Design of Seismic-Resistant Steel Building Structures

5. Buckling Restrained Braced Frames

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American Institute of Steel Construction.

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Design of Seismic-Resistant Steel Building Structures

1 - Introduction and Basic Principles

2 - Moment Resisting Frames

3 - Concentrically Braced Frames

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5 - Buckling-Restrained Braced Frames

6 - Special Plate Shear Walls

5 - Buckling-Restrained Braced Frames (BRBFs)

- Description and Basic Behavior of Buckling-Restrained Braced Frames and Buckling-Restrained Braces
- AISC Seismic Provisions for Buckling-Restrained Braced Frames

Buckling-Restrained Braced Frames (BRBFs)

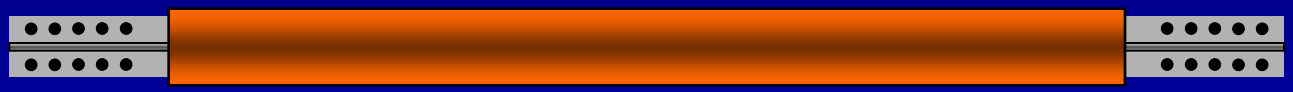
- Description and Basic Behavior of Buckling-Restrained Braced Frames and Buckling-Restrained Braces
- AISC Seismic Provisions for Buckling-Restrained Braced Frames

Buckling-Restrained Braced Frames (BRBFs)

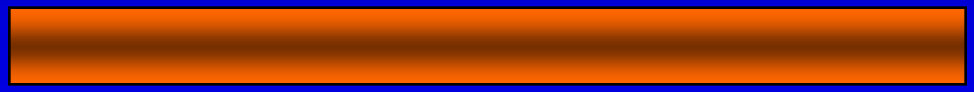
- Type of concentrically braced frame.
- Beams, columns and braces arranged to form a vertical **truss**. Resist lateral earthquake forces by truss action.
- Special type of brace members used: ***Buckling-Restrained Braces (BRBs)***. BRBS yield both in tension and compression - *no buckling !!*

- Develop ductility through inelastic action (cyclic tension and compression yielding) in BRBs.
- System combines high stiffness with high ductility.

Buckling-Restrained Brace



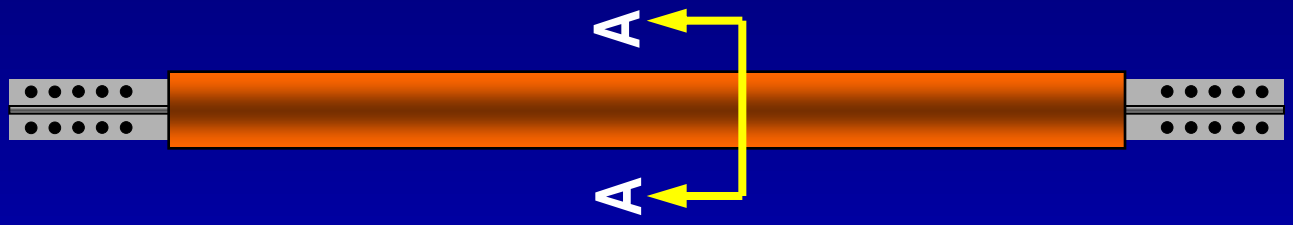
Buckling-Restrained Brace:
Steel Core
+
Casing



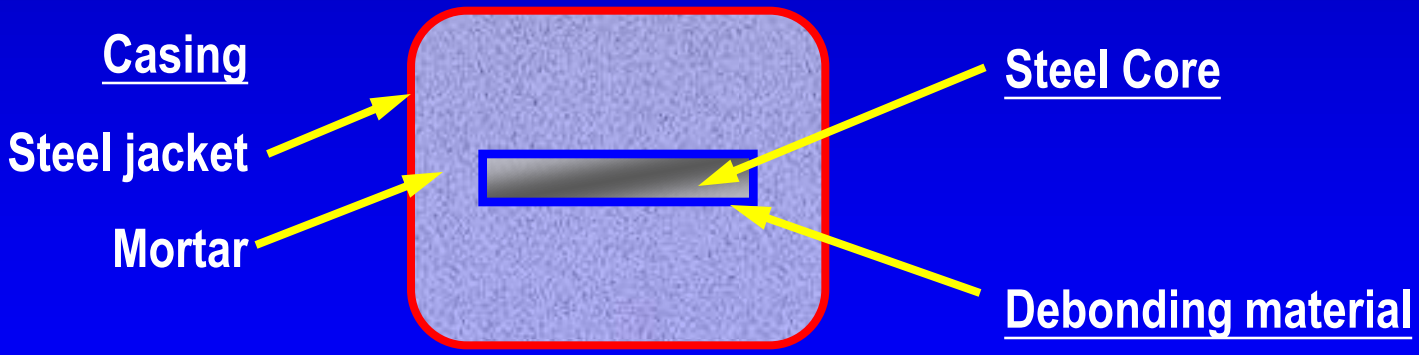
Casing

Steel Core

Buckling-Restrained Brace



Buckling-Restrained Brace:
Steel Core
+
Casing



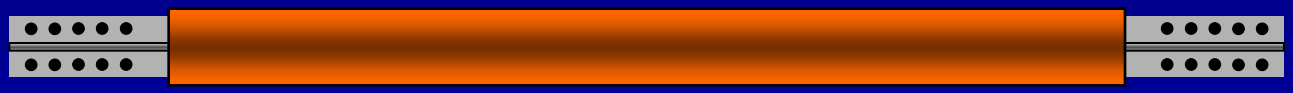
Section A-A

Buckling-Restrained Brace

Steel core resists entire axial force P

Casing is debonded from steel core
- casing does not resist axial force P
- flexural stiffness of casing restrains buckling of core

Buckling-Restrained Brace

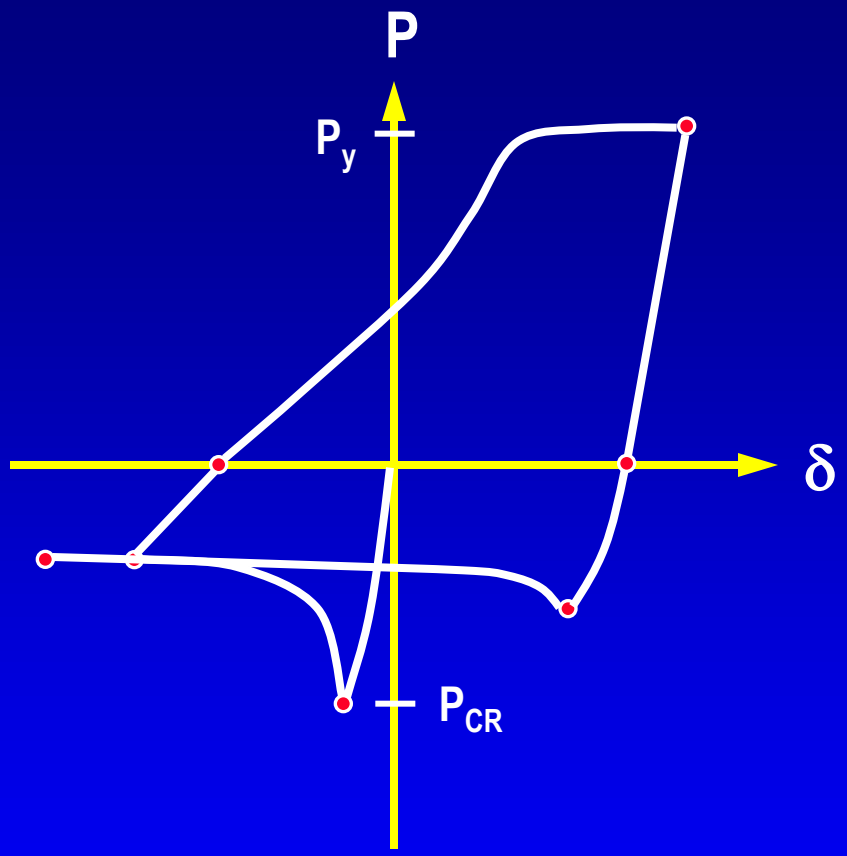


Buckling-Restrained Brace:
Steel Core
+
Casing

Steel Core

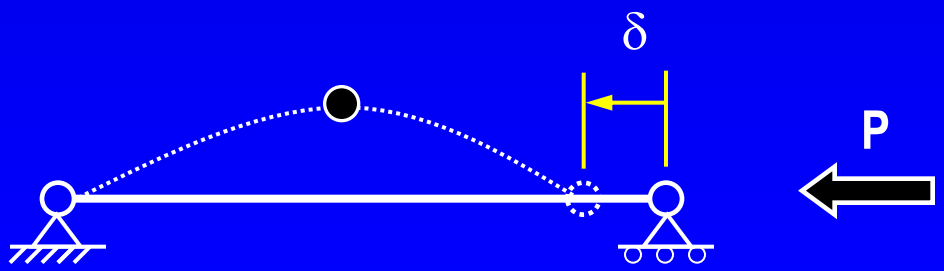
Core projection and brace connection segment

