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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.





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



Course objectives

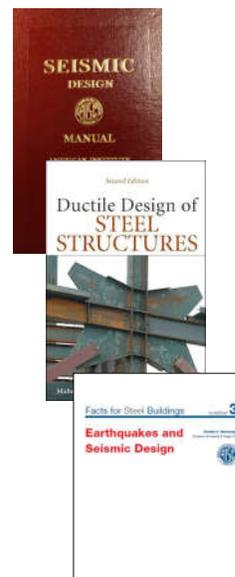
- Understand the principles of seismic design of steel structures.
- Understand the application of those principles to two common systems:
 - Special Moment Frames
 - Buckling-Restrained Braced Frames.
- Understand the application of design requirements for those systems.



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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



Session topics

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



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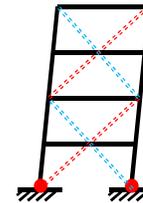
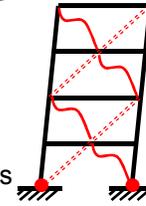
Braced-frame systems

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Braced frame systems

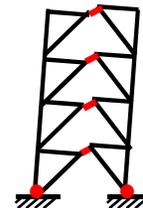
- Concentrically braced frames
 - Special Concentrically Braced Frames
 - Inelastic drift through buckling & yielding of braces
 - Ordinary Concentrically Braced Frames
 - Limit inelastic drift demand through strength
 - Not covered in this course
 - Buckling Restrained Braced Frames
 - Inelastic drift through yielding of brace cores



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Braced frame systems

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



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Special Concentrically Braced Frames



SCBF

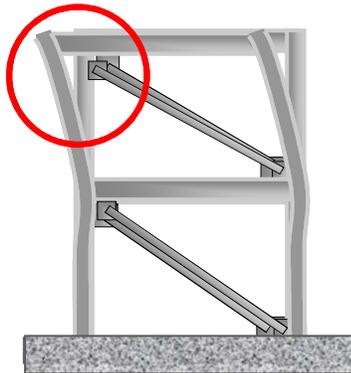
- Inelastic drift through brace axial ductility
 - Tension yield
 - Compression buckling
- Braces sized for compression
 - High overstrength due to tension capacity
- Frame resistance due mostly to brace tension strength
- Braces must survive buckling and maintain tension strength
- Frame members designed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



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Post-Elastic Behavior

Unfavorable Modes: Connection Fracture

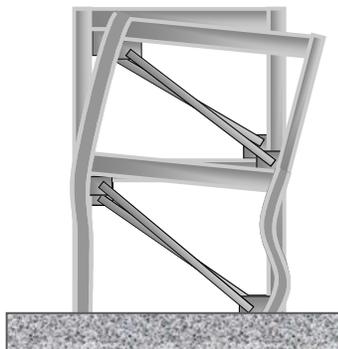


Connection fracture must not be the governing limit state.



Post-Elastic Behavior

Unfavorable Modes: Column Buckling

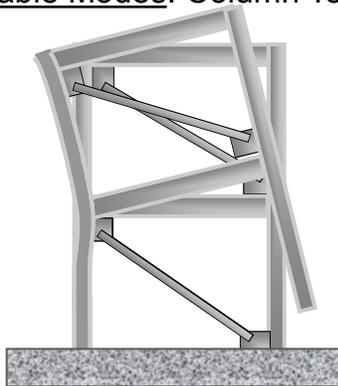


Column buckling must not be the governing limit state.



Post-Elastic Behavior

Unfavorable Modes: Column Tension Fracture



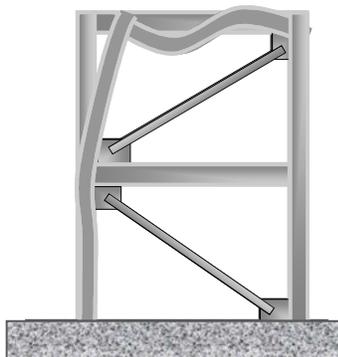
Column tension fracture must not be the governing limit state.



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Post-Elastic Behavior

Unfavorable Modes: Beam Failure



Beam failure must not be the governing limit state.

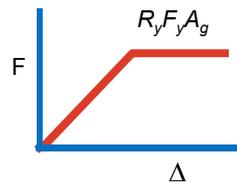
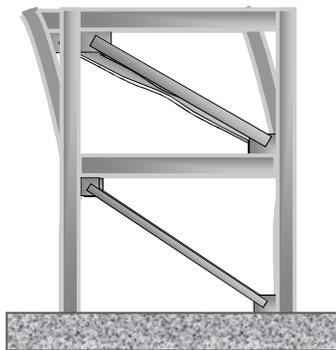


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Post-Elastic Behavior

Preferred Modes: Brace Tension Yielding

Brace yielding should be a governing limit state.



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



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Brace Elongation (Tension Only)



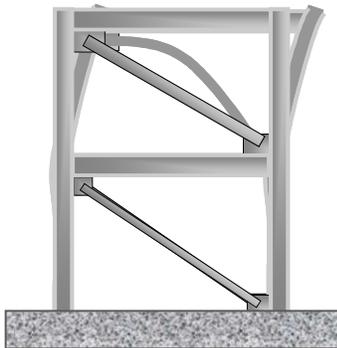
Courtesy of R. Tremblay



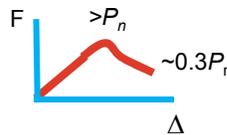
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Post-Elastic Behavior

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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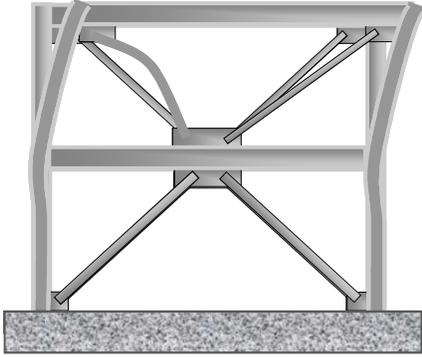
Brace Buckling



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System Behavior with Brace Yielding

Column Flexure



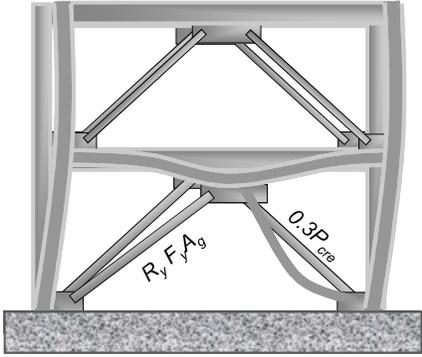
Columns must bend when braces buckle and yield.



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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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There's always a solution in steel.

