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Course Description

Session 3: Seismic Design of Braced Frames

March 5, 2018

This live webinar includes presentation of braced-frame configurations, discussion of behavior of braced frames in earthquakes and in testing and detailed treatment of brace behavior in tension and compression. The session provides an overview of configuration-related issues and discussion of the behavior of beam-column-gusset connection assemblies at large drifts and related design approaches. Lastly, treatment of design issues for gusset plates and connection analysis are presented.

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Learning Objectives

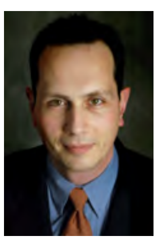
- Compare the various braced-frame configurations.
- Describe the behavior of brace members in both tension and compression.
- Describe the behavior of beam-column-gusset connection assemblies that ensure inelastic drift capacity.
- Describe the behavior of a BRBF and how it differs from an SCBF.

There's always a solution in steel.

Seismic Design in Steel: Concepts and Examples

Session 3: Seismic Design of Braced Frames

March 5, 2018



Rafael Sabelli, SE

structural STEEL

Course objectives

- Understand the principles of seismic design of steel structures.
- Understand the application of those principles to two common systems:
  - o Special Moment Frames
  - o Buckling-Restrained Braced Frames.
- Understand the application of design requirements for those systems.

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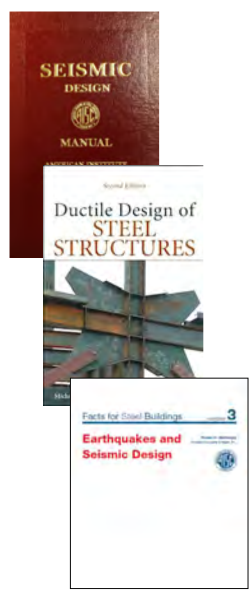
Resources



- AISC *Seismic Design Manual*
- *Ductile Design of Steel Structures*, Bruneau, Uang, and Sabelli, McGraw Hill.
- *Earthquakes and Seismic Design,* Facts for Steel Buildings #3. Ronald O. Hamburger, AISC.
- Other publications suggested in each session

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Other resources

- AISC Solutions Center
  - 866.ASK.*AISC* (866-275-2472)
  - Solutions@AISC.org
- AISC Night School
  - Nightschool@AISC.org

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Course outline

Part I: Concepts

1. Introduction to effective seismic design
2. Seismic design of moment frames
3. **Seismic design of braced frames**
4. Seismic design of buildings

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Course outline

Part II: Application

5. Planning the seismic design
6. Building analysis and diaphragm design
7. Design of the moment frames
8. Design of the braced frames

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Session 3: Seismic design of braced frames

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Session topics

- Braced-frame systems
- Special Concentrically Braced Frames
- Buckling Restrained Braced Frames
- Gusset connections
- Additional topics (time permitting)

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Braced-frame systems

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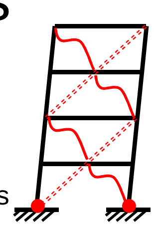
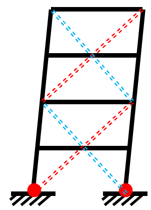
Braced frame systems

- Concentrically braced frames
  - o Special Concentrically Braced Frames
    - Inelastic drift through buckling & yielding of braces

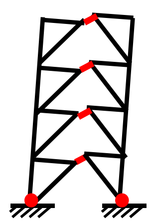


  - o Ordinary Concentrically Braced Frames
    - Limit inelastic drift demand through strength
    - Not covered in this course
  - o Buckling Restrained Braced Frames
    - Inelastic drift through yielding of brace cores



Braced frame systems

- Eccentrically braced frames
  - o Inelastic drift from yielding of link beam
  - o Not covered in this course



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Special Concentrically Braced Frames

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SCBF

- Inelastic drift through brace axial ductility
  - Tension yield
  - Compression buckling
- Braces sized for compression
  - High overstrength due to tension capacity
- Frame resistance due mostly to brace <u>tension</u> strength
- Braces must survive buckling and maintain tension strength
- Frame members designed for maximum brace forces
  - Prevents unfavorable modes of behavior

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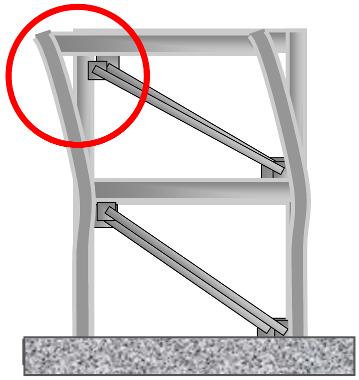
Post-Elastic Behavior

Unfavorable Modes: Connection Fracture



Connection fracture must not be the governing limit state.

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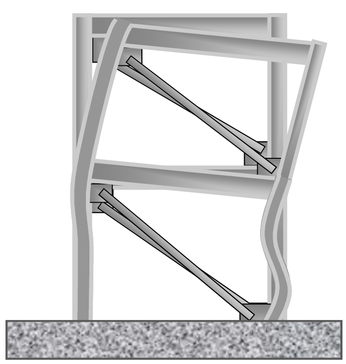
Post-Elastic Behavior

Unfavorable Modes: Column Buckling



Column buckling must not be the governing limit state.

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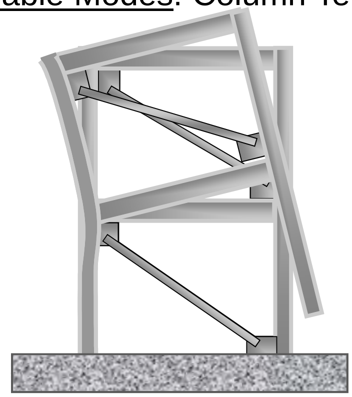
Post-Elastic Behavior

Unfavorable Modes: Column Tension Fracture



Column tension fracture must not be the governing limit state.

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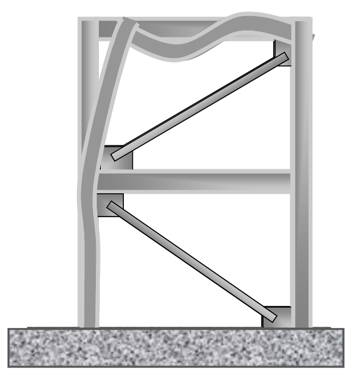
Post-Elastic Behavior

Unfavorable Modes: Beam Failure



Beam failure must not be the governing limit state.

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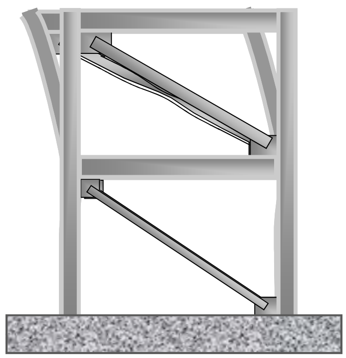
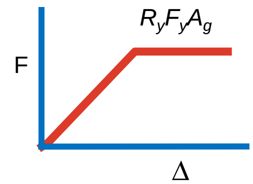
Post-Elastic Behavior

Preferred Modes: Brace Tension Yielding

Brace yielding should be a governing limit state.





Consider maximum effects due to brace force ($R_yF_yA_g$)

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Brace Elongation (Tension Only)

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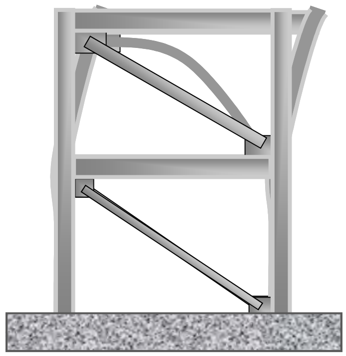
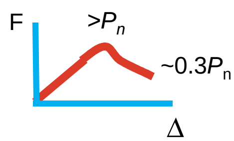
Post-Elastic Behavior

Preferred Modes: Brace Buckling (SCBF)

Brace buckling should be a governing limit state.





Consider maximum effects due to brace force (sometimes $P \sim R_y P_n$, sometimes $P \sim 0.3P_n$)

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Brace Buckling

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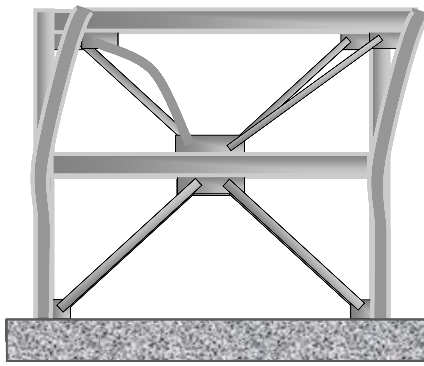
System Behavior with Brace Yielding

Column Flexure



Columns must bend when braces buckle and yield.