Brace Behavior Under Cyclic Axial Loading

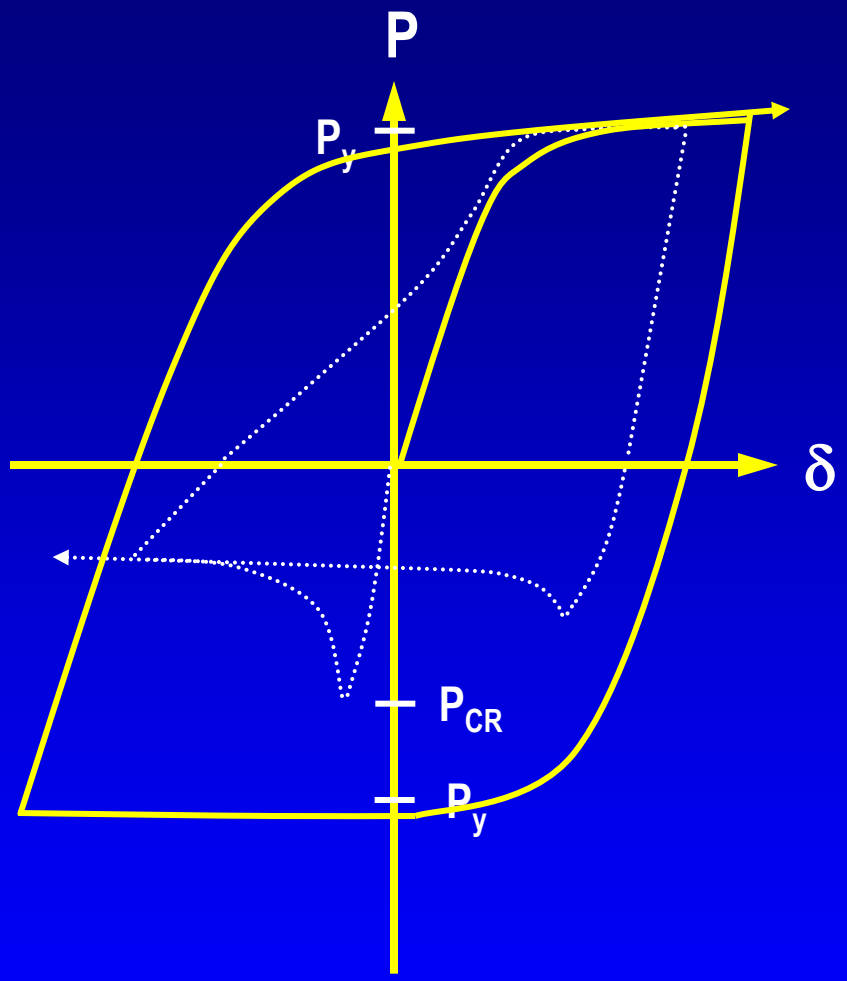


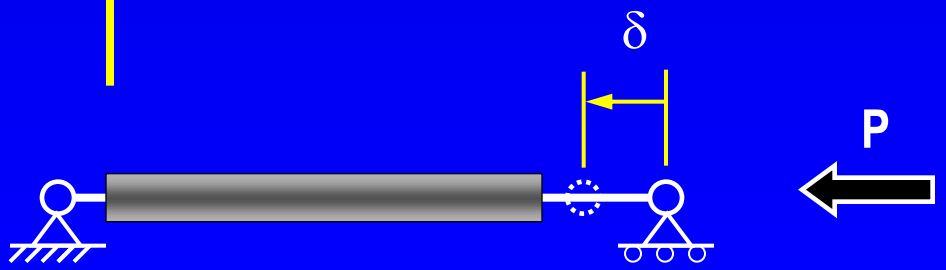
Conventional Brace:

- yields in tension (ductile)
- buckles in compression (nonducile)
- significantly different strength in tension and compression



Brace Behavior Under Cyclic Axial Loading

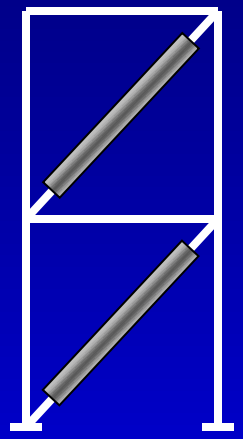




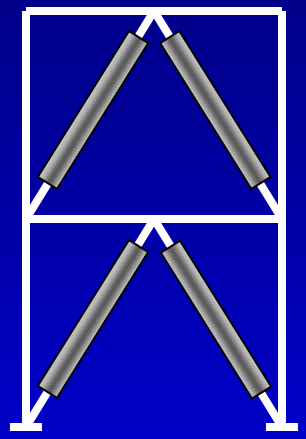
Buckling-Restrained Brace:

- yields in tension (ductile)
- yields in compression (ductile)
- similar strength in tension and compression (slightly stronger in compression)