Design of SCBF



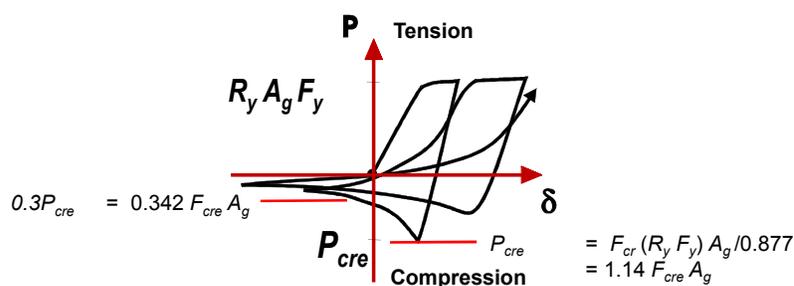
Design of SCBF

- Force-based design
 - Design for basic load combinations
 - Size braces
- Design beams and columns for maximum forces from braces
 - Consider expected strength
 - Consider buckling behavior
 - 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
 - Compactness limits
 - Slenderness limits
- Pick/determine plane of buckling
 - End fixity in each plane
 - Brace shape (Kl/r in each axis)
- Accommodate buckling in plane of buckling
- Provide fixity in orthogonal plane

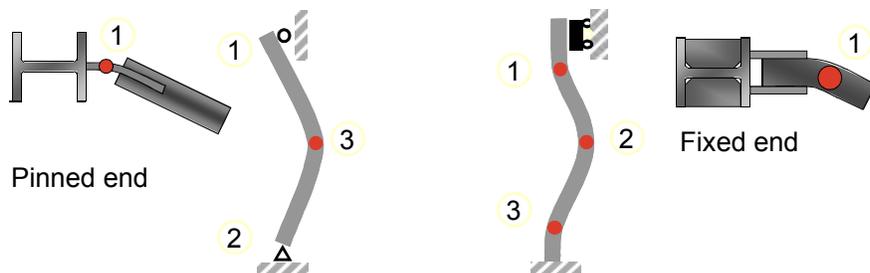


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Brace Buckling

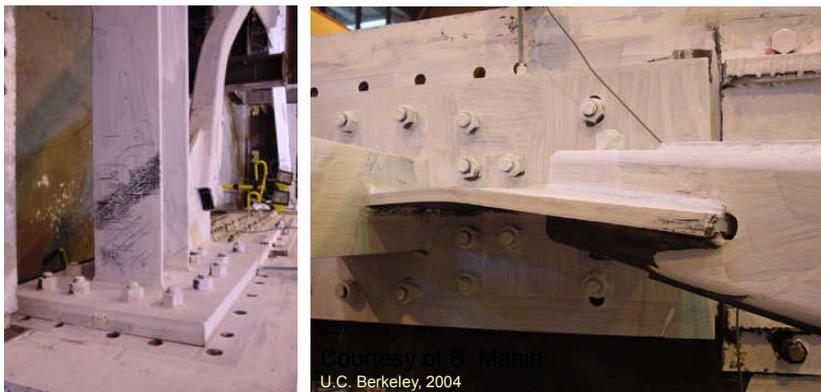
Flexural buckling (Compression)

Buckling: 3 hinges



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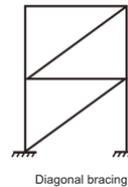
Pinned-End Gusset Hinging



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Configuration

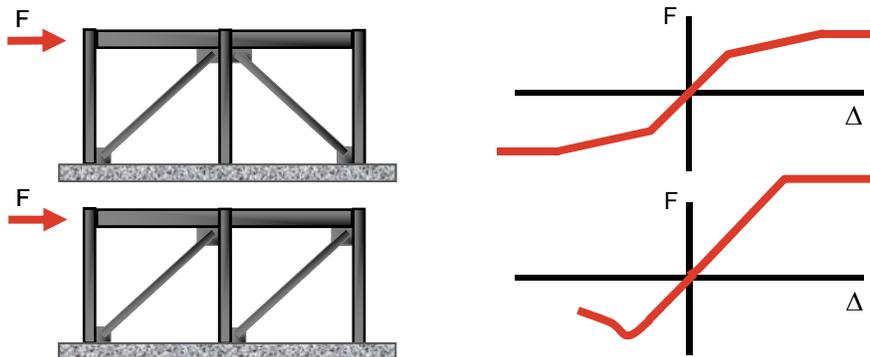
- Single diagonal
 - Unequal response in opposite directions
 - Use in pairs
 - AISC allows single diagonals
 - Design braces for $\Omega_o E$



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Bracing Members: Limitations

Lateral force distribution



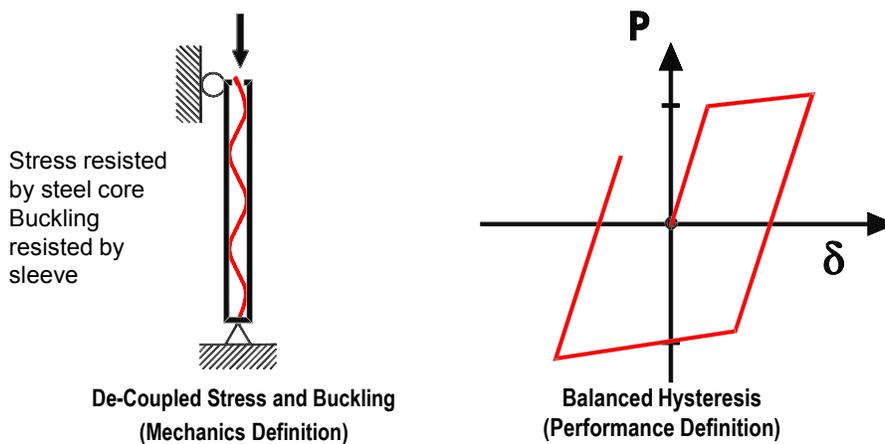
40

There's always a solution in steel.