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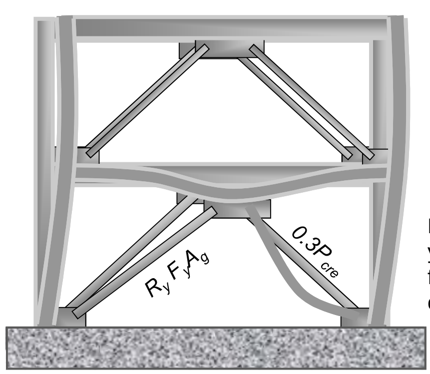
System Behavior with Brace Yielding

Beam Flexure



Brace buckling and yielding induce flexural forces in beams in this configuration.

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Design of SCBF

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Design of SCBF

- Force-based design
  - o Design for basic load combinations
  - o Size braces
- Design beams and columns for maximum forces from braces
  - o Consider expected strength
  - o Consider buckling behavior
  - o Plastic mechanism analysis

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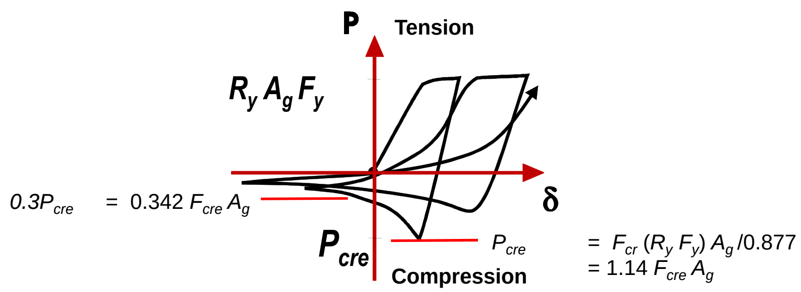
Brace cyclic behavior (SCBF)



Brace behavior is asymmetric with respect to tension and compression and is subject to strength and stiffness degradation

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Design of SCBF braces

- Limits
  - o Compactness limits
  - o Slenderness limits
- Pick/determine plane of buckling
  - o End fixity in each plane
  - o Brace shape (Kl/r in each axis)
- Accommodate buckling in plane of buckling
- Provide fixity in orthogonal plane

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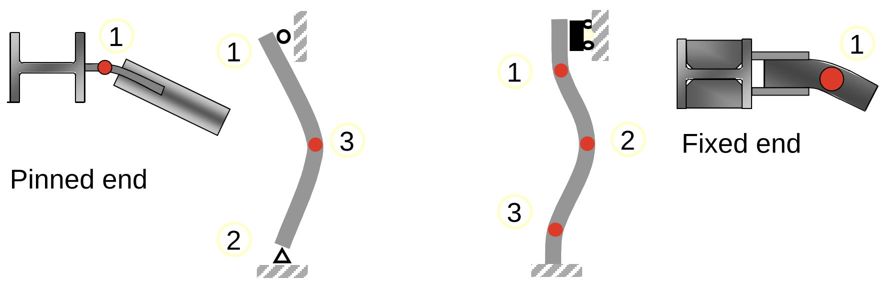
Brace Buckling

Flexural buckling (Compression)

Buckling: 3 hinges



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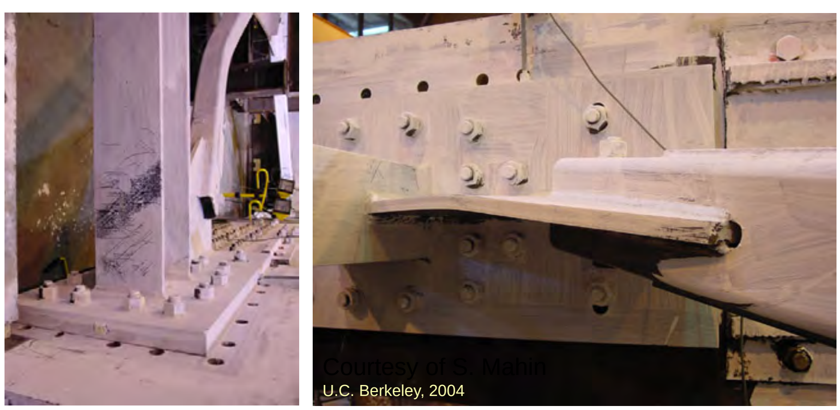
Pinned-End Gusset Hinging



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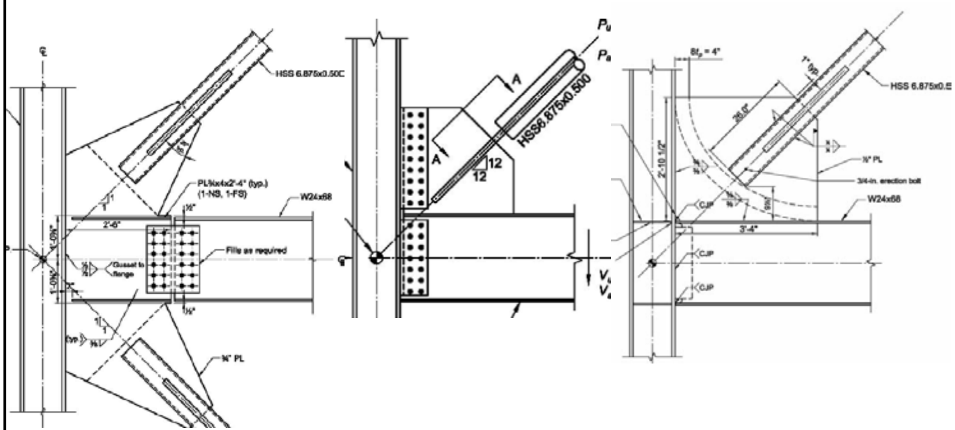
Accommodating buckling



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Fixed-End Brace Connection

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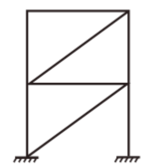
Configuration

- Single diagonal
  - o Unequal response in opposite directions
  - o Use in pairs
  - o AISC allows single diagonals
    - Design braces for $\Omega_o E$


Diagonal bracing

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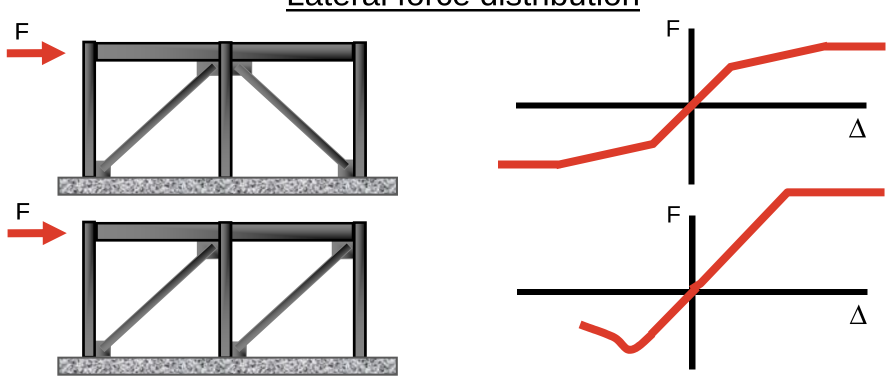
Bracing Members: Limitations

Lateral force distribution



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Buckling Restrained Braced Frames

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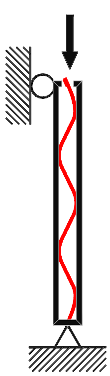
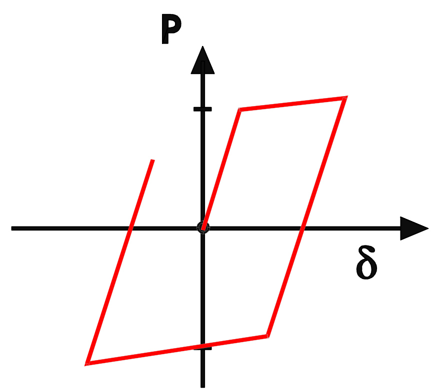
What is a Buckling-restrained Brace? Two Definitions

Stress resisted by steel core
Buckling resisted by sleeve



De-Coupled Stress and Buckling
(Mechanics Definition)



Balanced Hysteresis
(Performance Definition)

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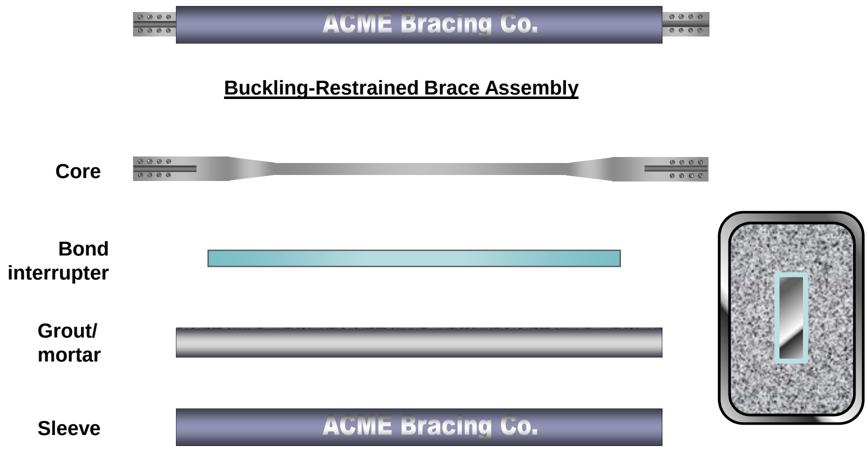
Buckling Restrained Braces



