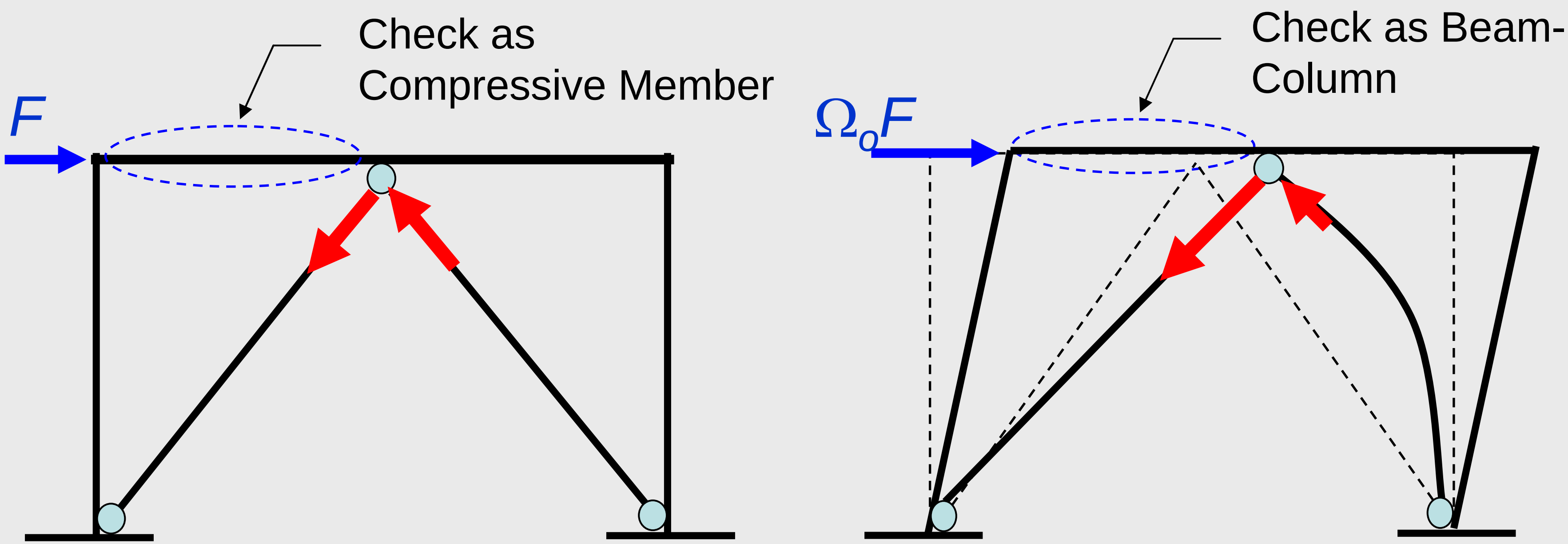
  $1.2D + f_1 L + 1.0E_m$

  Seismic Force Level III Force for Force-Controlled Elements (Capacity Design Needed)

Internal Force Distribution

- At Seismic Force Level II (Basic Load Combination)–Use Elastic Structural Analysis to Determine Internal Force Distribution
- At Seismic Force Level III (Basic Load Combination)–Internal Force Re-distribution Occurs due to Nonlinear Response

Example



(a) Seismic Force Level II

(b) Seismic Force Level III

Capacity Design

- Think beyond Elastic Response Mentality
- Use Expected Material Strength for Estimate Maximum Force Developed in Structural Fuse

  (Note: Structural Fuse Material Strength too High Is not Desirable for Seismic Design)
- Two Methods to Calculate Seismic Force Level III for Capacity Design

Expected Material Strength

- AISC SP §6.2
- Expected Yield Stress, $F_{ye} = R_y F_y$

TABLE I-6-1
R_y and R_t Values for Different Member Types

Application	R_y	R_t
Hot-rolled structural shapes and bars:		
• ASTM A36/A36M	1.5	1.2
• ASTM A572/572M Grade 42 (290)	1.3	1.1
• ASTM A572/572M Grade 50 (345) or 55 (380), ASTM A913/A913M Grade 50 (345), 60 (415), or 65 (450)	1.1	1.1