Buckling Restrained Braced Frames

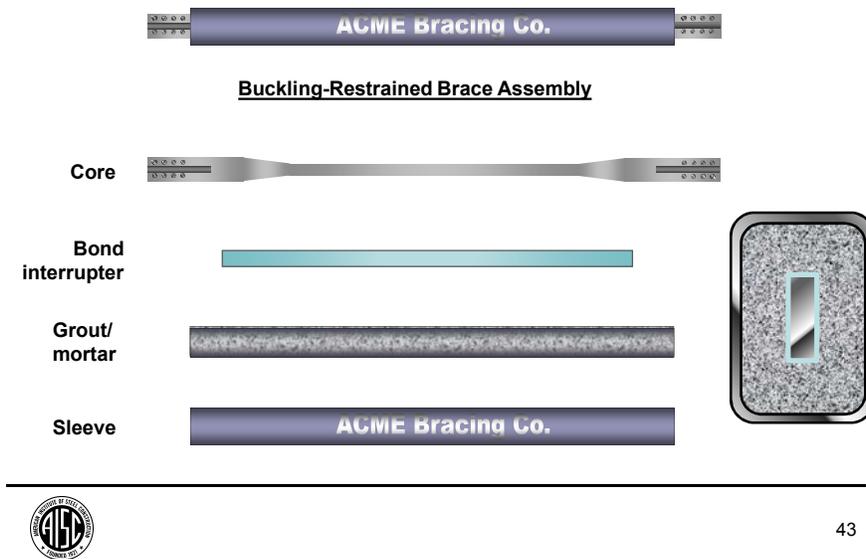


What is a Buckling-restrained Brace? Two Definitions

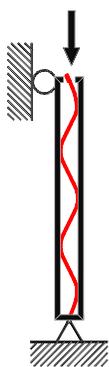


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Buckling Restrained Braces

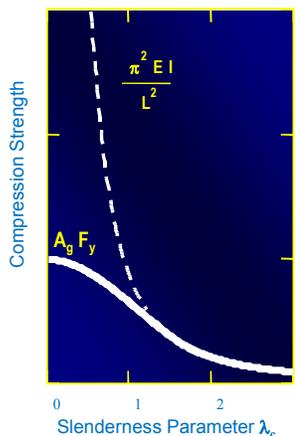


BRB Definitions Explained: Sleeved Column

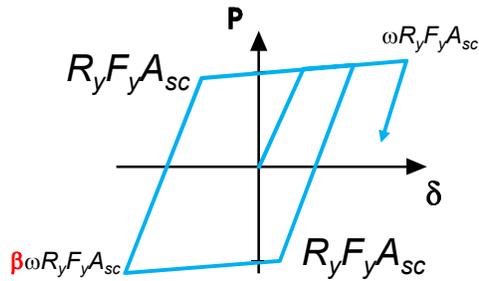
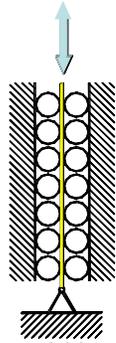


Steel core achieves F_y
 $kl/r \sim 0$

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



Buckling Restrained Braces

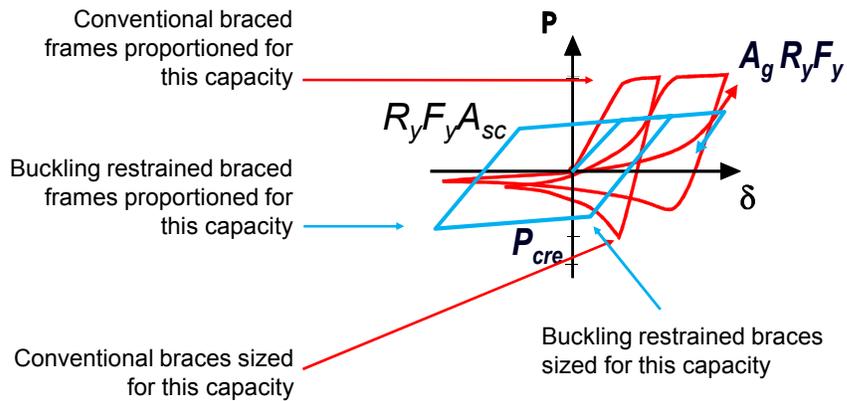


- Balanced Hysteresis
 - Slightly Stronger in Compression (β)
- Hysteretic Energy Dissipation
- Hysteretic Stability
 - Strength
 - Stiffness
- Long Fracture Life



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Capacity design

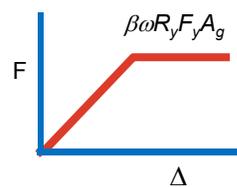
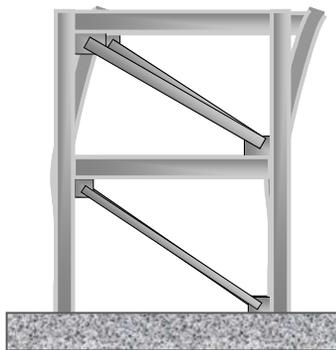


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Post-Elastic Behavior

Preferred Modes: 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



Courtesy of
K.C. Tsai

Courtesy of
STARSeismic



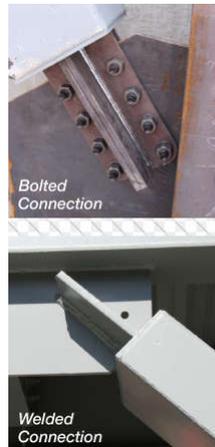
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Buckling-Restrained Brace Types



Direct bolting of core

Courtesy of
CoreBrace



Bolted
Connection

Welded
Connection

Courtesy of
STAR Seismic



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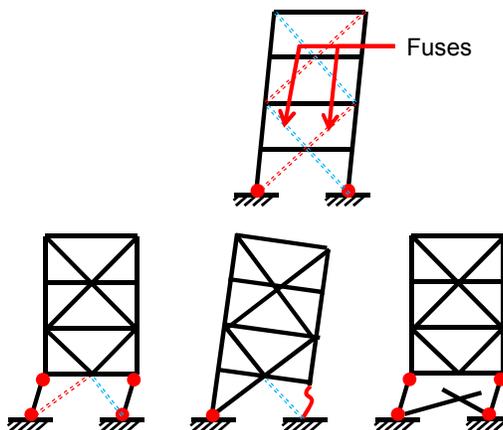
There's always a solution in steel.

Design of Buckling Restrained Braced Frames



Design of Buckling Restrained Braced Frames

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



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Fuse concept

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

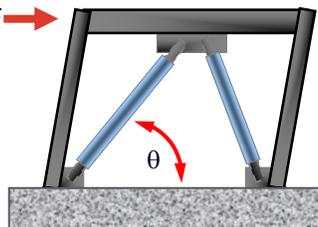


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Force-based design

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

- 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

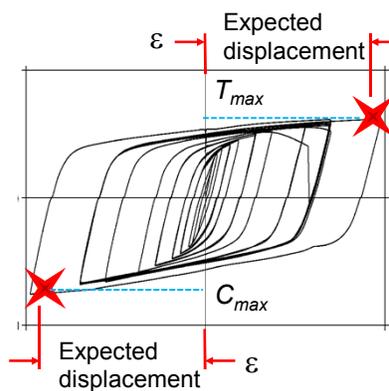
- Estimate fuse capacity
 - Expected material strength
 - Strain hardening
- Based on testing

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 $1.3 \leq \omega \leq 1.5$

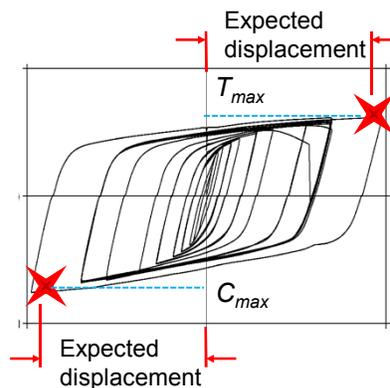
$$\beta \omega = C_{max} / A_g F_y$$

Typical $1.1 \leq \beta \leq 1.25$

- For design

$$R_u(\text{tension}) = \omega A_g R_y F_y$$

$$R_u(\text{compression}) = \beta \omega A_g R_y F_y$$



AISC 341 F4.3

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Analysis: brace stiffness

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



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Analysis: brace stiffness

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

$K \sim EA_{sc} / L_y$
 $= K_F EA_{sc} / L_{wp}$
 $1.2 \leq K_F \leq 1.8$



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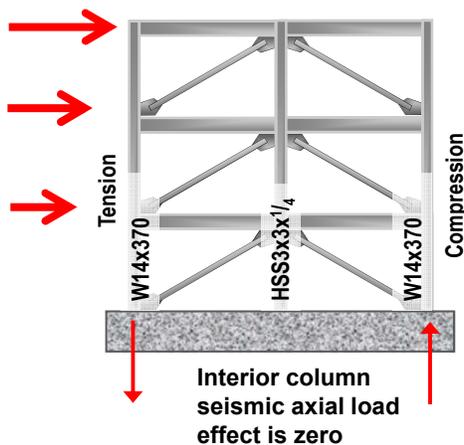
Plastic mechanism analysis

There's always a solution in steel.