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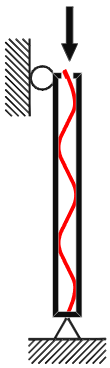
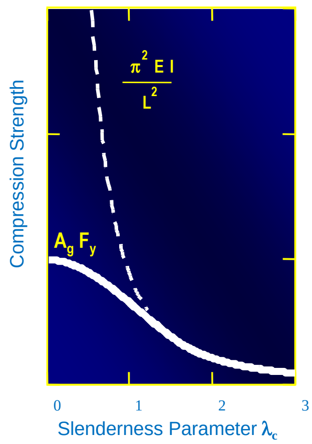
BRB Definitions Explained: Sleeved Column



Steel core achieves F_y

$^{kl}/_{r} \sim 0$

- Sleeve achieves $\pi^2 EI/L^2$
  - o Stress is zero
  - o No material stress limit



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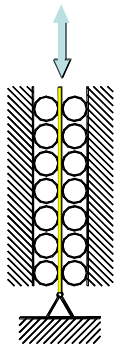
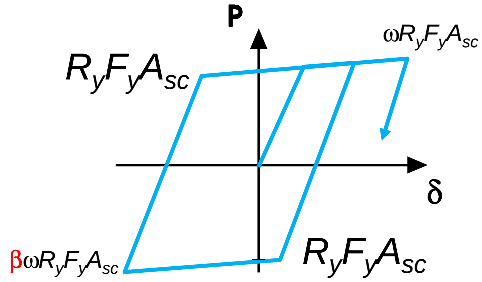
Buckling Restrained Braces





- Balanced Hysteresis
  - Slightly Stronger in Compression (β)
- Hysteretic Energy Dissipation
- Hysteretic Stability
  - Strength
  - Stiffness
- Long Fracture Life

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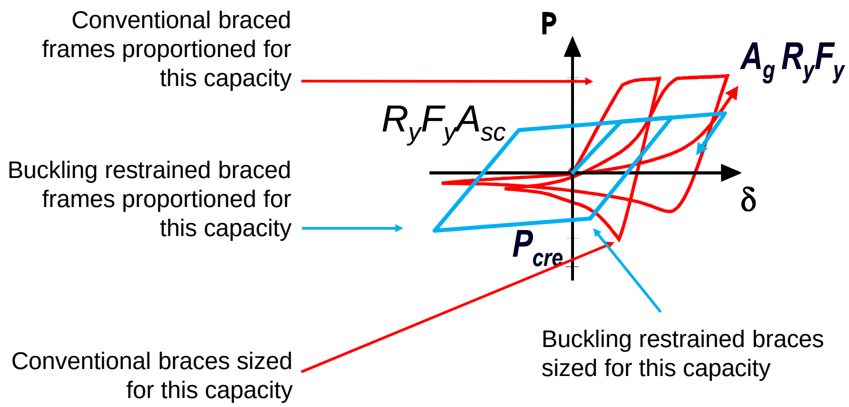
Capacity design



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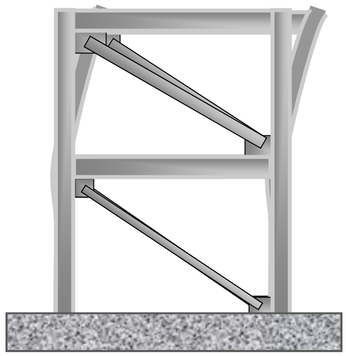
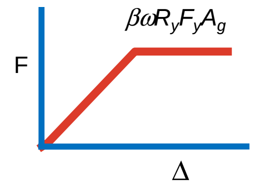
Post-Elastic Behavior

<u>Preferred Modes</u>: Brace Compression Yielding (BRBF)

Brace yielding should be a governing limit state.





Consider maximum effects due to brace force ($\beta\omega R_y F_y A_g$)

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Buckling-Restrained Brace Types

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Buckling-Restrained Brace Types

Direct bolting of core

Courtesy of CoreBrace

Courtesy of STAR Seismic

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Design of Buckling Restrained Braced Frames

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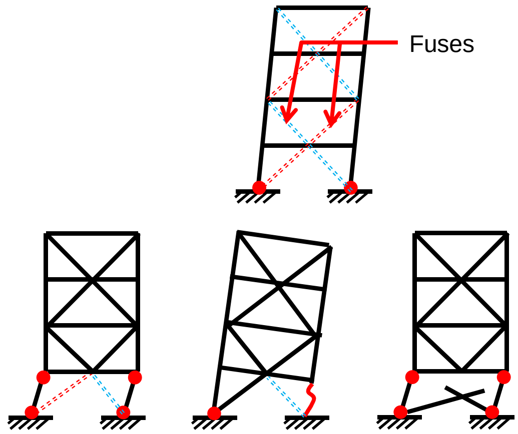
Design of Buckling Restrained Braced Frames

- Encourage
  - o Yielding of braces
- Avoid
  - o Flexural hinging in columns (story mechanisms)
  - o Buckling of beams or columns
  - o Connection failure



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Fuse concept

- Select appropriate fuses
  - o BRBs!
- Size fuses to
  - o Provide adequate strength
  - o Control drift
- Consider maximum fuse capacity as load on other members
  - o Capacity design
  - o Precludes undesirable mechanisms

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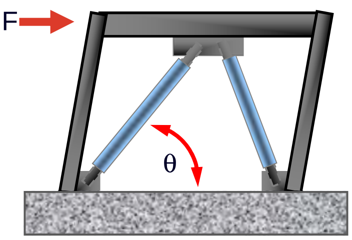
Force-based design

$$P_u = \frac{F}{2\cos\theta}$$

- Assume braces resist 100% of story shear F



$$A_{sc} = \frac{P_u}{\phi F_y}$$

Design braces precisely to calculated capacity ($P_u = \phi P_n = \phi F_y A_{sc}$)

Do not include gravity load

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Brace demands on frame

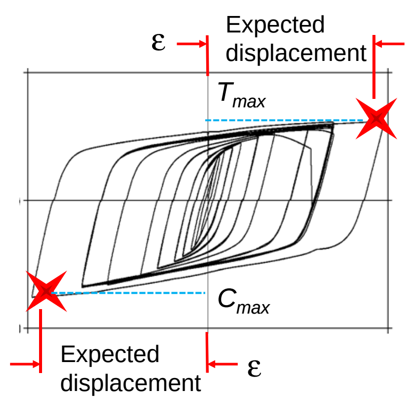
- Estimate fuse capacity
  - o Expected material strength
  - o Strain hardening
- Based on testing

Calculate deformation

$$\Delta_{bm} = \Delta \cos(\theta)$$

$$\Delta = 2\%\, h$$

$$\varepsilon = \Delta_{bm} / L_y$$



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Brace demands on frame

- Based on testing

  $\omega = T_{max}/A_g F_y$

  Typical $1.3 \leq \omega \leq 1.5$

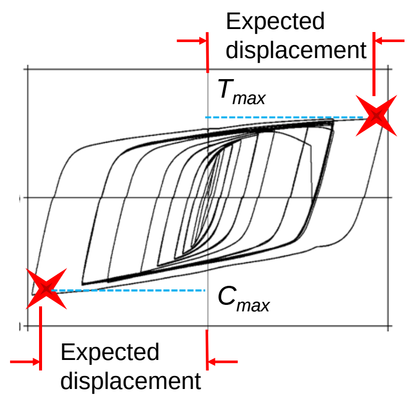
  $\beta\omega = C_{max}/A_g F_y$

  Typical $1.1 \leq \beta \leq 1.25$

- For design

  $R_{u\ (tension)} = \omega A_g R_y F_y$

  $R_{u\ (compression)} = \beta\omega A_g R_y F_y$



AISC 341 F4.3

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Analysis: brace stiffness

- Braces are non-prismatic
  - o Stiffness depends on
    - Core area (proportional to strength)
    - Length of yielding core
      - o Connection length required
        - Varies with brace type
        - Varies with brace strength
      - o Varies with configuration
        - Shorter for chevron than for single-diagonal