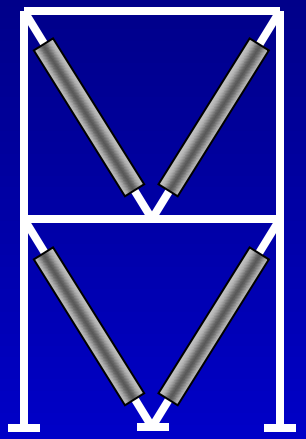
Bracing Configurations for BRBFs



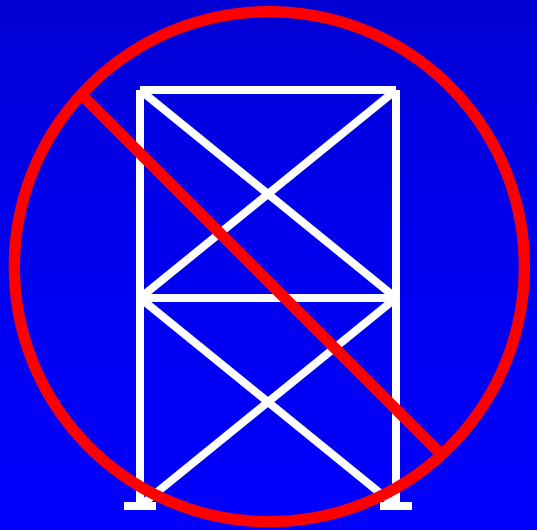
Single Diagonal



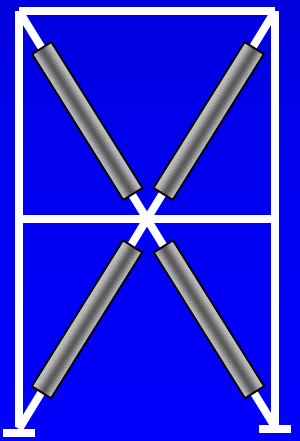
Inverted V- Bracing



V- Bracing



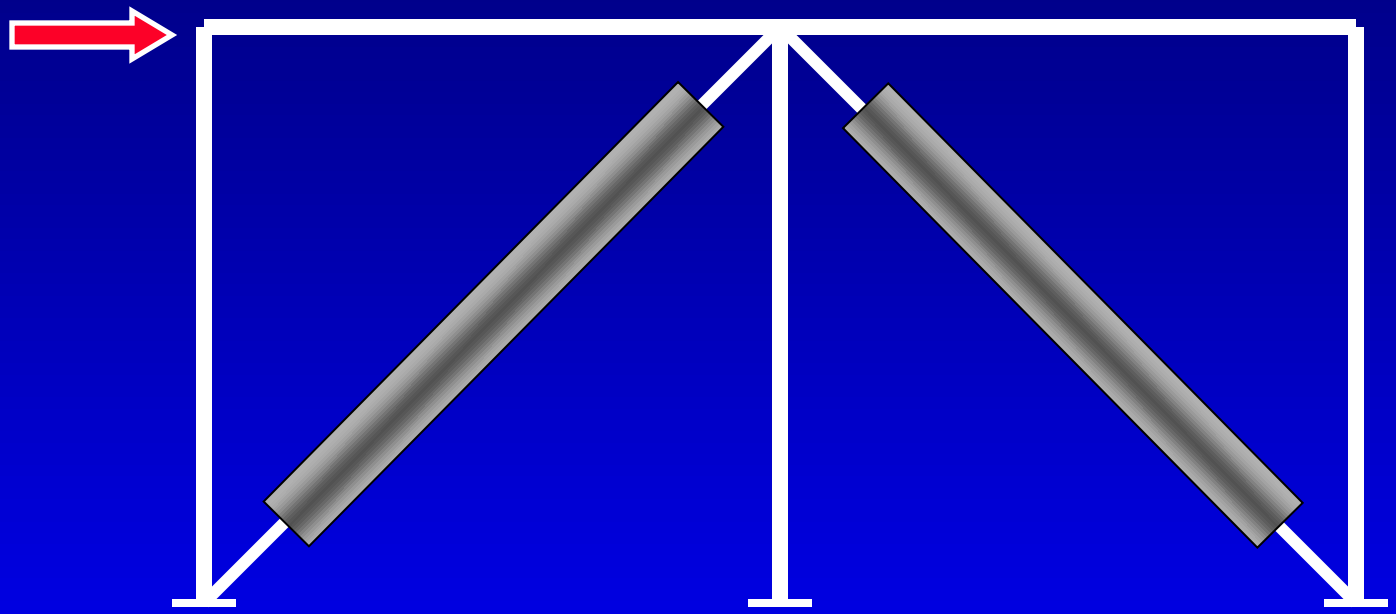
X- Bracing

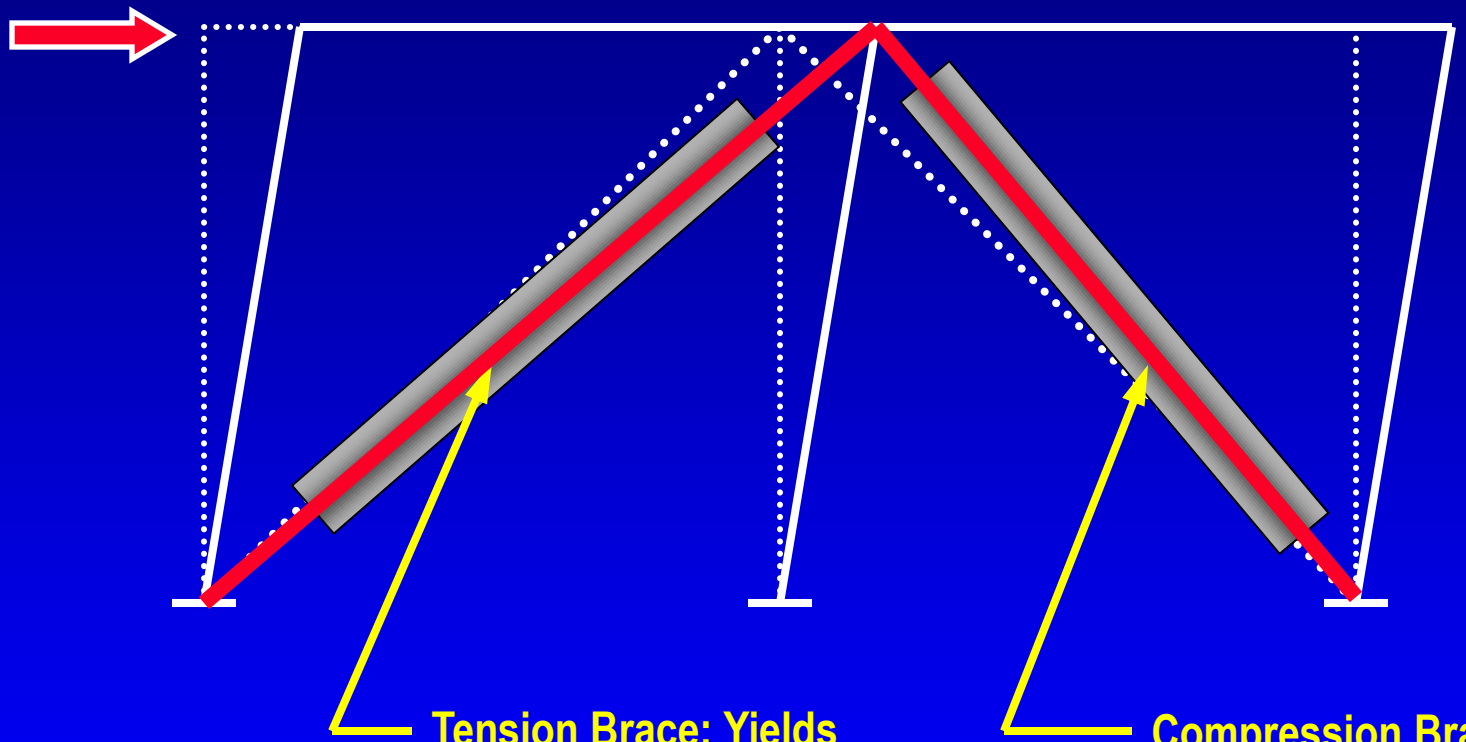


Two Story X- Bracing

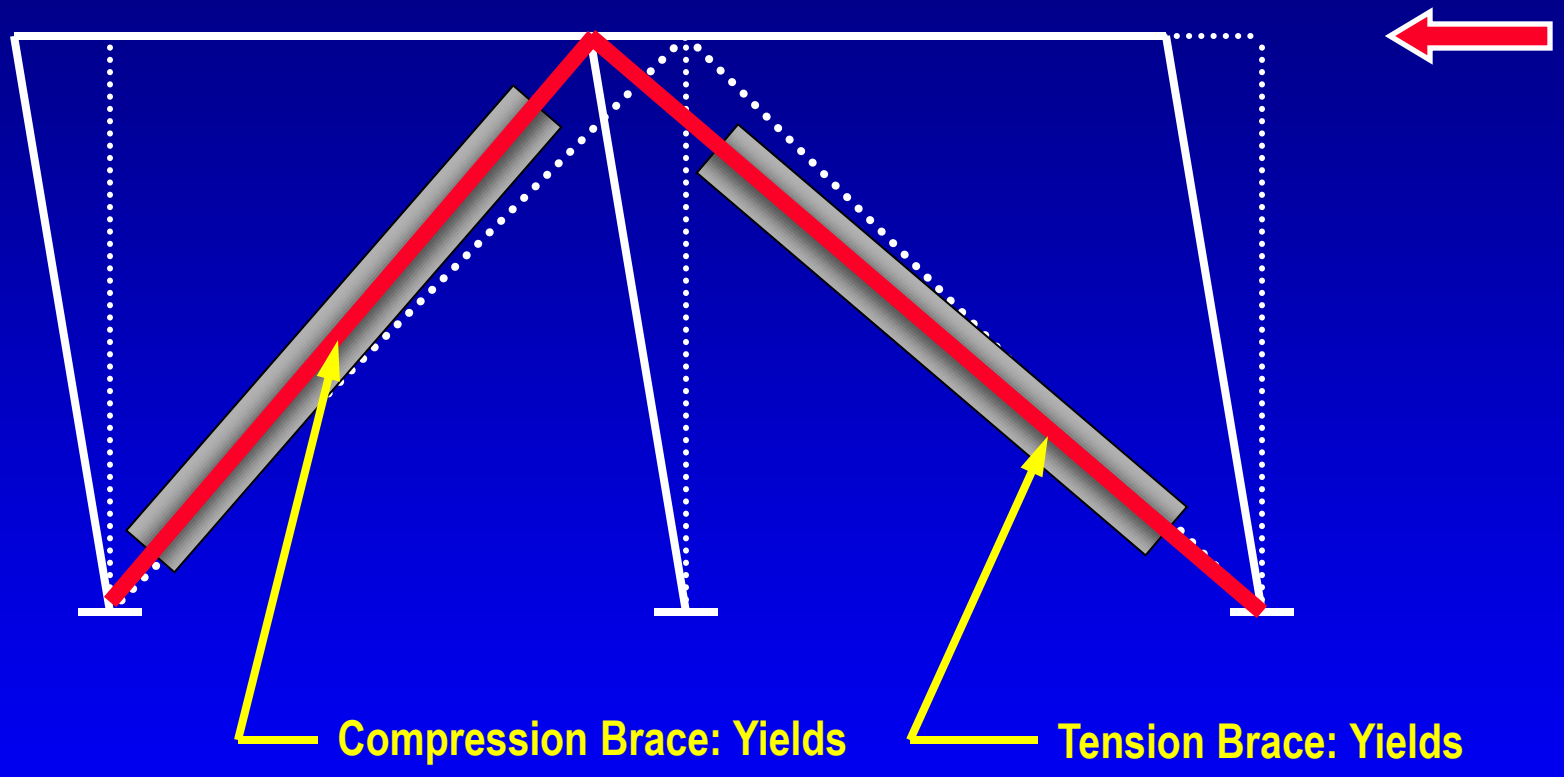

Herrick
Herrick
4 5 2006

Inelastic Response of BRBFs under Earthquake Loading



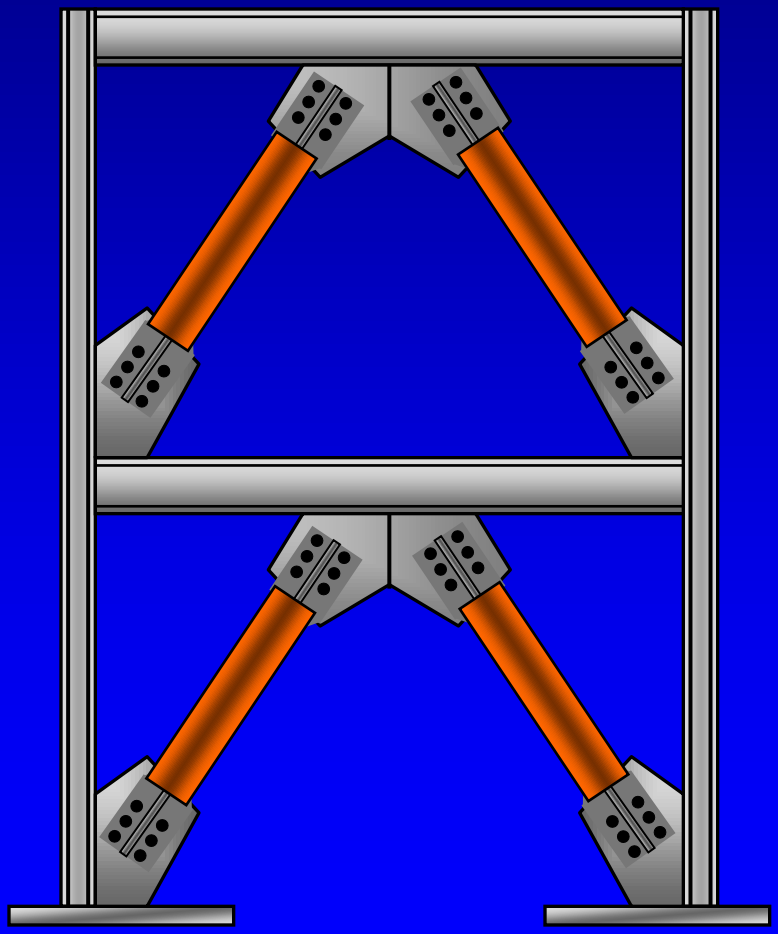


Columns and beams: remain essentially elastic



Columns and beams: remain essentially elastic

Design of BRBFs - General Approach



- Size BRB core for code specified forces (strength and stiffness)
- Choose BRB design with performance verified by testing (Per Appendix T)
- Design all other frame elements (beams, columns, brace connections, column bases) for maximum forces that can be generated by fully yielded and strain hardened BRBs

Buckling-Restrained Braced Frames (BRBFs)

- Description and Basic Behavior of Buckling-Restrained Braced Frames and Buckling-Restrained Braces
- AISC Seismic Provisions for Buckling-Restrained Braced Frames

2005 AISC Seismic Provisions

Section 16 Buckling-Restrained Braced Frames (BRBF)

16.1 Scope

16.2 Bracing Members

16.3 Bracing Connections

16.4 Special Requirements Related to Bracing Configuration

16.5 Beams and Columns

16.6 Protected Zone

16.1 Scope