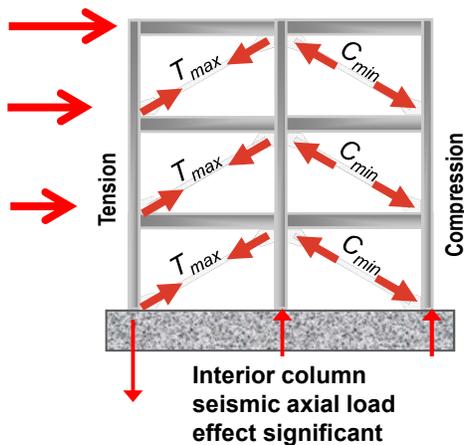
structural STEEL₅₈

What elastic analysis misses

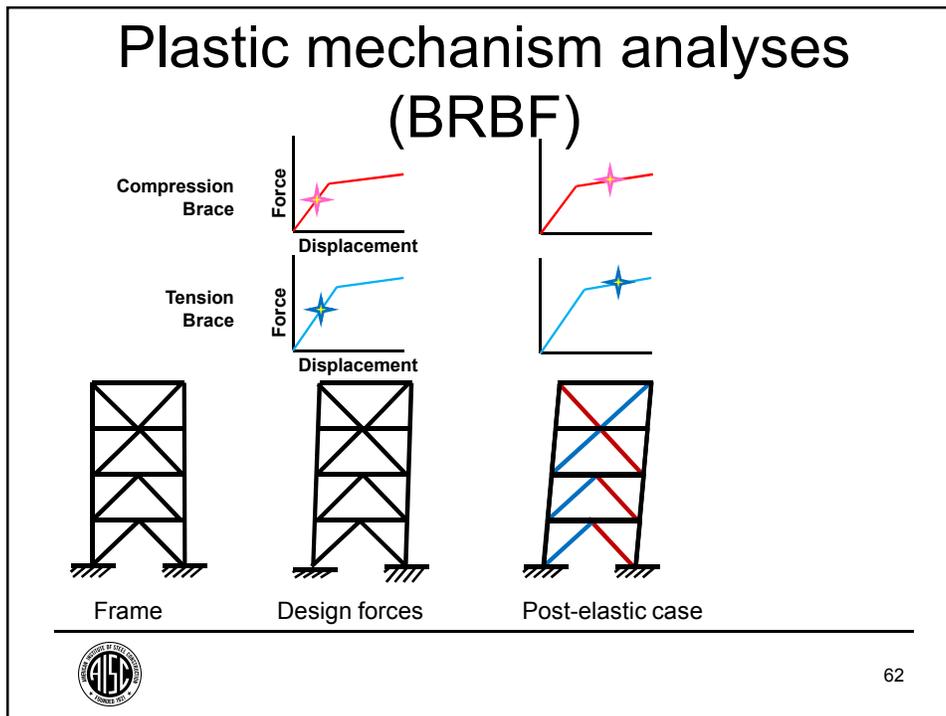
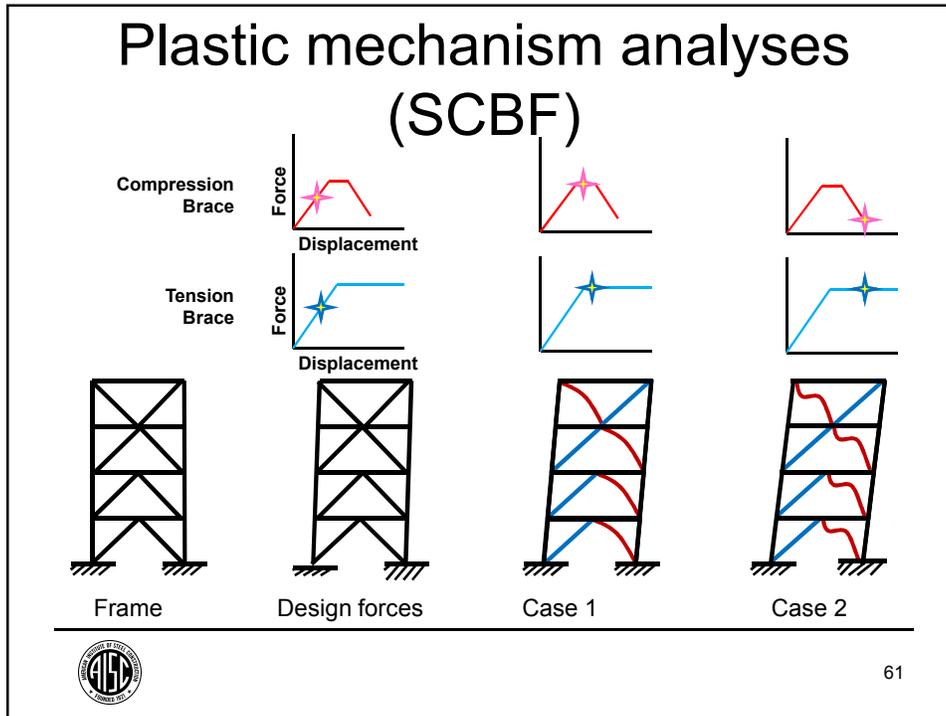