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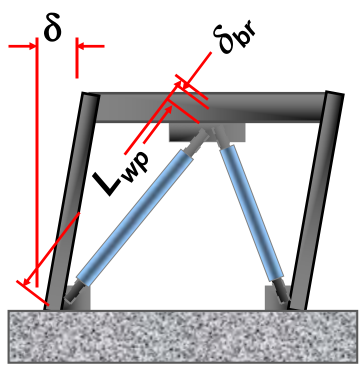
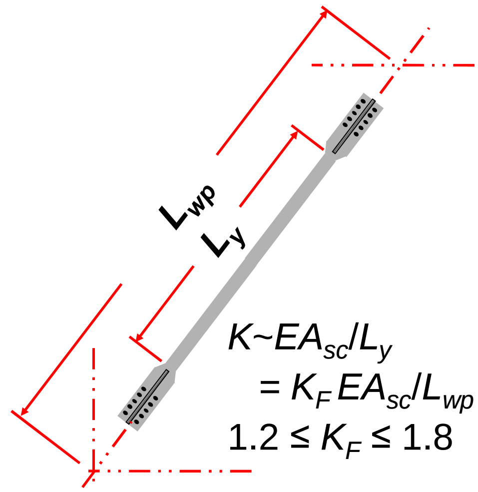
Analysis: brace stiffness



$\varepsilon \sim (\delta_{br}/L_{wp})(L_{wp}/L_y)$



$K \sim EA_{sc}/L_y$

$= K_F EA_{sc}/L_{wp}$

$1.2 \leq K_F \leq 1.8$

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Plastic mechanism analysis

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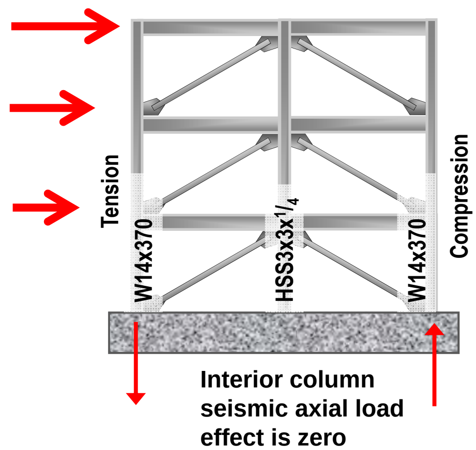
What elastic analysis misses



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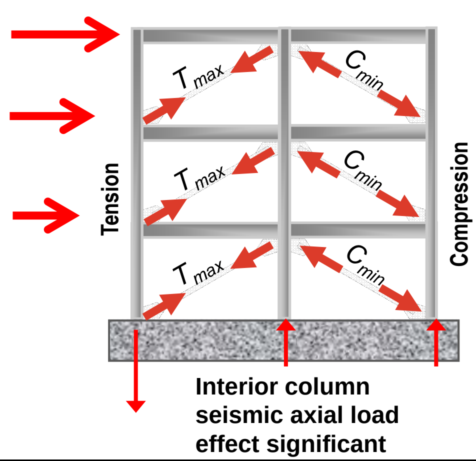
What elastic analysis misses



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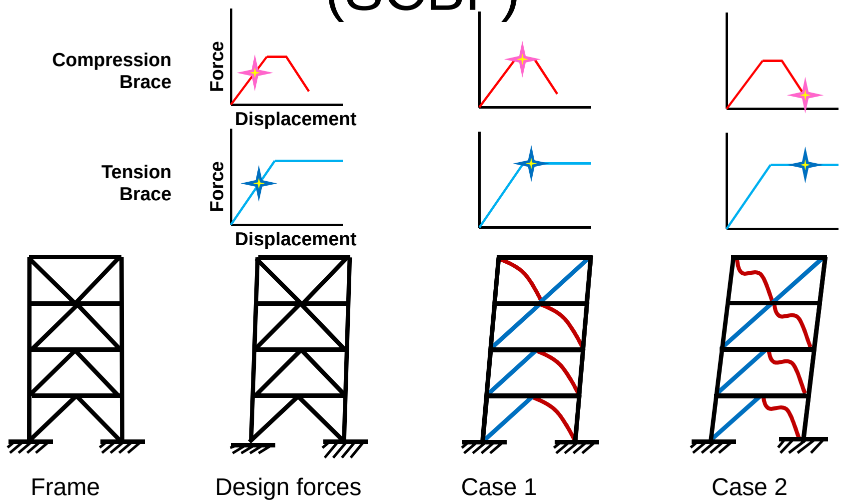
Plastic mechanism analyses (SCBF)



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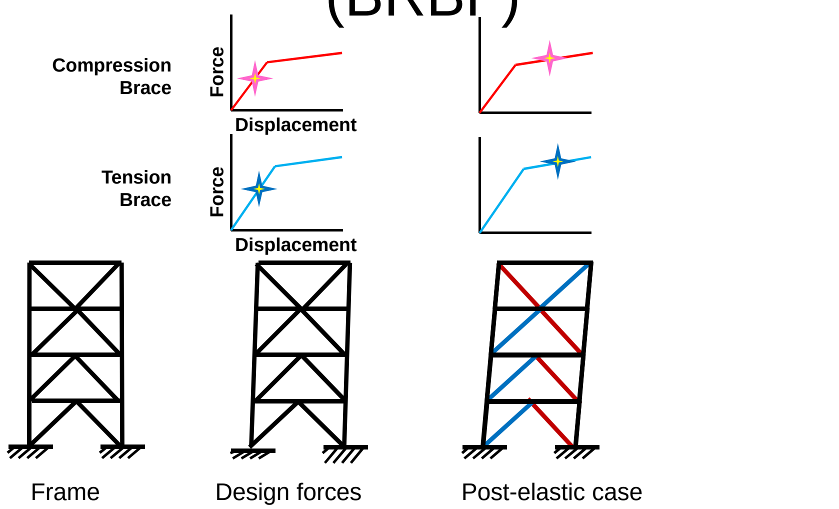
Plastic mechanism analyses (BRBF)



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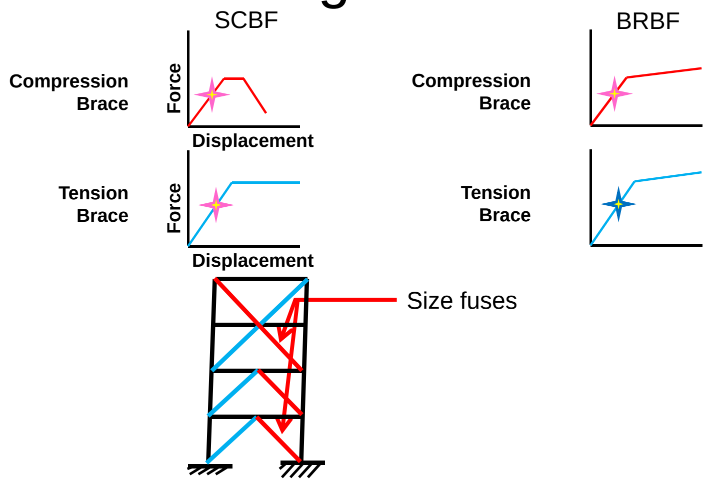
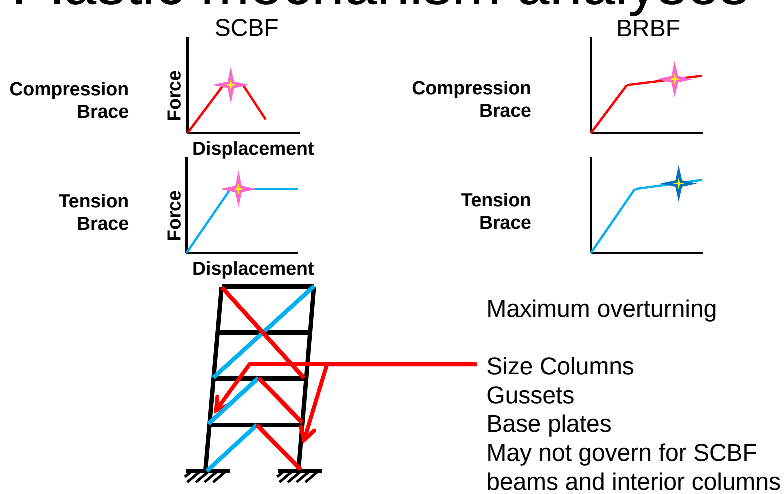
Design forces



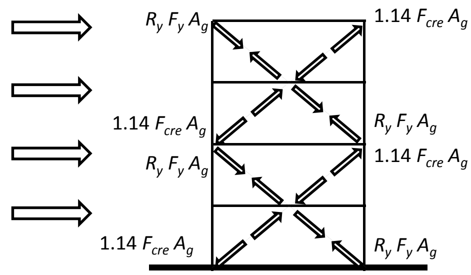
Design forces

Plastic mechanism analyses



Condition 1 (SCBF and BRBF)

Plastic mechanism analyses



If 1.14 $F_{cre} A_g > R_y F_y A_g$
Use $R_y F_y A_g$

Case 1

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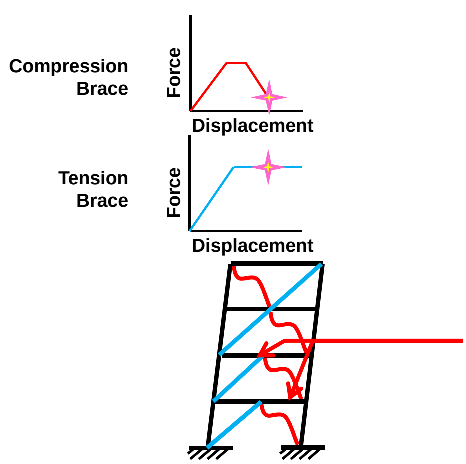
Plastic mechanism analyses