Capacity Design–Method 1

- When the Structural Fuse Is Next to Force-Controlled Element
- Apply Statics at “Local” Level
- Seismic Force Level II not Needed
- An Upper-Bound Estimate of Seismic Force Level III

Example 1: SCBF Bracing Connection

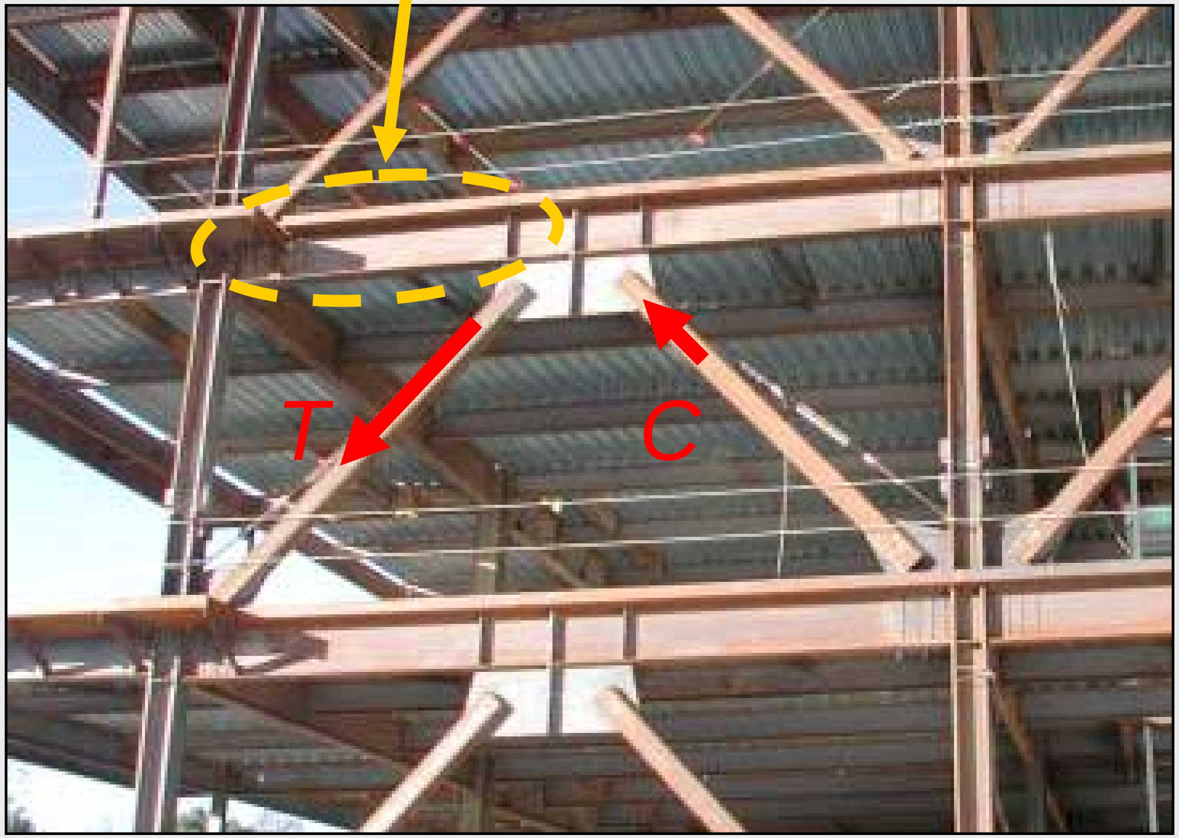
- Bracing is Structural Fuse
- AISC SP § 13.3 Bracing Connection Design

$$\begin{cases} T = R_y F_y A_g \\ C = 1.1 R_y P_n \end{cases}$$

Don't Oversize Structural Fuse!