Buckling-restrained braced frames **(BRBF) are expected to withstand significant inelastic deformations when subjected to the forces resulting from the motions of the design earthquake.**

16.2 Bracing Members

Bracing members shall be composed of a structural steel core and a system that restrains the steel core from buckling.

16.2 Bracing Members

16.2a Steel Core

The *steel core* shall be designed to resist the entire axial force in the brace.

The brace *design axial strength* = ϕP_{ysc}

$\phi = 0.9$ $\quad$ $P_{ysc} = F_{ysc} A_{sc}$

16.2 Bracing Members

16.2a Steel Core

$$\phi P_{ysc} = (0.9) F_{ysc} A_{sc}$$

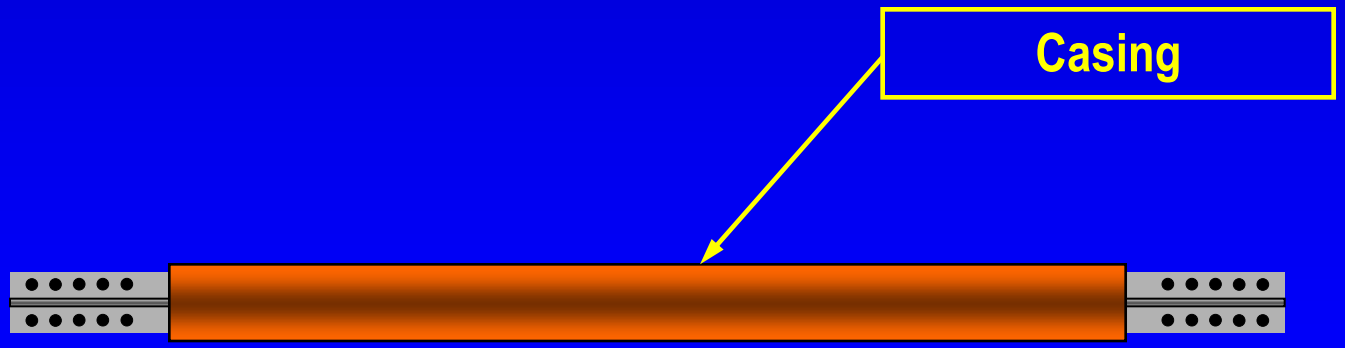
A_{sc} = area of steel core (yielding segment)

F_{ysc} = specified minimum yield stress of core, or actual yield stress from coupon test

16.2 Bracing Members

16.2b Buckling-Restraining System

The buckling-restraining system shall consist of the casing for the steel core. In stability calculations, beams, columns, and gussets connecting the core shall be considered part of this system.



16.2 Bracing Members

16.2b Buckling-Restraining System

The buckling-restraining system shall limit local and overall buckling of the steel core for deformations corresponding to 2.0 times the *design story drift*. The buckling-restraining system shall not be permitted to buckle within deformations corresponding to 2.0 times the *design story drift*.