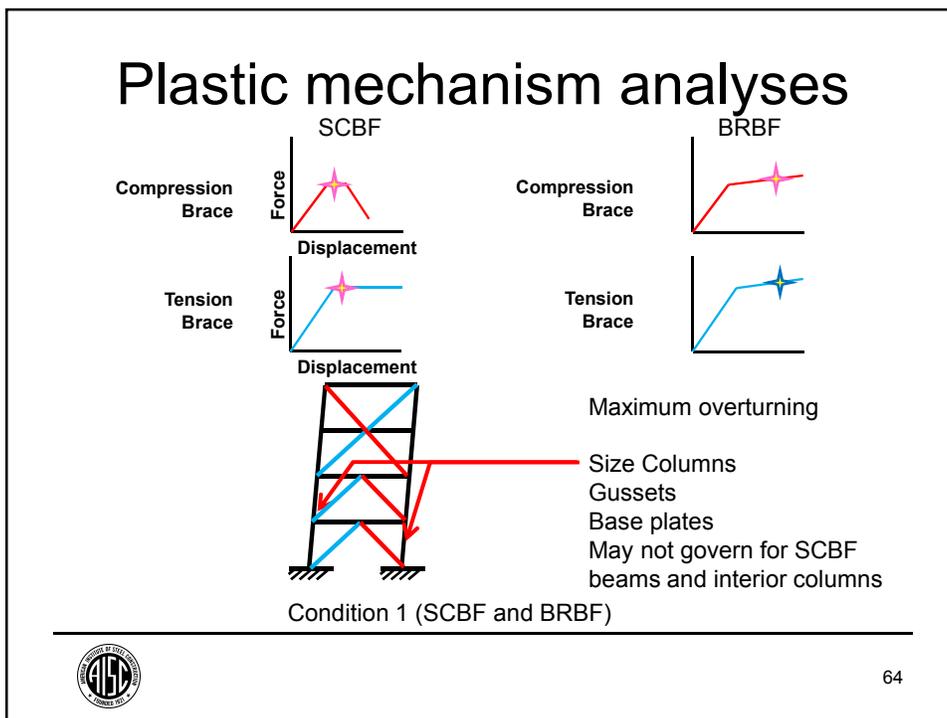
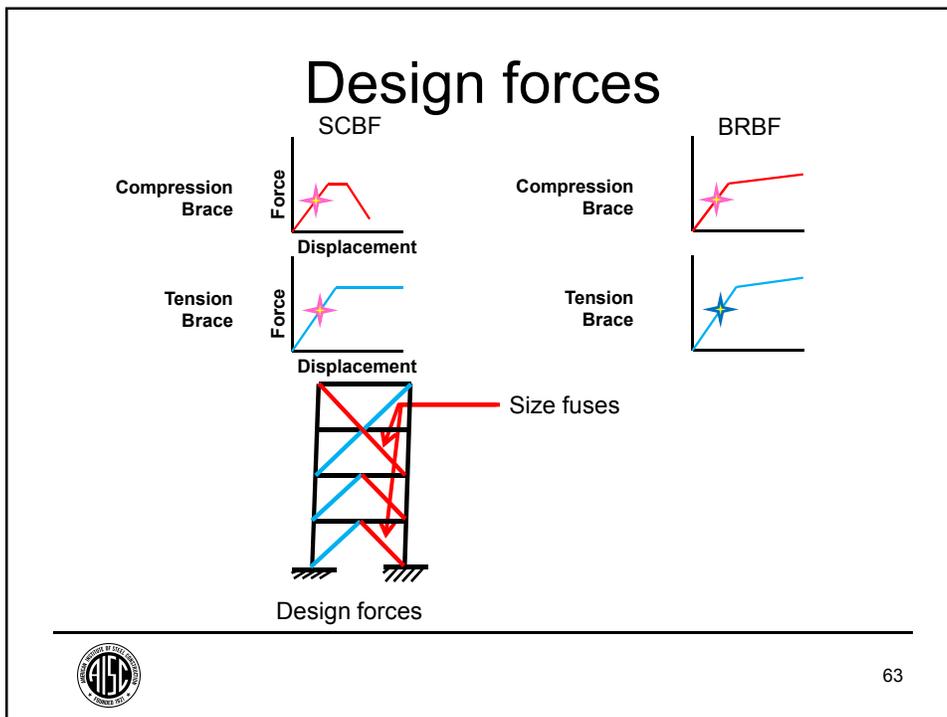
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What elastic analysis misses

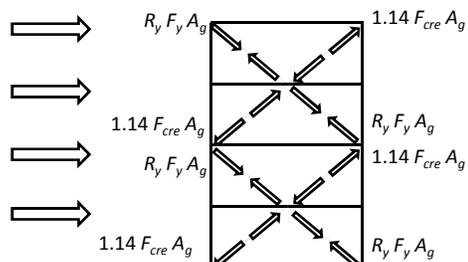


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Plastic mechanism analyses



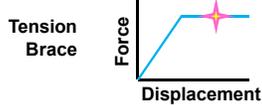
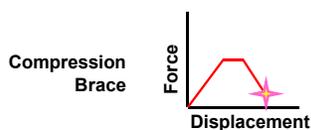
If $1.14 F_{cre} A_g > R_y F_y A_g$
 Use $R_y F_y A_g$

Case 1

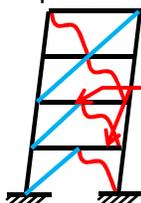


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Plastic mechanism analyses



Force redistribution:
 Compression braces
 participate less
 Force zig-zags



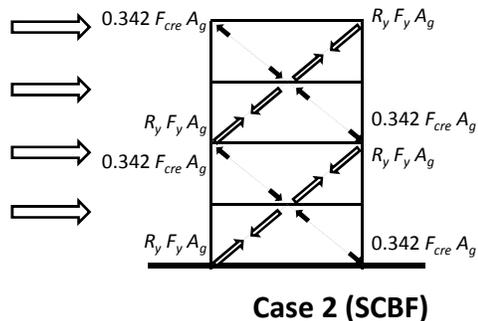
Size beams &
 interior columns

Condition 2 (SCBF only)



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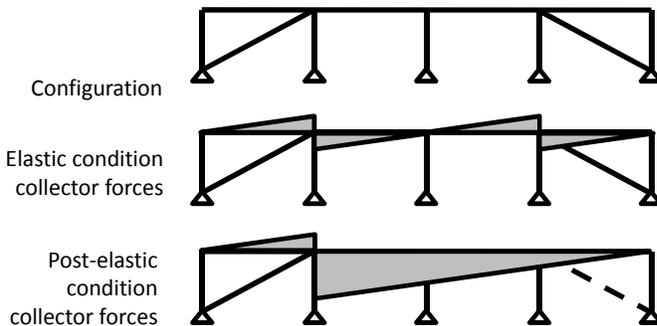
Plastic mechanism analyses



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Layout

- Post-elastic offsets



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Plastic mechanism analyses

Case 2 Load Path

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Temperature method of mechanism analysis

Equivalent to imposing strain
 Redefine brace material properties

$$\alpha = 1 \text{ in./in.}/8F$$

$$E = 1 \text{ ksi}$$

Apply temperature to braces:

$$T = -\omega R_y F_y 8F/\text{ksi}$$

($R_y F_y 8F/\text{ksi}$ [SCBF])

$$C = \omega \beta R_y F_y 8F/\text{ksi}$$

($1.14 F_{cre} 8F/\text{ksi}$ [SCBF case 1])
 ($0.342 F_{cre} 8F/\text{ksi}$ [SCBF case 2])

Restrain lateral movement
 Analyze

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Temperature method of mechanism analysis

Multiple springs may be used to represent distributed mass

The diagram illustrates the temperature method of mechanism analysis for a braced frame. On the left, a grid of springs represents distributed mass. On the right, a braced frame is shown with blue and red diagonal members and three levels of mass represented by circles.