Force redistribution:
Compression braces participate less
Force zig-zags

Size beams &
Interior columns

Condition 2 (SCBF only)

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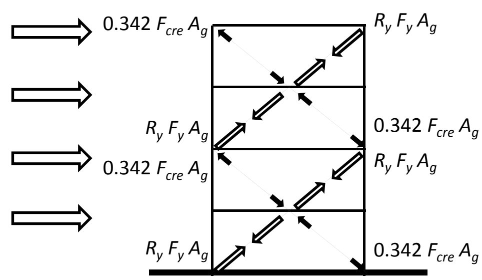
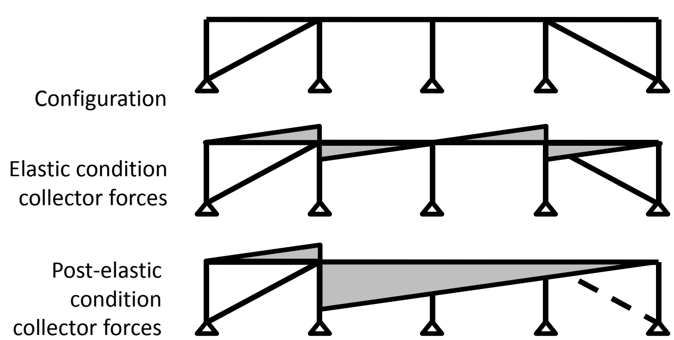
Plastic mechanism analyses



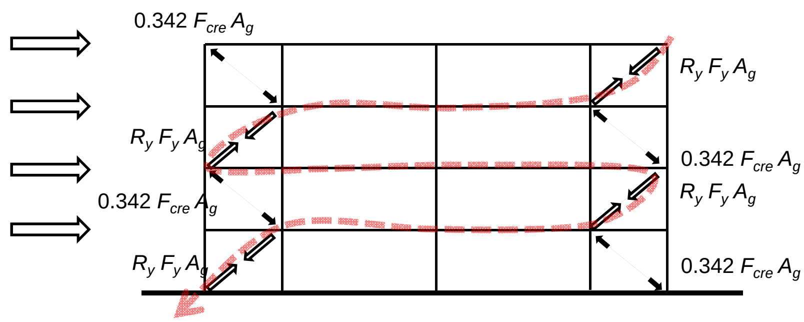
Case 2 (SCBF)

Layout

- Post-elastic offsets



Plastic mechanism analyses



Case 2 Load Path

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Temperature method of mechanism analysis

Equivalent to imposing strain

Redefine brace material properties

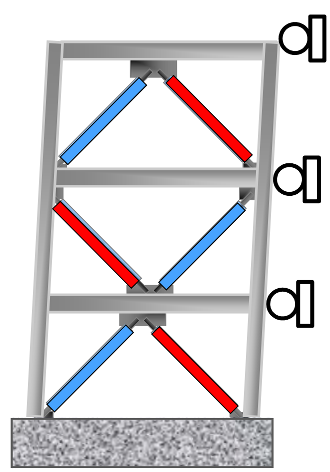
- $\alpha = 1^{in.}/_{in.}/8F$
- $E = 1$ ksi

Apply temperature to braces:

- T = $-\ \omega R_y F_y$ 8F/ksi
  - ($R_y F_y$ 8F/ksi [SCBF])
- C = $\omega\beta R_y F_y$ 8F/ksi
  - (1.14 F_{cre} 8F/ksi [SCBF case1])
  - (0.342F_{cre} 8F/ksi [SCBF case 2])

Restrain lateral movement

Analyze



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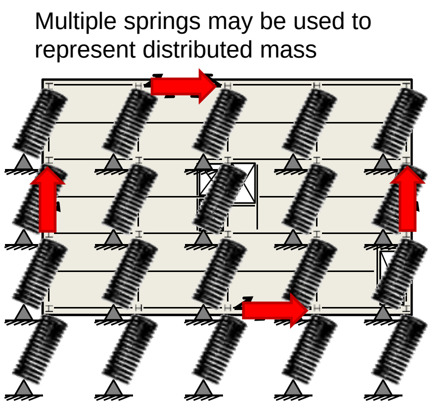
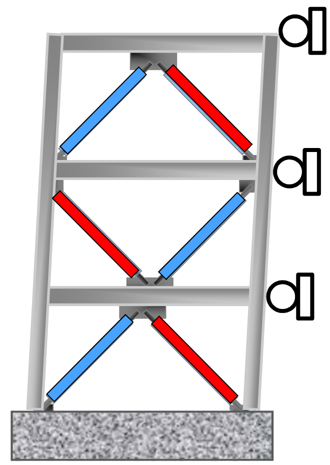
Temperature method of mechanism analysis





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There's always a solution in steel.

Connections

structural STEEL

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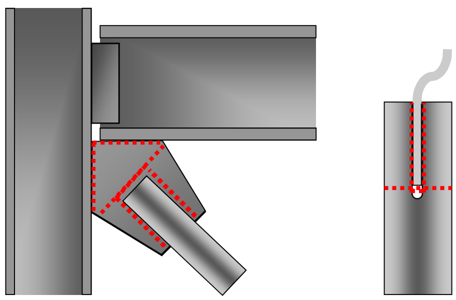
Connection limit states

Connections: Brace End



Brace net section fracture

Brace block shear fracture

Brace-to-gusset weld fracture

Gusset block shear fracture

Gusset tension yield or fracture

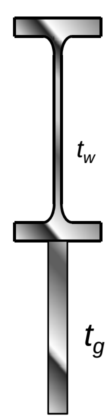
Gusset or weld failure at column

Gusset or weld failure at beam

Gusset buckling

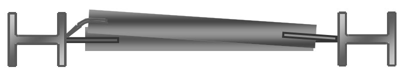
Connection limit states

- Web proportioning
  - o Where thick gussets are required thin webs may be inadequate
  - o Research ongoing
  - o Check web local yielding
  - o Rule of thumb:
    - $t_w \geq ¾\, t_g$

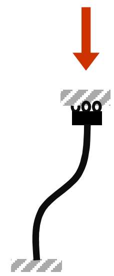


Connection limit states

Connections: Brace End



Gusset buckling



Refer to AISC Design Guide 29
gusset K factors

Gusset design

TECHNICAL NOTE

Effective Length Factors for Gusset Plates in Chevron Braced Frames

ENGINEERING JOURNAL / THIRD QUARTER / 2012

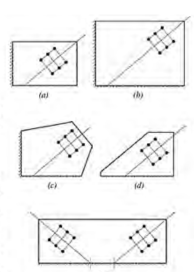


Table 3. Summary of Proposed Effective Length Factors[a]

Gusset Configuration	Effective Length Factor	Buckling Length
Compact corner	—[b]	—[b]
Noncompact corner	1.0	l_{avg}
Extended corner	0.6	l_1
Single brace	0.7	l_1
Chevron	0.65	l_1

[a] Table 7 from Dowswell (2006) with revisions.
[b] Yielding is the applicable limit state for compact corner gusset plates; therefore, the effective length factor and the buckling length are not applicable.

Connection Instability

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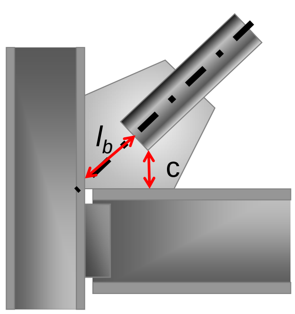
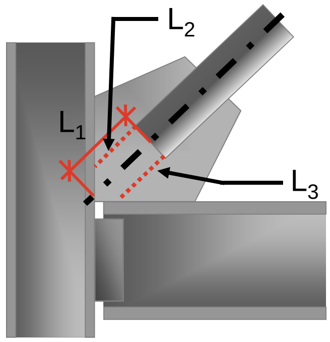
Connections: Compression



if $t_\beta < t_g$, the gusset will yield before it buckle (Dowswell, 2006)

$$t_\beta = 1.5\sqrt{\frac{F_y c^2}{E l_b}}$$

Connections: Compression



if $t_\beta > t_g$, K = 0.6 (Dowswell, 2006) for conventional braces

Dowswell (2006)

3 Options (all reasonably reliable)

L = Ave (L)?

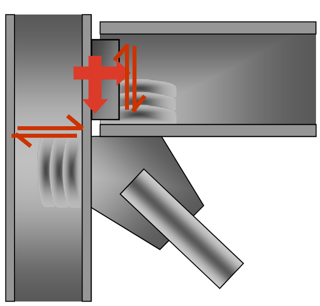
L = Max (L)?

L = ℄ (L)?