Example 1: SCBF Beam Design

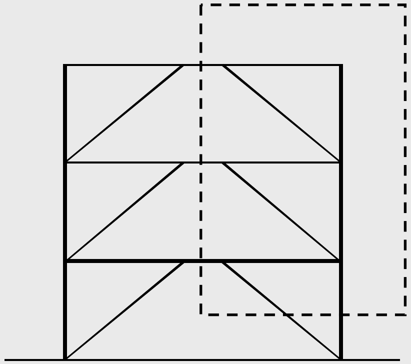
Check as Beam-Column



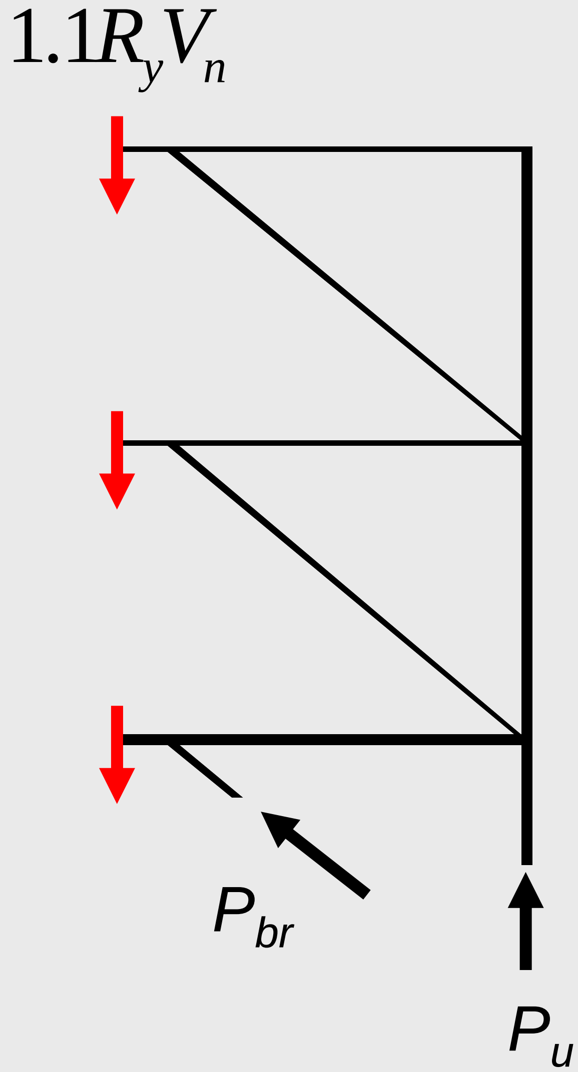
- AISC SP § 13.4a Beam Design for V-Type Bracing

$$\begin{cases} T = R_y F_y A_g \\ C = 0.3P_n \end{cases}$$

Example 2: EBF Column Design



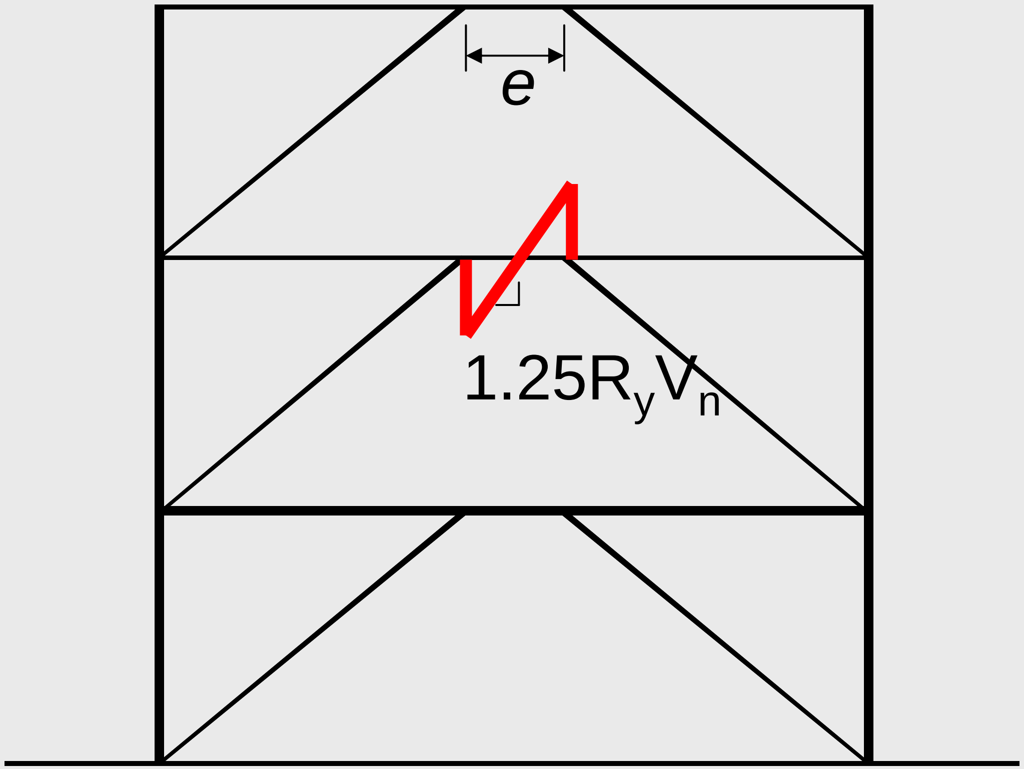
- Links Are Structural Fuse
- AISC SP § 15.8 for Column Design