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Connections

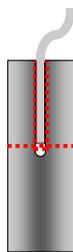
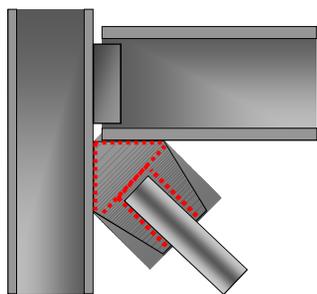
There's always a solution in steel.



structural
STEEL₇₂

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



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Connection limit states

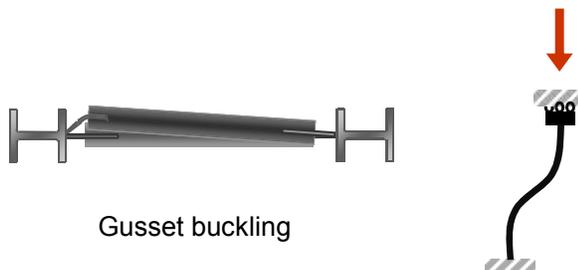
- Web proportioning
 - Where thick gussets are required thin webs may be inadequate
 - Research ongoing
 - Check web local yielding
 - Rule of thumb:
 - $t_w \geq \frac{3}{4} t_g$



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Connection limit states

Connections: Brace End



Gusset buckling



Refer to AISC Design Guide 29
 gusset K factors

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Gusset design

TECHNICAL NOTE

Effective Length Factors for Gusset Plates in Chevron Braced Frames

BO DOWSWELL

ENGINEERING JOURNAL / THIRD QUARTER / 2012

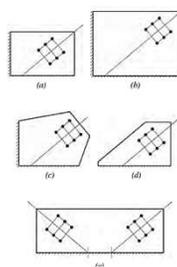


Table 3. Summary of Proposed Effective Length Factors^a

Gusset Configuration	Effective Length Factor	Buckling Length
Compact corner	$\frac{b}{l}$	$\frac{b}{l}$
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.



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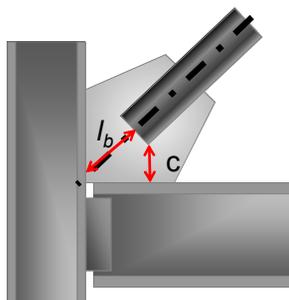


Connection Instability



77

Connections: Compression

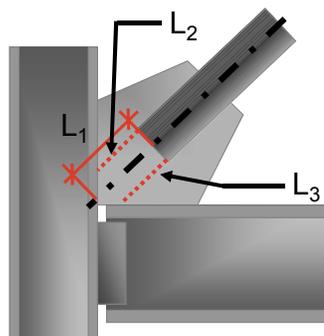


if $t_\beta < t_g$, the gusset will yield before it buckle (Dowswell, 2006)

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



Connections: Compression



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

Dowswell (2006)

3 Options (all reasonably reliable)

$L = \text{Ave } (L)?$

$L = \text{Max } (L)?$

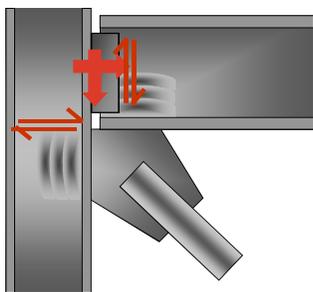
$L = \Phi (L)?$



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,
cripling, shear

Beam-column connection, shear

Beam-column connection, axial



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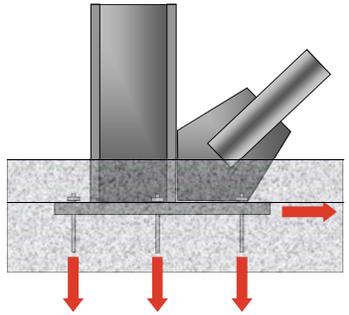
Beam Instability



81

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.

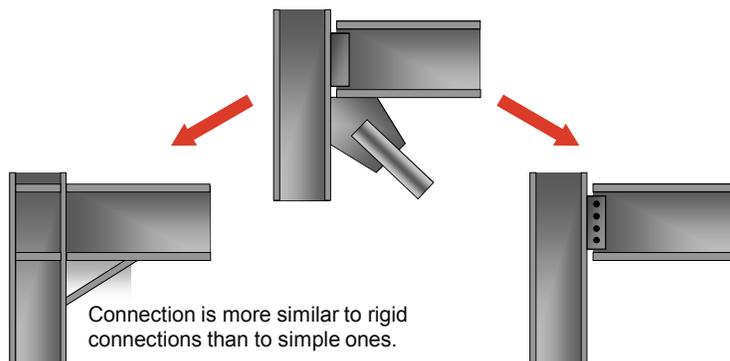


82



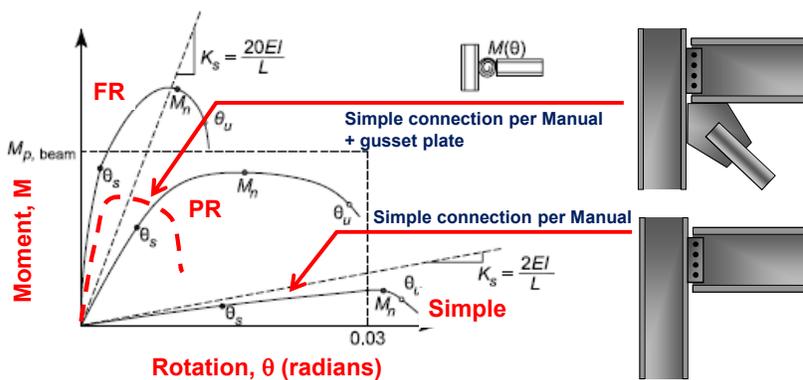
Fixity of gusset connections

Flexure: Connection Fixity



83

Rotation in gusseted beam-column connections



84

Rotation in gusseted beam-column connections

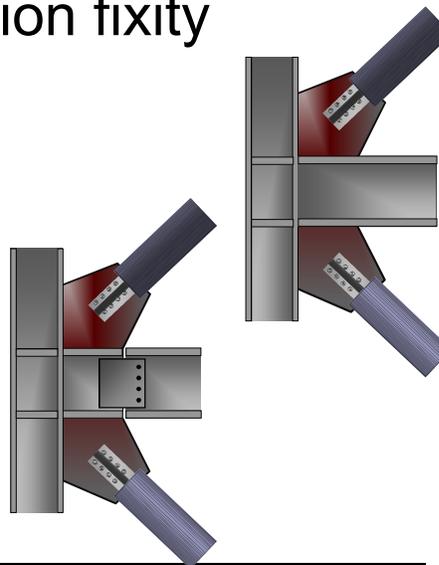
- UC Berkeley testing (and other testing) showed inability of simple+gusset connections to withstand large rotations



85

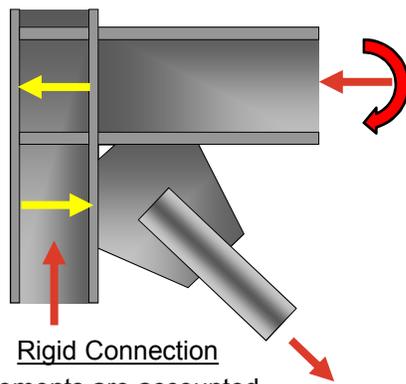
Connection fixity

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



86

Method of accommodating frame rotations



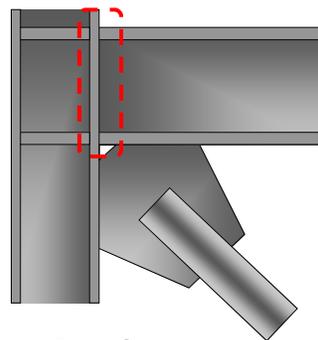
Connection strength exceeds beam strength

Rigid Connection
Moments are accounted for in design



87

Method of accommodating frame rotations



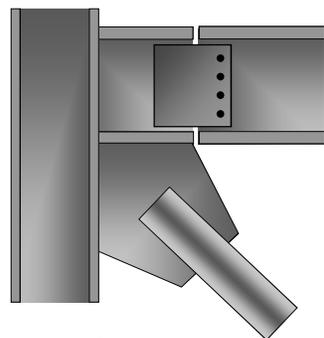
Connection consists of Ordinary Moment Frame (OMF) connection, plus gusset

Rigid Connection
Moments are implicitly accounted for



88

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



89

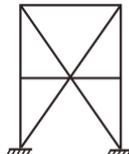
Additional topics

There's always a solution in steel.