Effective length for BRB gussets is longer; consult with manufacturer

Connection limit States

Connections: Brace End



- Column web yielding
- Column web crippling
- Column web shear
- Beam web yielding, crippling, shear
- Beam-column connection, shear
- Beam-column connection, axial

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Beam Instability

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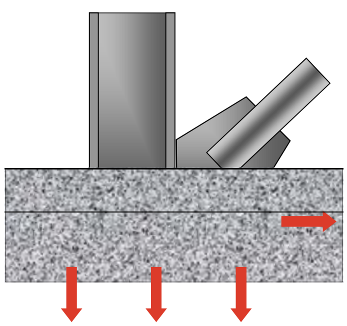
Base-plates

Connections: Base Plate



Shear

Tension

Resistance to horizontal and vertical force components must be provided. Different mechanisms (with different limit states) can be used.

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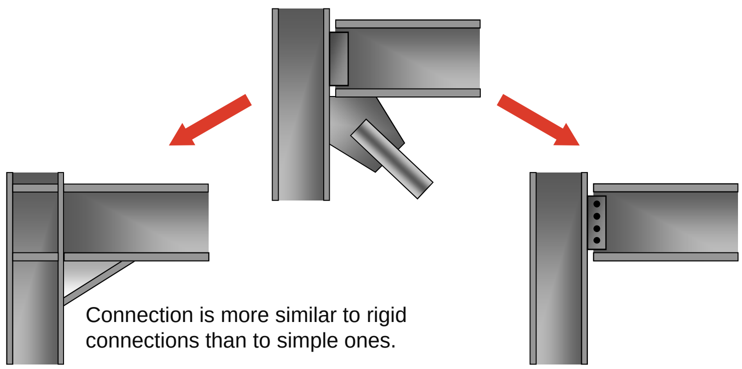
Fixity of gusset connections

Flexure: Connection Fixity



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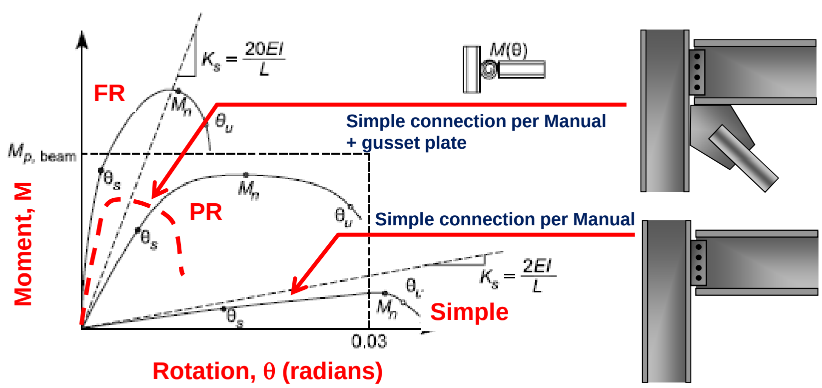
Rotation in gusseted beam-column connections



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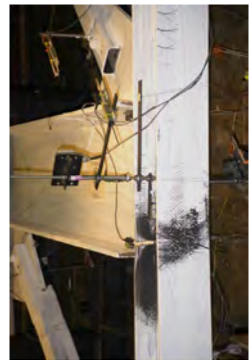
Rotation in gusseted beam-column connections

- UC Berkeley testing (and other testing) showed inability of simple+gusset connections to withstand large rotations



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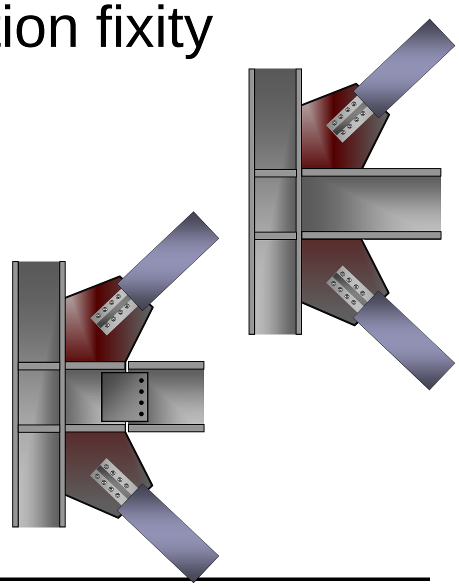
Connection fixity

- Ductile moment frames provide extra resistance
  - o Lateral strength and stiffness
  - o Resistance to story mechanisms
- Ductile moment connections difficult to achieve



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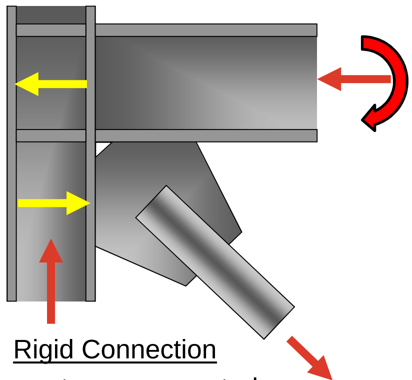
Method of accommodating frame rotations



Connection strength exceeds beam strength

Rigid Connection

Moments are accounted for in design

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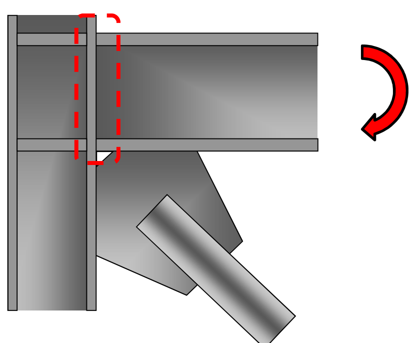
Method of accommodating frame rotations



Connection consists of Ordinary Moment Frame (OMF) connection, plus gusset

Rigid Connection

Moments are implicitly accounted for

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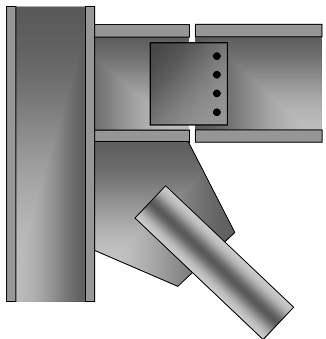
Method of accommodating frame rotations



Connection typically provides rotation by means similar to shear connections in AISC manual

2.5% rotation required

Flexible Connection

Rotations are accommodated

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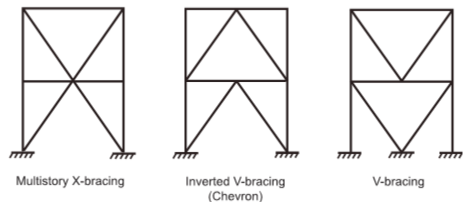
There's always a solution in steel.

Additional topics

structural STEEL

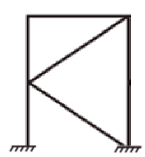
Configuration

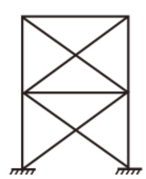
- Chevron
  - o V or inverted-V
  - o Formerly known as "K"
    - Until 1970s.
  - o Two-story X
  - o Post-elastic vertical forces on beams



Configuration

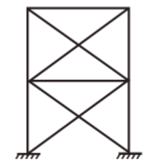
- K
  - o Post-elastic horizontal forces on columns
  - o Prohibited
- Tension-only braces
  - o Only allowed in OCBF

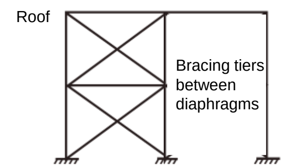




Configuration

- Cross bracing
  - o Tension-compression
  - o Increased (concentrated) brace ductility demand
  - o Half-length can be used
  - o Not possible for BRBF
- Multi-tiered braced frames
  - o AISC 341-16 has special provisions





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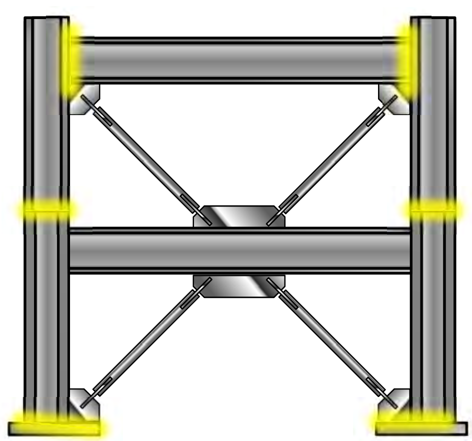
Demand critical welds



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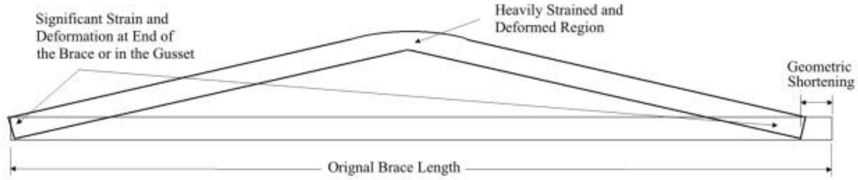
Detailing & Constructability

- Buckling deformation
- Interaction with architecture
- Protected zones
- Brace connection tolerances
- Direct-welded brace connections

SCBF 95

Buckling deformation (SCBF)

- 10% of brace length should be considered
- Provide clear zone.