Example 2: EBF Brace Design

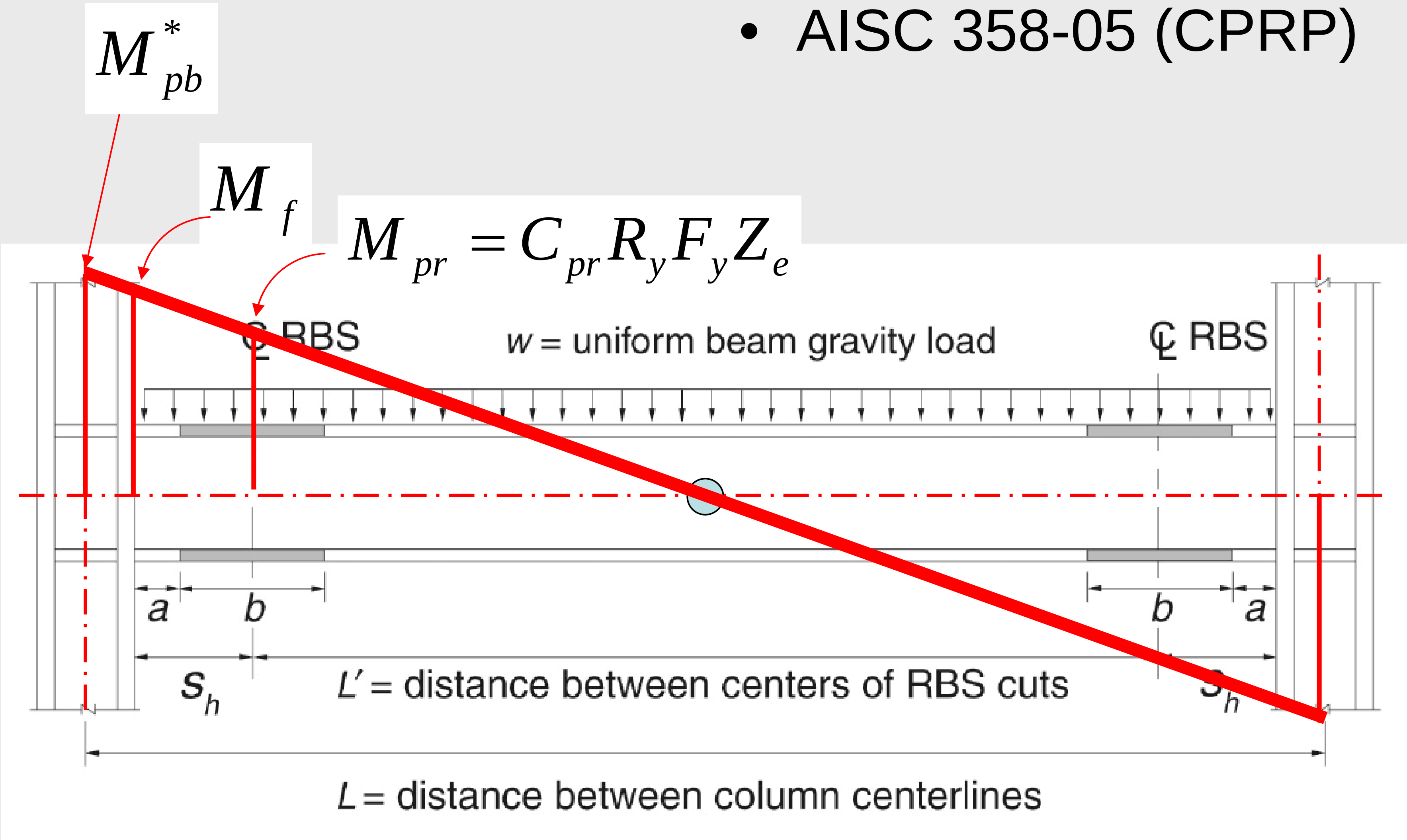
- Links Are Structural Fuse
- AISC SP § 15.6 for Beam/Bracing Design