16.2 Bracing Members

16.2b Buckling-Restraining System

Δ = design story drift = $C_d \times \Delta_E$

Δ_E = story drift under code specified earthquake forces

C_d = 5.5 for BRBF with non-moment resisting beam-column connections

= 5 for BRBF with moment-resisting beam-column connections

Buckling-restrained braces must be capable of sustaining story drifts up to $2 \times \Delta$

16.2 Bracing Members

16.2c Testing

The design of braces shall be based upon results of tests per Appendix T *"Qualifying Cyclic Tests of Buckling Restrained Braces"*

Appendix T - Qualifying Cyclic Tests of Buckling-Restrained Braces

Purpose of Testing:

- Verify brace performance of under cyclic loading up to deformation levels corresponding to 2 x design story drift
- Determine strength of brace in tension and compression at a deformation level corresponding to 2 x design story drift

Appendix T

Two tests required to qualify brace:

1. *Brace Test Specimen*

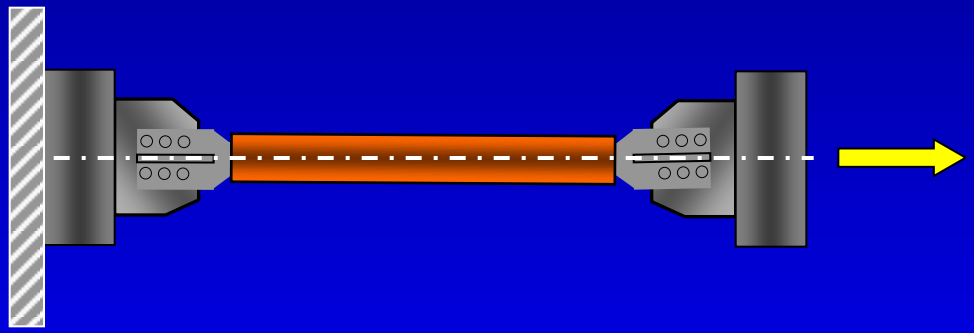
Verify ability to sustain large cyclic axial tension and compression without buckling or fracture

2. *Subassemblage Test Specimen*

Verify ability of brace and connections to accommodate axial and rotational demands imposed by frame

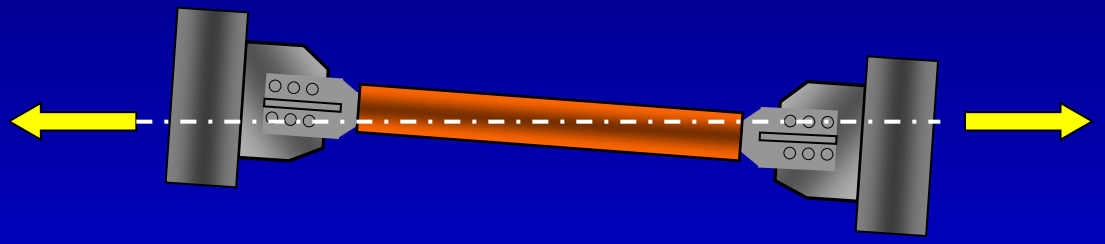
Appendix T

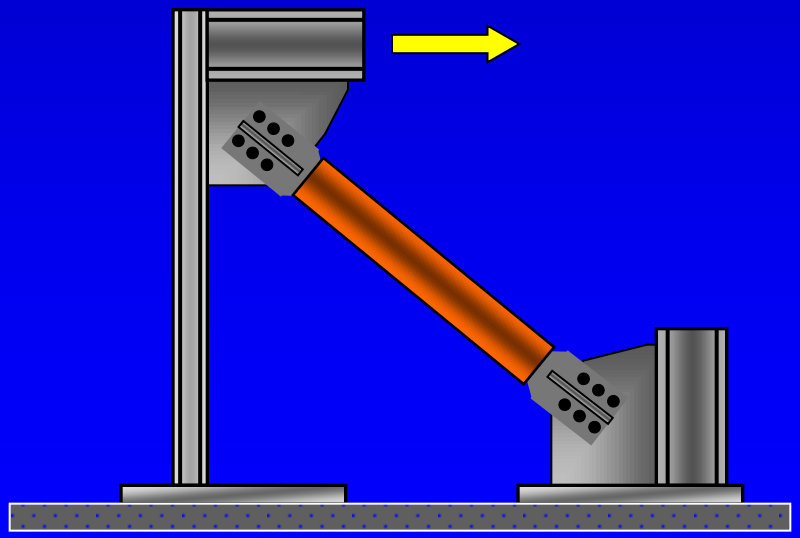
Brace Test Specimen: Uniaxial Loading

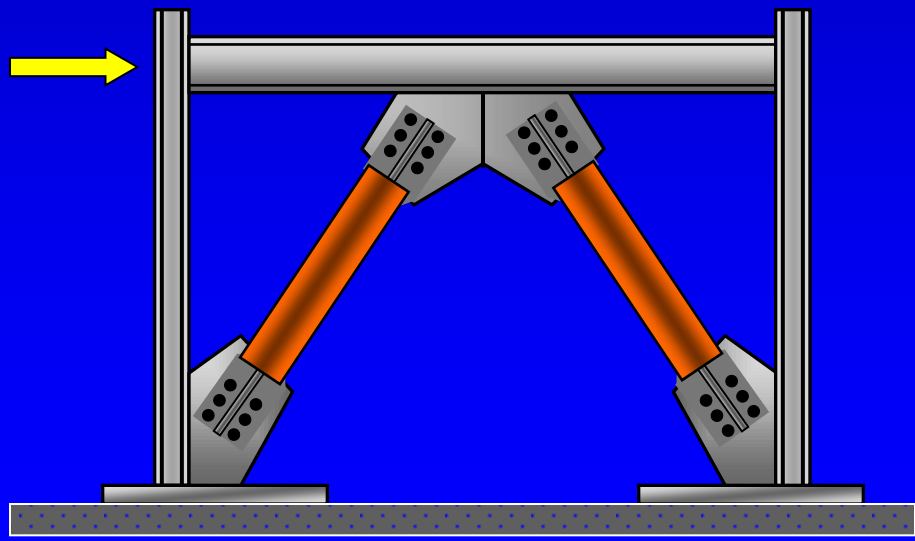


Appendix T

Subassemblage Test Specimen: Axial + Rotational Loading







Appendix T

Scale Requirements for Test Specimens:

1. *Brace Test Specimen*

$$0.5\,[\,P_{ysc}\,]_{prototype} \le [\,P_{ysc}\,]_{specimen} \le 1.5\,[\,P_{ysc}\,]_{prototype}$$

2. *Subassemblage Test Specimen*

$$[\,P_{ysc}\,]_{specimen} \ge [\,P_{ysc}\,]_{prototype}$$

Appendix T

Definitions:

Δ_b = deformation quantity used to control test

= total brace axial deformation for the **brace test specimen**

= total brace end rotation for the **subassemblage test specimen**

Δ_{bm} = value of deformation quantity, Δ_b, corresponding to the **design story drift**

Δ_{by} = value of deformation quantity, Δ_b, at first significant yield of the test specimen

Appendix T

When calculating Δ_{bm}, the **design story drift** shall not be taken less that 0.01 × story height

Design story drift = larger of

$$\begin{cases} C_d \times \Delta_E \\ 0.01 \times \text{story height} \end{cases}$$

Appendix T

Loading Sequence

2 cycles at: $\Delta_b = \pm \Delta_{by}$

2 cycles at: $\Delta_b = \pm 0.5\, \Delta_{bm}$

2 cycles at: $\Delta_b = \pm 1.0\, \Delta_{bm}$

2 cycles at: $\Delta_b = \pm 1.5\, \Delta_{bm}$

2 cycles at: $\Delta_b = \pm 2.0\, \Delta_{bm}$

Continue with additional cycles at $\Delta_b = \pm 1.5\, \Delta_{bm}$ for the *brace test specimen* to achieve cumulative axial deformation at least 200 times Δ_{by} (not required for subassemblage test specimen)