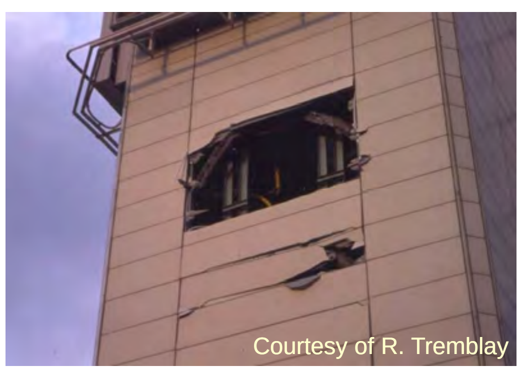
SCBF 96

Interaction with architecture (SCBF)

- Braces concealed in walls
  - o Allow for brace buckling
    - Double walls for in-plane buckling
  - o Allow gussets to flex or fold where required to accommodate brace buckling
    - Composite deck
    - Ground-floor slabs

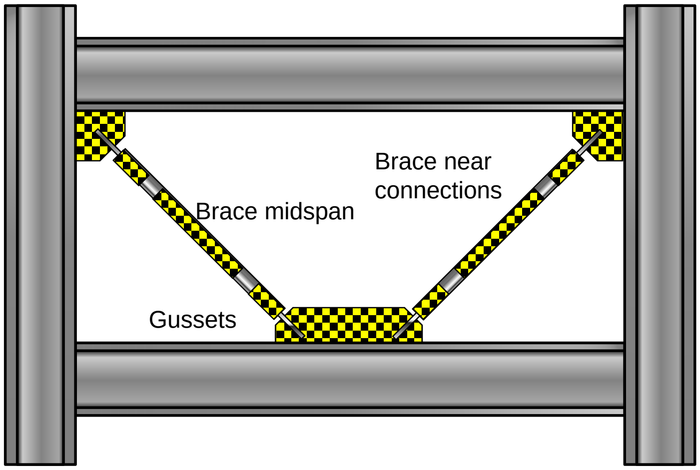
SCBF 97

Brace Buckling: Effect on Other Elements



SCBF 98

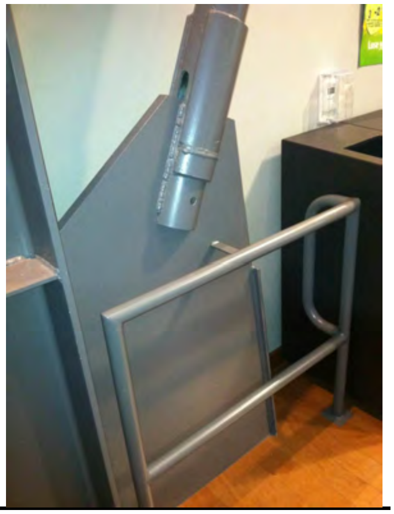
Protected zones (SCBF)



SCBF 99

Protected zones

- Areas of anticipated inelastic strain
- Attachments prohibited
  - o Assumed to create fracture-initiation points
- Area of ongoing research



SCBF 100

Brace connection tolerances

- Oversize holes
  - AISC requires design for overstrength factor Ω_o
- Slots
  - $^1/_8$" wider than plate
  - 2" longer than final position
    - Assume erectors may position brace min. 1" off
      - Sufficient lap with gusset for weld, block shear
      - Sufficient reinforcement length in assumed final position

SCBF 101

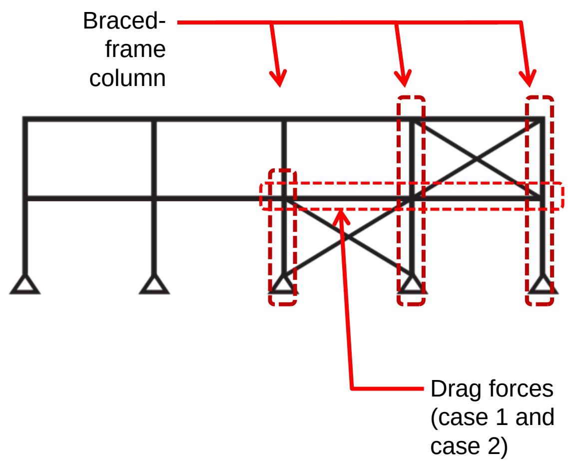
HSS availability

- A500
  - Material is often dual certified
    - Grade B/Grade C
  - Grade C is preferred
  - Many round shapes published but only available in mill quantities
    - Check AISC website
    - Service centers
- New ASTM A1085
  - R_y=1.25

SCBF 102

Configuration

- Overturning



SCBF 103

SCBF Connections in the AISC Seismic Design Manual

- F2.6b: Provide a beam-to-column connection which is fixed or allowed to rotate
- F2.6c(3): Accommodate brace buckling

Example	Method of complying with AISC *Seismic Provisions* Section F2.6b	Method of complying with AISC *Seismic Provisions* Section F2.6c(3)
5.3.10	Detailed to provide rotation per Section F2.6b(a)	Linear hinge zone
5.3.11	Detailed as FR connection per Section F2.6b(b)(i)	Elliptical hinge zone
5.3.12	Designed to resist moments per Section F2.6b(b)	Hinge plate for in-plane brace buckling
		Fixed-end brace connection

SCBF 104

Direct-welded connections

- Provide full brace strength
- Provide fixity in both planes
  - o Provide load path for brace-buckling fixed-end moments
- Investigate all geometrical conditions

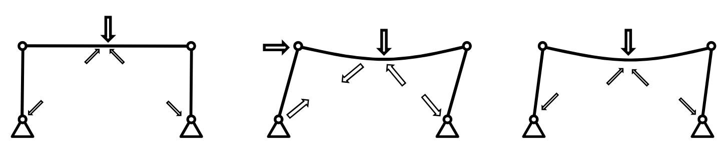
SCBF 105

Gravity forces in BRBs

Gravity Forces in Braces

Neglect

Effective tension and compression strength will be equal for subsequent cycles



Gravity load applied
Braces compress

Lateral load applied
Braces yield
Compression 1st?
Tension brace pulls down

Lateral load released
Beam pulls up and gravity load pushes down
Braces compressed
$\frac{1}{2}(\beta-1)\,\omega R_y A_{sc} F_y$

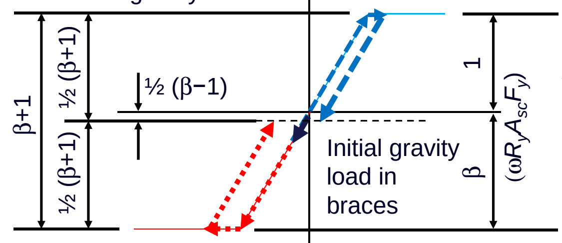
BRBF 106

Gravity forces in BRBs

Gravity Forces in Braces

Neglect

Effective tension and compression strength will be equal for subsequent cycles



Same unloading stiffness for both braces

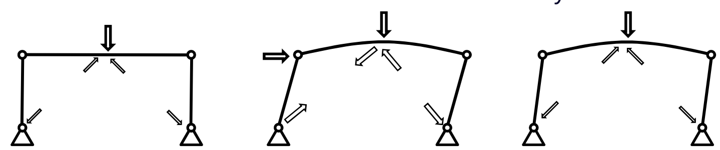
BRBF 107

Gravity forces in BRBs

Gravity Forces in Braces

Neglect

Effective tension and compression strength will be equal for subsequent cycles



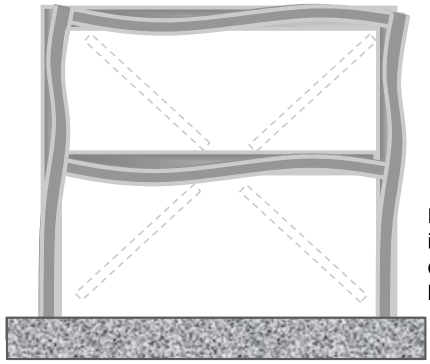
Gravity load applied
Braces compress

Lateral load applied
Braces yield
Tension 1st?
Compression brace pushes up

Lateral load released
Beam and gravity load push down
Braces compressed
½ (β-1) $\omega R_y A_{sc} F_y$

BRBF 108

Frame Participation



Flexural forces are induced in rigidly-connected columns and beams due to drift.

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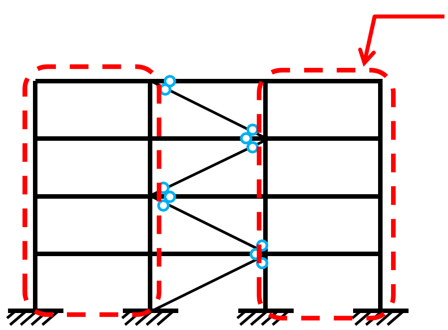
Connection fixity



If moment frames are needed, consider locating them in bays that are free of braces

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There's always a solution in steel.