Don't Oversize Links



Example 3: SMF

- AISC 358-05 (CPRP)



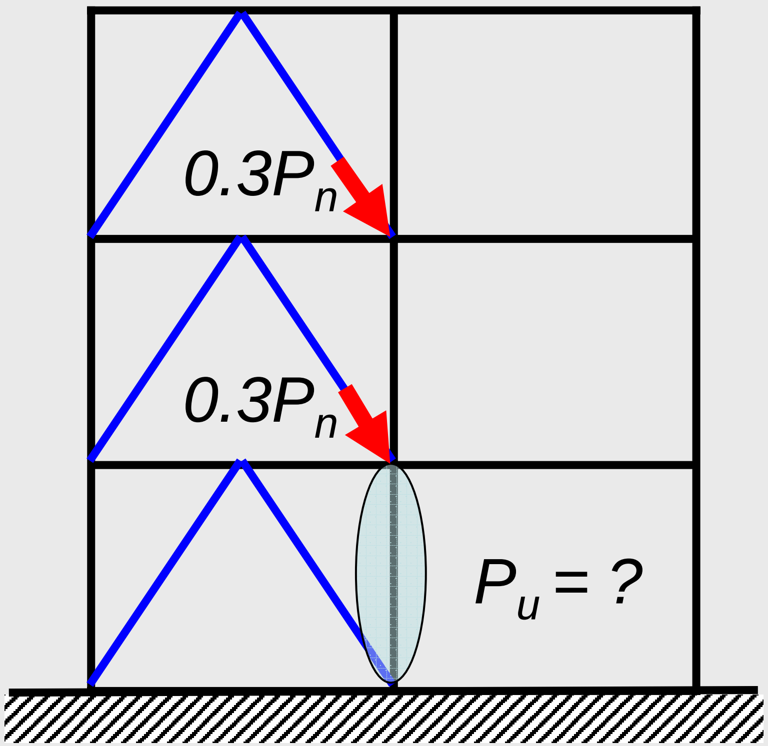
Capacity Design–Method 2

- An Approximate (or "Lazy") Method:

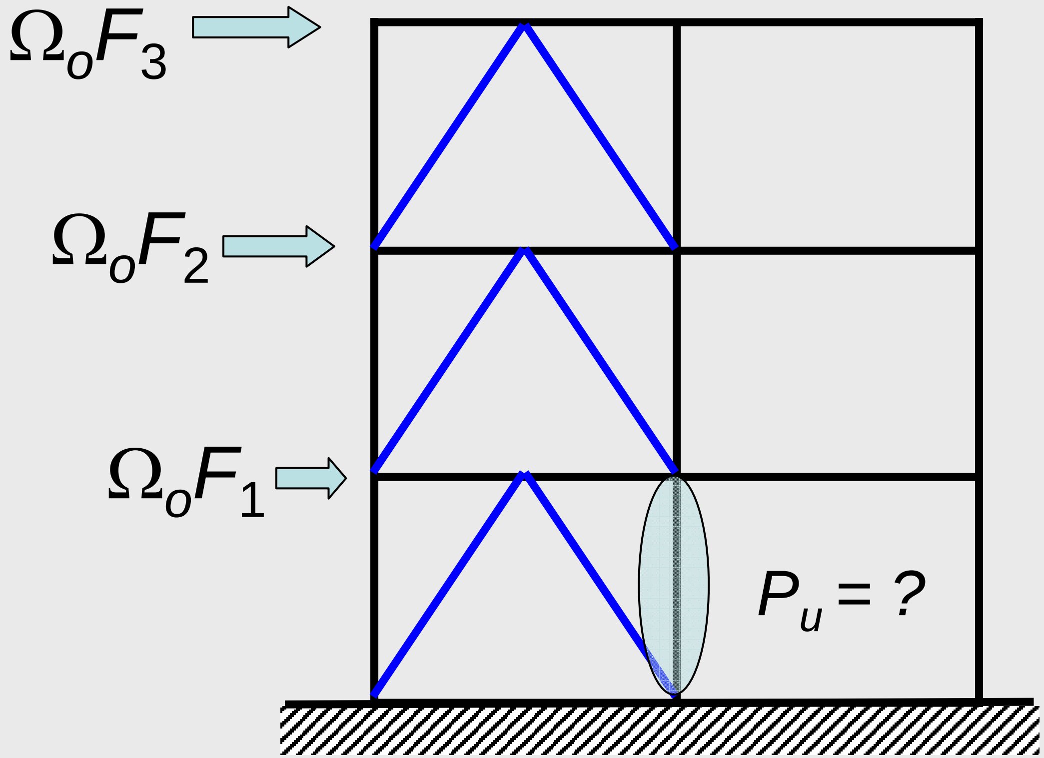
$$\underbrace{\Omega_o}_{\boxed{\text{ASCE 7}}} \times \underbrace{(\text{Seismic Force Level II})}_{\boxed{\text{Elastic Analysis}}}$$