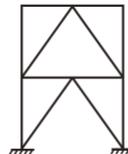


Configuration

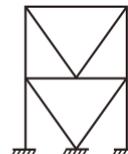
- Chevron
 - V or inverted-V
 - Formerly known as “K”
 - Until 1970s.
 - Two-story X
 - Post-elastic vertical forces on beams



Multistory X-bracing



Inverted V-bracing (Chevron)



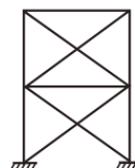
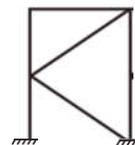
V-bracing



91

Configuration

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



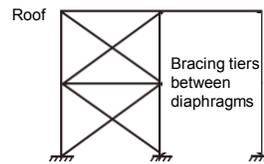
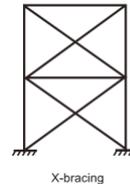
X-bracing



92

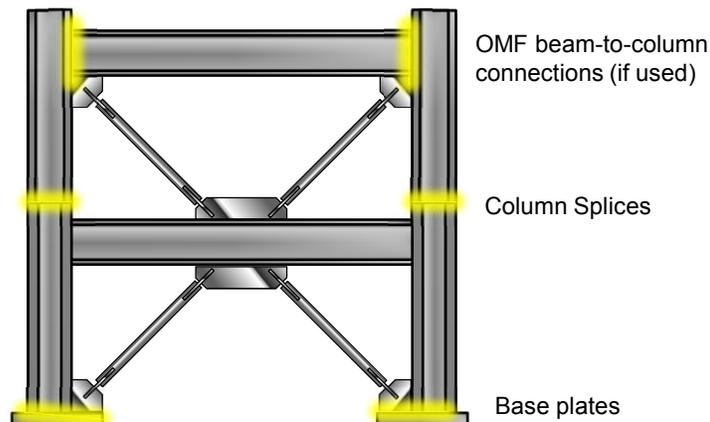
Configuration

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



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Demand critical welds



94

Detailing & Constructability

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

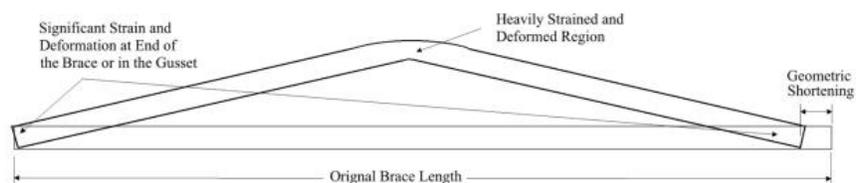


SCBF

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Buckling deformation (SCBF)

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

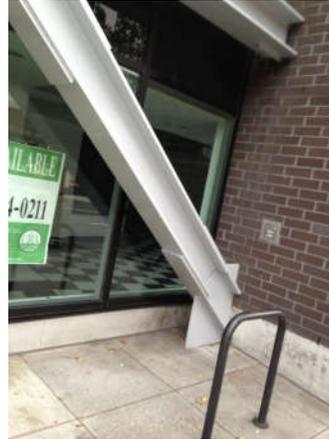


SCBF

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Interaction with architecture (SCBF)

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



SCBF

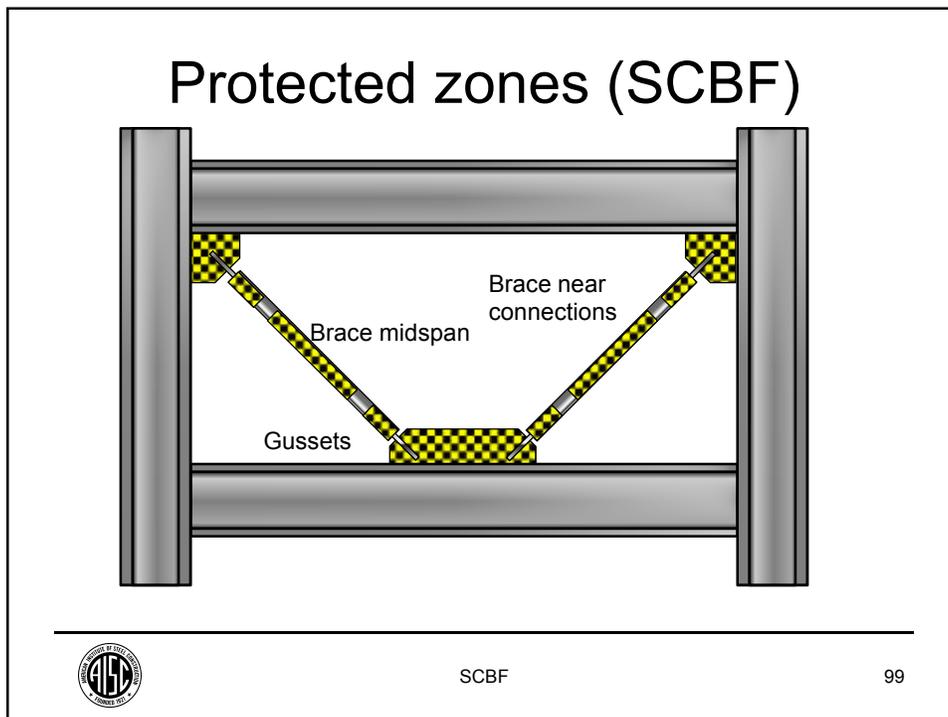
97

Brace Buckling: Effect on Other Elements



SCBF

98



Protected zones

- Areas of anticipated inelastic strain
- Attachments prohibited
 - 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

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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 <i>Seismic Provisions</i> Section F2.6b	Method of complying with AISC <i>Seismic Provisions</i> 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

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Direct-welded connections

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



SCBF

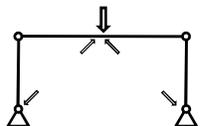
105

Gravity forces in BRBs

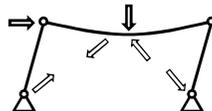
Gravity Forces in Braces

Neglect

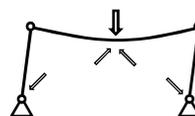
Effective tension and compression strength will be equal for subsequent cycles