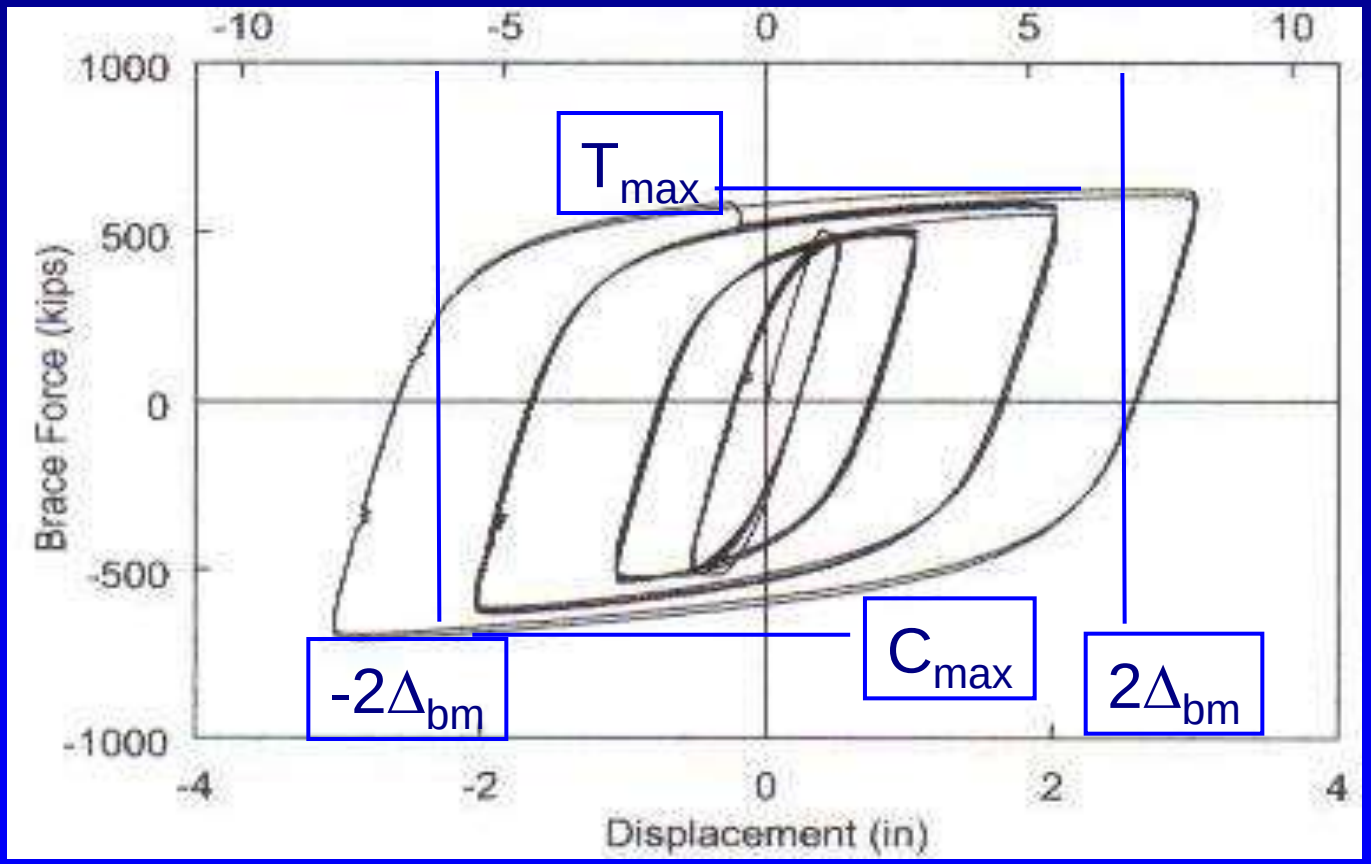
Appendix T

Acceptance Criteria for Test Specimens:

- No fracture, brace instability or brace end connection failure
- Positive incremental stiffness (no strength degradation)
- For **Brace Test Specimen**:
  - $T_{max} \geq P_{ysc}$ *and* $C_{max} \geq P_{ysc}$
  - $C_{max} \leq 1.3\, T_{max}$

Appendix T

Example of Results for Brace Test Specimen



16.2 Bracing Members

16.2d Adjusted Brace Strength

Tension

$$\text{Adjusted Brace Strength} = \omega R_y P_{ysc}$$

Compression

$$\text{Adjusted Brace Strength} = \beta \omega R_y P_{ysc}$$

ω = strain hardening adjustment factor

β = compression strength adjustment factor

} Determine from Appendix T brace tests

Take R_y = 1.0 if P_{syc} is computed using coupon values of F_{ysc}

16.2 Bracing Members

16.2d Adjusted Brace Strength

ω = strain hardening adjustment factor

β = compression strength adjustment factor

} Determine from Appendix T brace tests

$$\omega = \frac{T_{max}}{F_{ysc} A_{sc}}$$

$$\beta = \frac{C_{max}}{T_{max}}$$

16.3 Bracing Connections

16.3a Required Strength

The *required strength* of bracing connections in tension and compression shall be 1.1 × adjusted brace strength in compression

$$P_u = 1.1\,\beta\,\omega\,R_y\,P_{ysc}$$

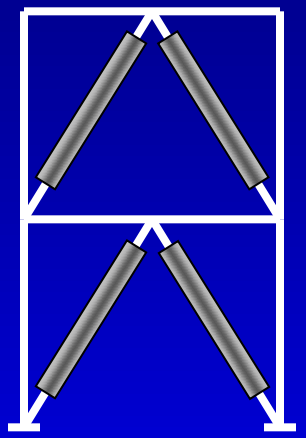
16.3b Gusset Plates

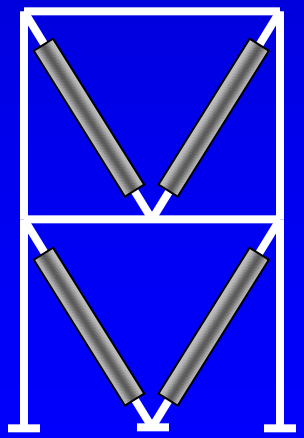
The design of connections shall include considerations of local and overall buckling. Bracing consistent with that used in the tests upon which the design is based is required.


1FBS-E

16.4 Special Requirements Related to Bracing Configuration

For V-type and Inverted V-type bracing:



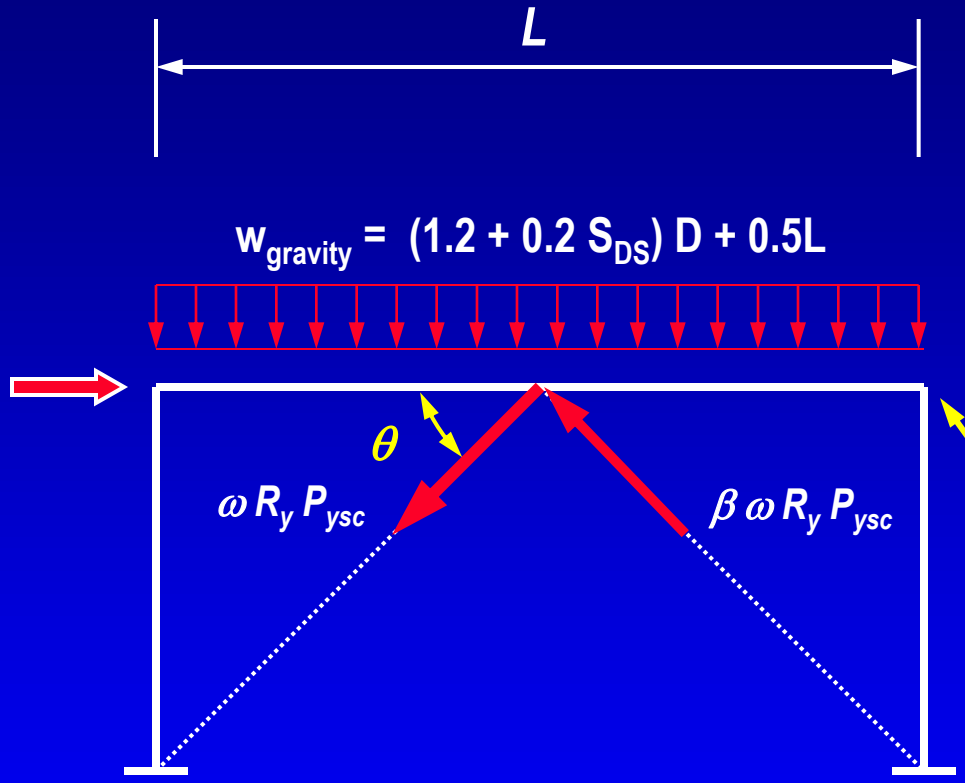


(1) Design beams for unbalanced load resulting from the adjusted brace strengths in tension and compression.