- Use It When Method 1 Cannot Be Applied Easily
- Usually Applied at the "Global" (or System) Level
- Can Be Dangerous If Not Properly Applied

Example 1–SCBF Column Design

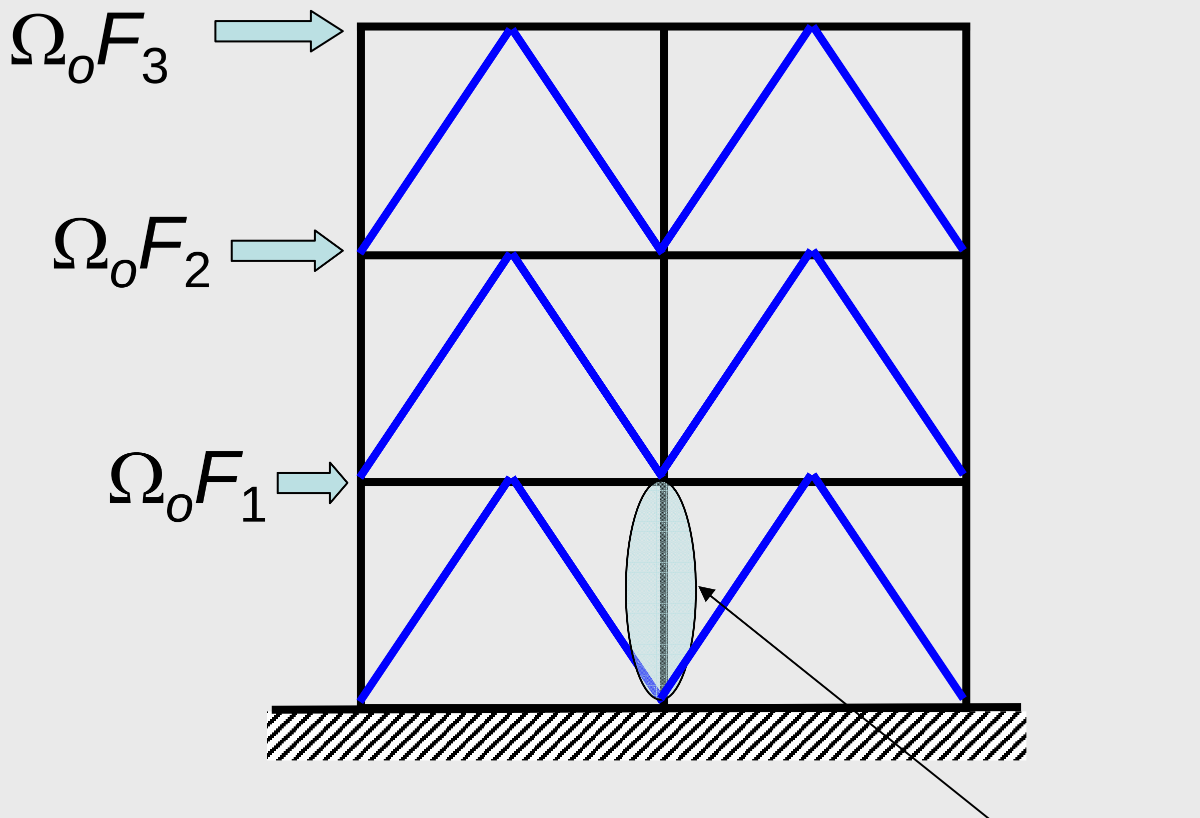


Method 1



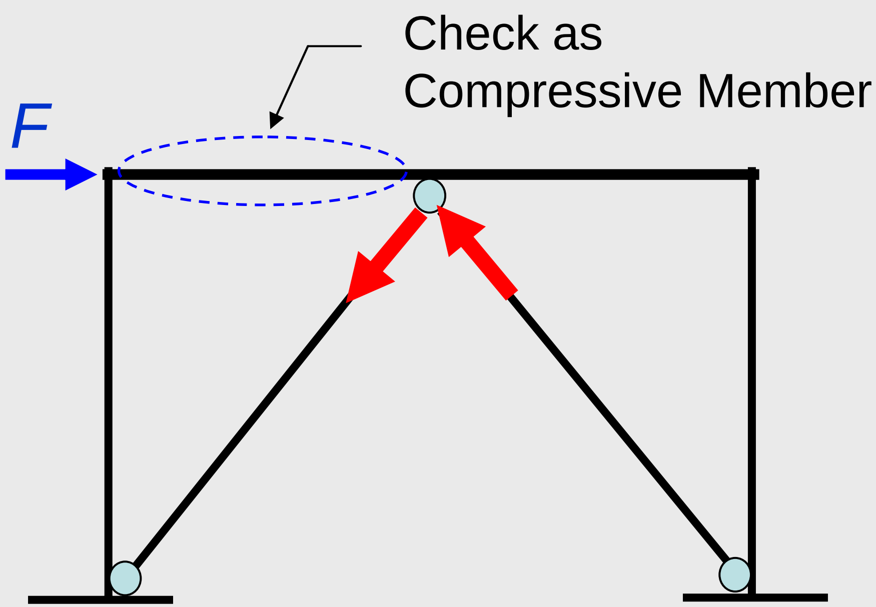
Method 2

Example 1–SCBF Column Design

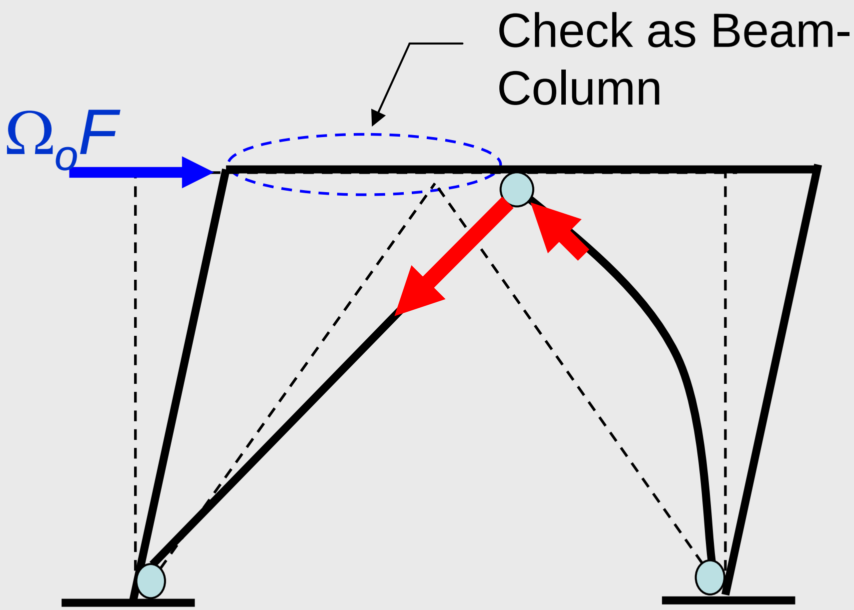


Method 2

Example 1–SCBF



(a) Seismic Force Level II



(b) Seismic Force Level III

(Method 2 Will not Work)

Ductility vs. Capacity Design

	Ductility Design (Deformation-Controlled Elements)	**Capacity Design** (Force-Controlled Elements)
Research Effort	More	
Design Effort	Easier (Straightforward)	Requires Understanding/Judgment