Summary

structural
STEEL

Summary

- Braces provide inelastic drift through brace axial ductility
- SCBF braces yield in tension and buckle in compression
- BRBF braces have a core that yields in tension and compression
- OCBF limit inelastic demand thorough higher strength
- Gusset-plate detailing and proportioning is necessary to ensure inelastic drift capacity

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There's always a solution in steel.

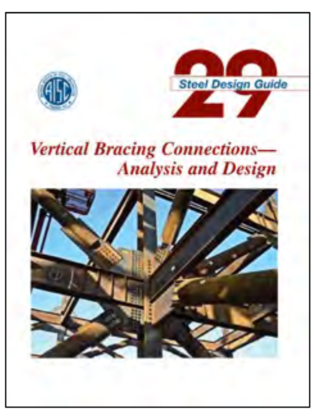
End of session 2

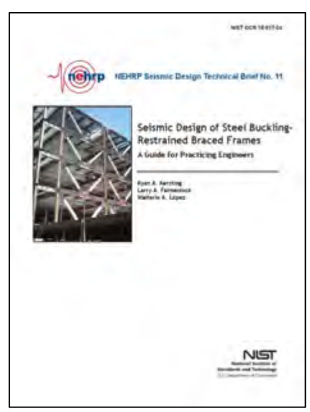
Next:

Seismic design of buildings

structural STEEL

Additional resources





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Question time

structural STEEL

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!

Individual Webinar Registrants

CEU/PDH Certificates

Within 2 business days…

- New reporting site (URL will be provided in the forthcoming email).
- Username: Same as AISC website username.
- Password: Same as AISC website password.

8-Session Registrants

CEU/PDH Certificates

One certificate will be issued at the conclusion of all 8 sessions.

8-Session Registrants

Access to the quiz: Information for accessing the quiz will be emailed to you by Wednesday. 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.

8-Session Registrants

Access to the recording: Information for accessing the recording will be emailed to you by this Wednesday. The recording will be available for three weeks. For 8-session registrants only. EMAIL COMES FROM NIGHTSCHOOL@AISC.ORG.

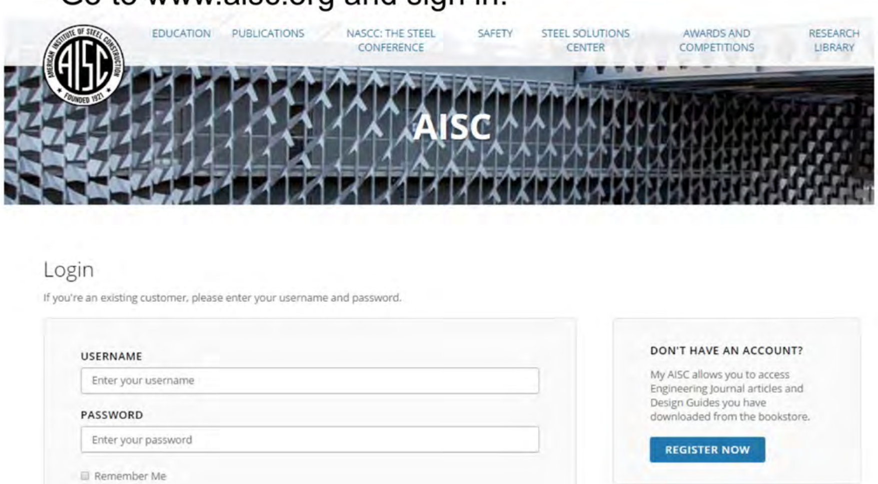
CEUs/PDHS – If you watch a recorded session you must take AND PASS the quiz for CEUs/PDHs.

Night School Resources for 8-session package Registrants

Find all your handouts, quizzes and quiz scores, recording access, and attendance information all in one place!

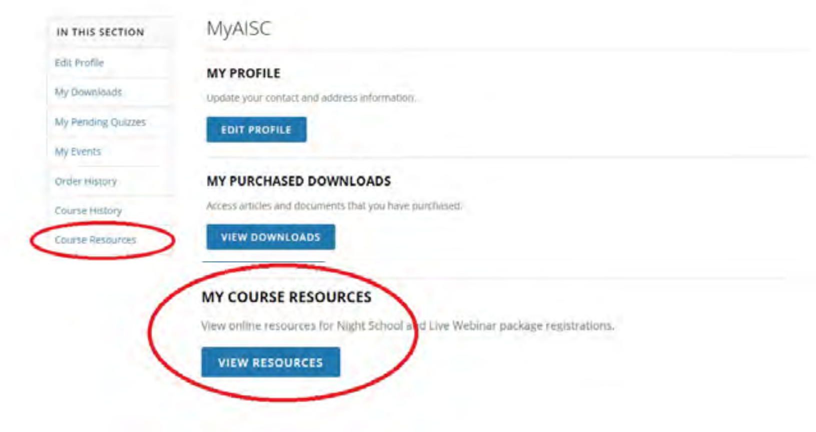
Night School Resources for 8-session package Registrants

Go to www.aisc.org and sign in.

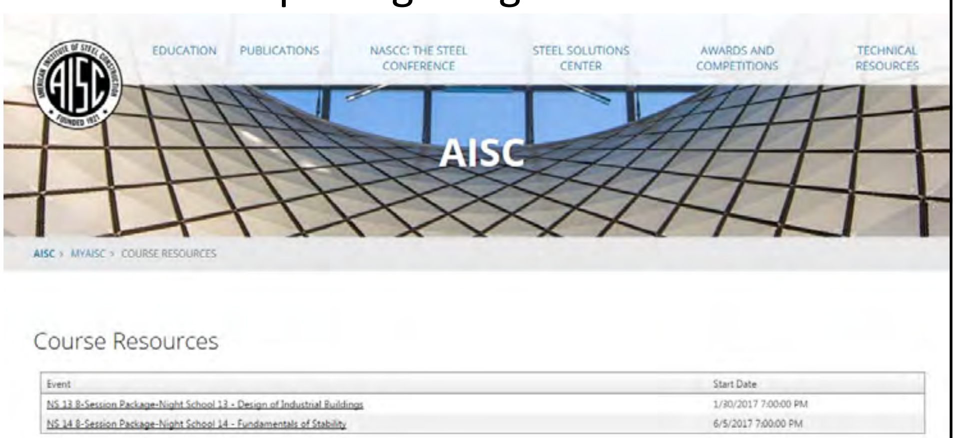


Night School Resources for 8-session package Registrants

Go to www.aisc.org and sign in.



Night School Resources for 8-session package Registrants



Night School Resources for 8-session package Registrants

Night School 13: Design of Industrial Buildings

8-SESSION PACKAGE RESOURCES

Event	Date	Handouts	Video	Quiz	Attendance
NS13 - Design Criteria	1/30/2017 7:00:00 PM	Handouts	View Passcode: NS13DSN	Pass Score: 80	Pending
NS13 - Economic Considerations	2/6/2017 7:00:00 PM	Handouts	Available 02/08/2017 5pm EST	Available 02/08/2017 5pm EST	Pending
NS13 - Lateral Load Systems and Details	2/13/2017 7:00:00 PM	Handouts	Available 02/15/2017 5pm EST	Available 02/15/2017 5pm EST	Pending
NS13 - Preliminary Design Procedures	2/27/2017 7:00:00 PM	Handouts	Available 03/01/2017 5pm EST	Available 03/01/2017 5pm EST	Pending
NS13 - Crane Girder Design and Frame Analysis	3/6/2017 7:00:00 PM	Handouts	Available 03/08/2017 5pm EST	Available 03/08/2017 5pm EST	Pending
NS13 - Frame Member and Connection Design	3/13/2017 7:00:00 PM	Handouts	Available 03/15/2017 5pm EST	Available 03/15/2017 5pm EST	Pending
NS13 - Transfer Crane Girder & Longitudinal Bldg Bracing Dsn	3/27/2017 7:00:00 PM	Handouts	Available 03/29/2017 5pm EST	Available 03/29/2017 5pm EST	Pending
NS13 - Building Envelope and Bracing Design	4/3/2017 7:00:00 PM	Handouts	Available 04/05/2017 5pm EST	Available 04/05/2017 5pm EST	Pending
NS13 - Final Exam	4/10/2017 7:00:00 PM			Available 04/12/2017 5pm EST	

Night School Resources for 8-session package Registrants

- Weekly "quiz and recording" email.
- Weekly updates of the master Quiz and Attendance record found at www.aisc.org/nightschool. Scroll down to Quiz and Attendance records.
  - Updated on Tuesday mornings.

Night School Resources for 8-session package Registrants

- Webinar connection information:
  - Found in your registration confirmation/receipt.
  - Reminder email sent out Monday mornings.
- Link to handouts also found here.

There's always a solution in steel.

Thank You

Please give us your feedback!
Survey at conclusion of webinar.

structural STEEL