Take force in tension brace: $\omega R_y P_{ysc}$

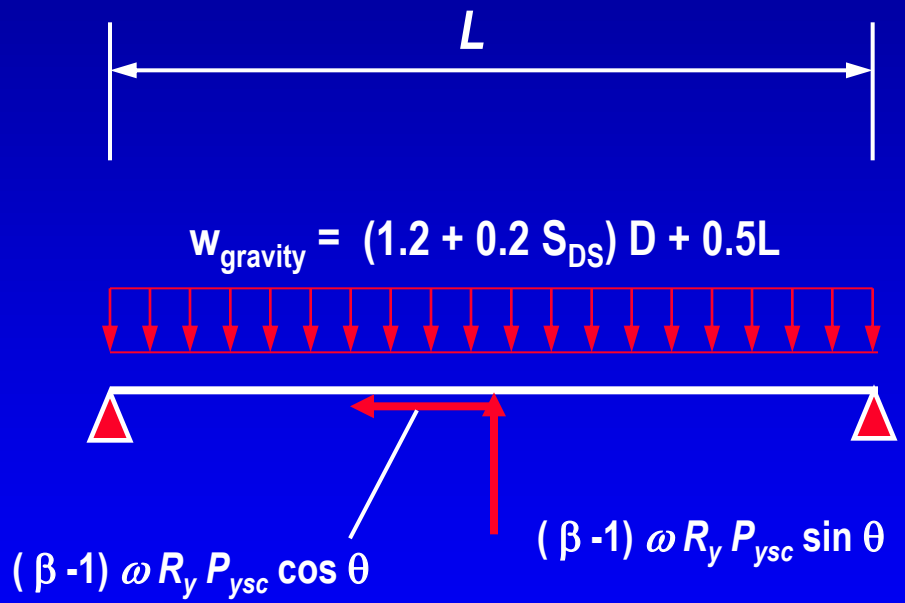
Take force in compression brace: $\beta \omega R_y P_{ysc}$

Assume beam has no vertical support between columns.

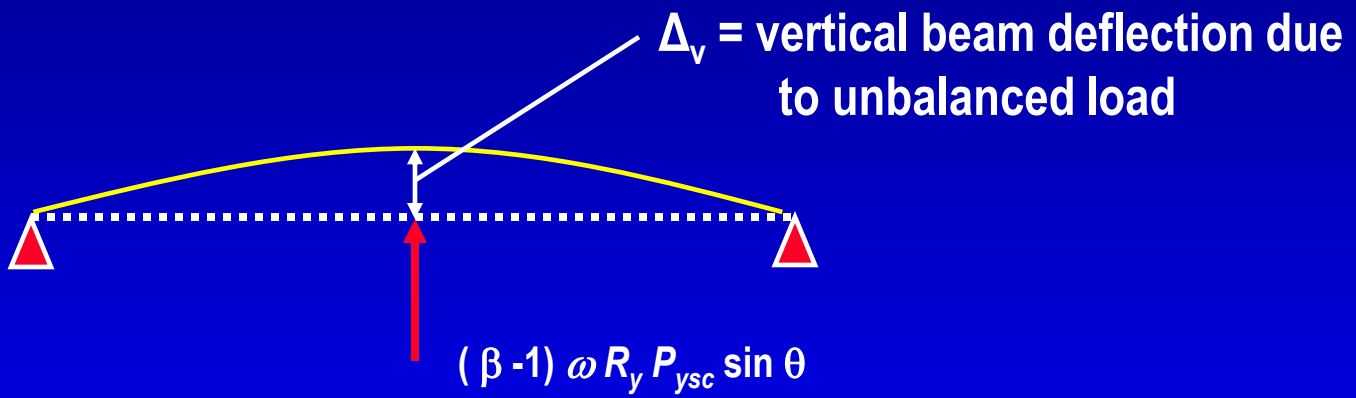


Beam-to-column connections: simple framing

Forces acting on beam:



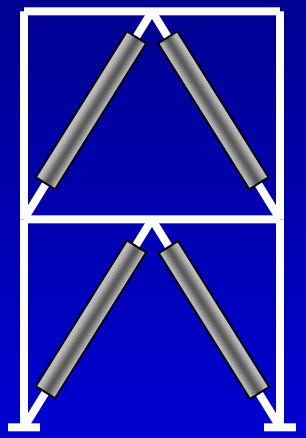
Beam deflection due to unbalanced loads:

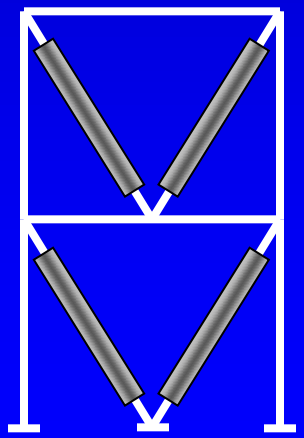


When testing braces per Appendix T: Include additional brace elongation resulting from vertical beam deflection when determining Δ_{bm}

16.4 Special Requirements Related to Bracing Configuration

For V-type and Inverted V-type bracing:





(2) Both flanges of beams must be provided with lateral braces to resist computed forces resulting from unbalanced brace forces. Design lateral braces per Appendix 6 of AISC *Specification*

Both flanges of the beam must be braced at the point of intersection of the braces.

16.5 Beams and Columns

16.5a Width-Thickness Limitations

Beam and column members shall meet the requirements of Section 8.2b.