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

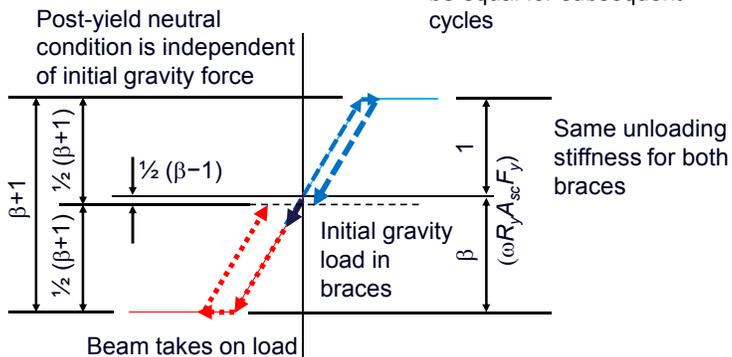
106



Gravity forces in BRBs

Gravity Forces in Braces

Neglect



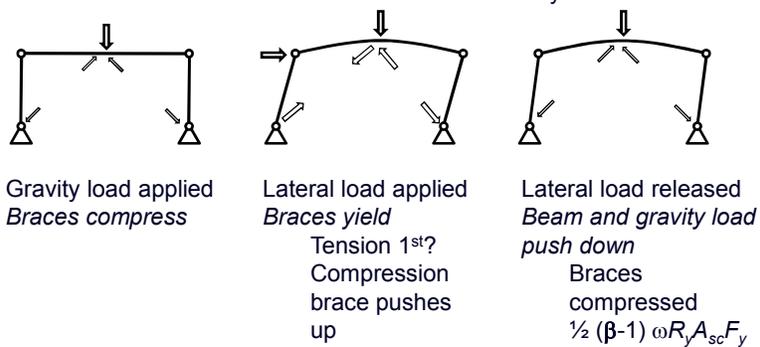
BRBF

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Gravity forces in BRBs

Gravity Forces in Braces

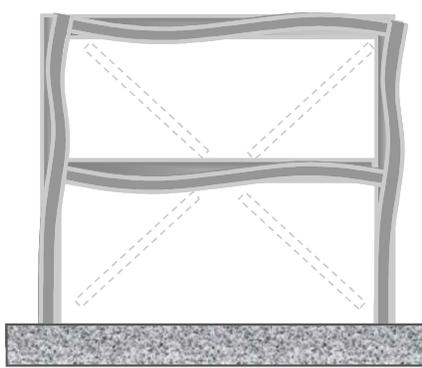
Neglect



BRBF

108

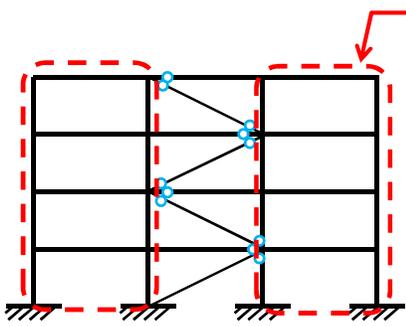
Frame Participation



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



Connection fixity



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



There's always a solution in steel.

Summary



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 through higher strength
- Gusset-plate detailing and proportioning is necessary to ensure inelastic drift capacity

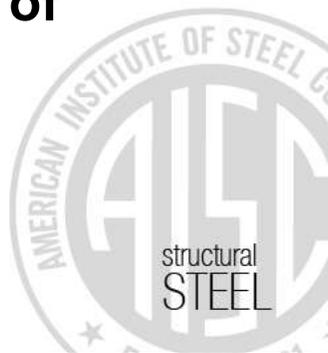


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There's always a solution in steel.

End of session 2

Next:
Seismic design of buildings



Additional resources

		114

There's always a solution in steel.

Question time



8-Session Package Registrants Course Resources

1. Log on to your AISC account and go to Course Resources.
<https://www.aisc.org/myaisc/course-resources/>
2. Locate your course.
3. Access handouts, videos, quizzes, quiz scores and attendance records.

AISC > MYAISC > COURSE RESOURCES > SEISMIC DESIGN IN STEEL

Seismic Design in Steel

8-SESSION PACKAGE RESOURCES

Event	Date	Handouts	Videos	Quiz	Attendance
R1 Introduction To Effective Seismic Design	N/A	Handouts	Video Passcode: 16A9F51	Available 07/23/2018 5:00 PM EDT	N/A
R2 Seismic Design Concepts - Moment Frames	N/A	Handouts	Video Passcode: 16Z1Z18	Available 07/23/2018 5:00 PM EDT	N/A
R3 Seismic Design Concepts - Braced Frames	N/A	Handouts	Video Passcode: 16E2305	Available 07/23/2018 5:00 PM EDT	N/A
R4 Seismic Design Concepts - Design	N/A	Handouts	Video Passcode: 11306	Available 07/23/2018 5:00 PM EDT	N/A
R5 Bonus Q+A	N/A		Video Available 08/31/2018 5:00 PM EDT	N/A	N/A
L1 Application - Planning the Seismic Design	Sep 10 2018 1:30PM EDT	Handouts	Video Available 09/12/2018 5:00PM EDT	Available 09/12/2018 5:00PM EDT	Pending
L2 Application - Building Analysis/Diaphragms	Sep 17 2018 1:30PM EDT	Handouts	Video Available 09/19/2018 5:00PM EDT	Available 09/19/2018 5:00PM EDT	Pending
L3 Application - Moment Frames	Sep 24 2018 1:30PM EDT	Handouts	Video Available 09/26/2018 5:00PM EDT	Available 09/26/2018 5:00PM EDT	Pending
L4 Design of the Braced Frames	Oct 1 2018 1:30PM EDT	Handouts	Video Available 10/03/2018 5:00PM EDT	Available 10/03/2018 5:00PM EDT	Pending
Seismic Design in Steel - Final Exam	Oct 2 2018 12:00AM EDT			Available 10/05/2018 5:00PM EDT	



8-Session Package Registrants

Videos and Quizzes

Videos

- For Sessions R1 – R4, find access to recordings starting July 16. Recording access expires on October 22.
- Bonus Q&A Session R5 will be available starting August 31.
- For Sessions L1 – L4, find access to recordings within two days after the live air date. Recording access expires three weeks after the live session.

Quizzes

- For Sessions R1 – R4, find access to quizzes starting July 23. Quizzes are due on October 22.
- For Sessions L1 – L4, find access to quizzes within two days after the live air date. Quizzes are due three weeks after the live session.
- A final exam will also be given.
- Quiz scores are displayed in the Course Resources table.



8-Session Package Registrants

Course Credit

Attendance and PDH Certificates

- For Sessions R1 – R4, you must pass the quiz to receive credit for the session.
- For Sessions L1 – L4, you have two options to receive credit for the session.
 - Option 1: Watch the session live. Credit for live attendance will be displayed in the Course Resources table within two days of the session.
 - Option 2: Watch the recording and pass the quiz.

EEU Certificates – Certificate of Completion

- In addition to PDH certificates earned for each individual session, an EEU (Equivalent Education Unit) certificate of completion will be issued for participants who complete the full course. Participants must pass at least 7 of 8 quizzes and the final exam to earn the EEU.

Distribution of Certificates

- All certificates (PDH and EEU) will be issued after the final session. Only the registrant will receive certificates for the course.
-