Beams and Columns: Seismically Compact

$$b/t \leq \lambda_{ps}$$

16.5 Beams and Columns

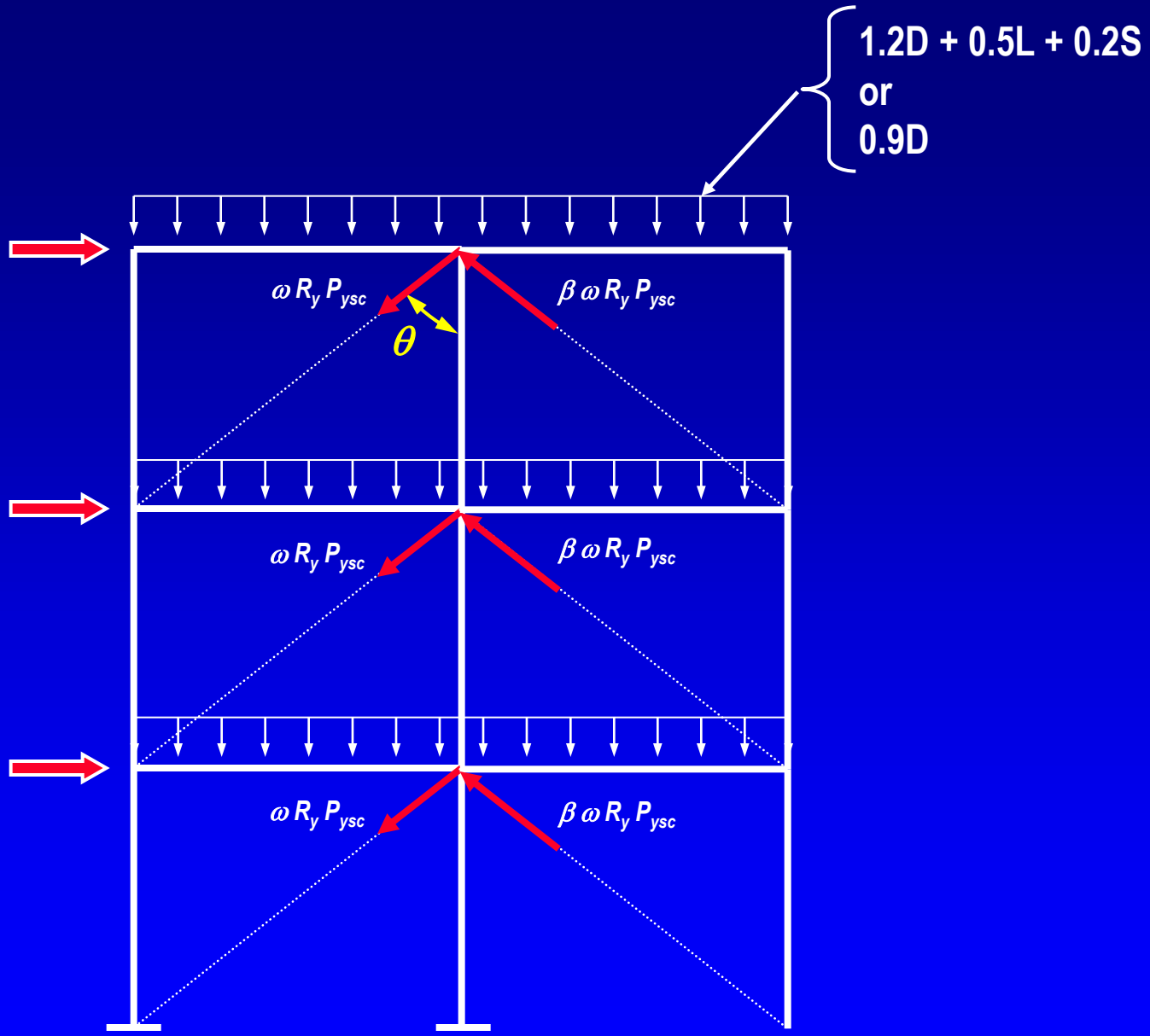
16.5b Required Strength

The *required strength* of beams and columns is determined from the **adjusted brace strengths** and factored gravity loads

1.2D + 0.5L + 02.S + E

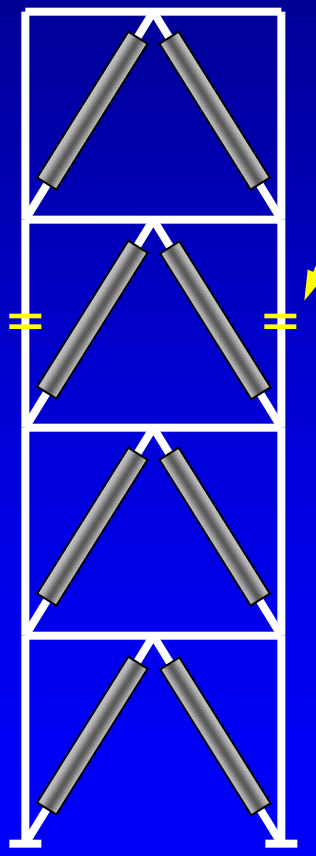
0.9D + E

⇨ "E" from adjusted brace strengths in tension and compression


1.2D + 0.5L + 0.2S
or
0.9D
$\omega R_y P_{ysc}$
$\beta \omega R_y P_{ysc}$
θ
$\omega R_y P_{ysc}$
$\beta \omega R_y P_{ysc}$
$\omega R_y P_{ysc}$
$\beta \omega R_y P_{ysc}$

16.5 Beams and Columns

16.5c Splices



Splice Requirements:

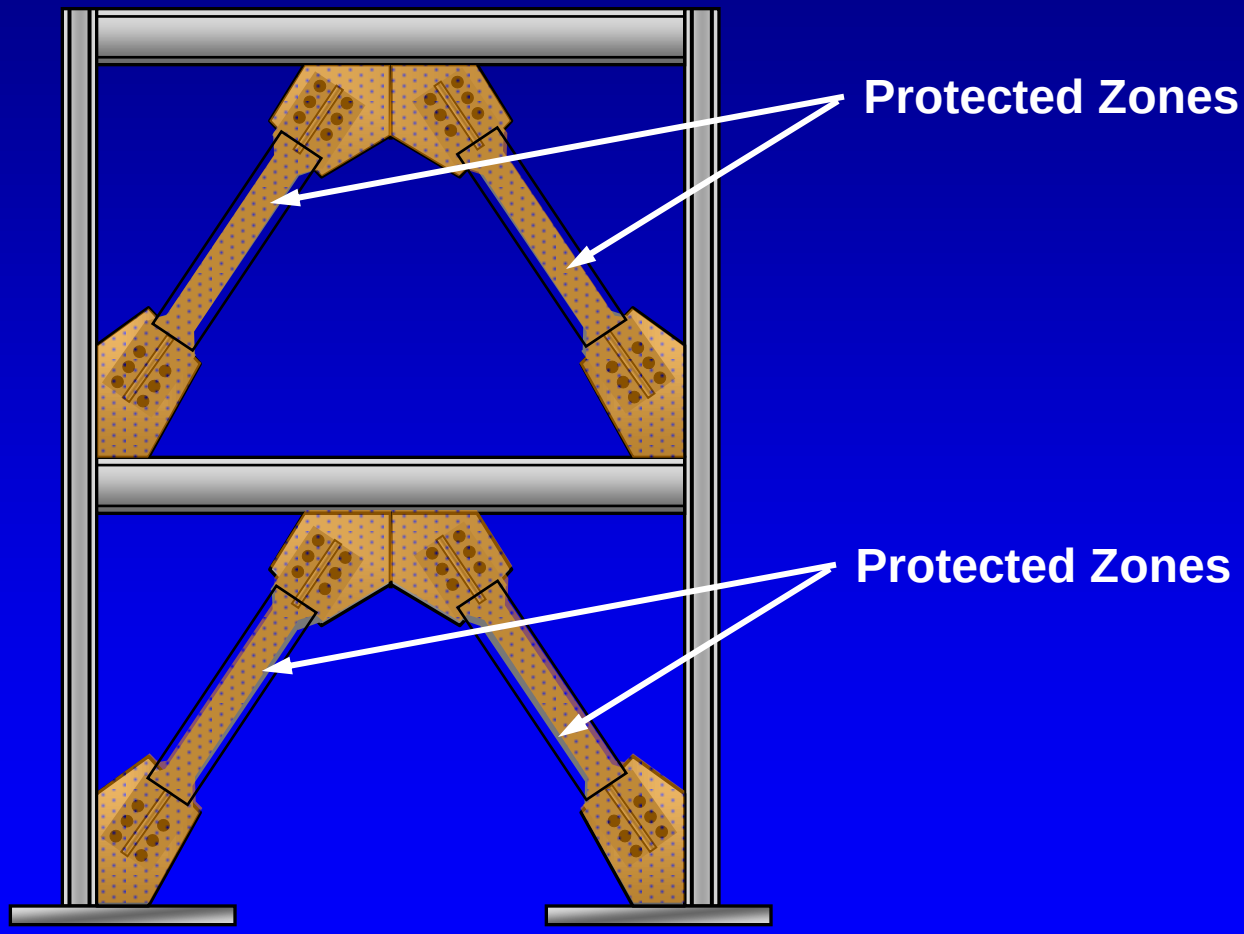
1. Satisfy requirements of Section 8.4
2. Required flexural strength = 0.5 x (0.9 M_{pc})
3. Required shear strength = $\Sigma M_{pc} / H$

16.6 Protected Zone

The **protected zone** shall include the steel core of bracing members and elements that connect the steel core to the beams and columns. These protected zones shall satisfy the requirements of Section 7.4.

No welded, bolted, screwed or shot in attachments for perimeter edge angles, exterior facades, partitions, duct work, piping, etc.

16.6 Protected Zone



Section 16 Buckling-Restrained Braced Frames (BRBF)

16.1 Scope

16.2 Bracing Members

16.3 Bracing Connections

16.4 Special Requirements Related to Bracing Configuration

16.5 Beams and Columns

16.6 Protected Zone