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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

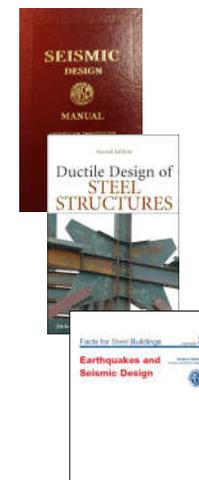
- Understand the principles of seismic design of steel structures.
- Understand the application of those principles to two common systems:
 - Special Moment Frames
 - Buckling-Restrained Braced Frames.
- Understand the application of design requirements for those systems.



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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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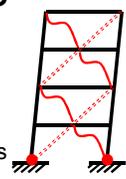
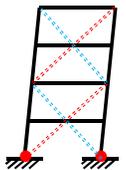
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Braced-frame systems



Braced frame systems

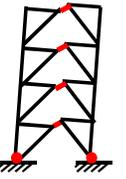
- Concentrically braced frames
 - Special Concentrically Braced Frames
 - Inelastic drift through buckling & yielding of braces
 - Ordinary Concentrically Braced Frames
 - Limit inelastic drift demand through strength
 - Not covered in this course
 - Buckling Restrained Braced Frames
 - Inelastic drift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



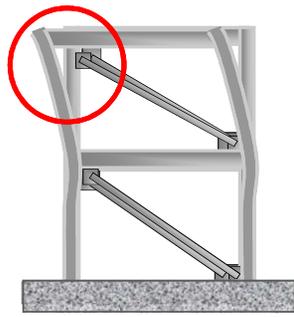
SCBF

- 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



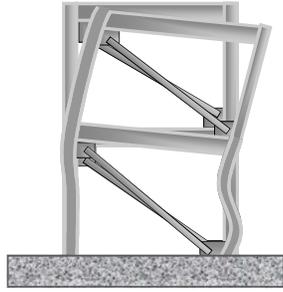
Connection fracture must not be the governing limit state.



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Post-Elastic Behavior

Unfavorable Modes: Column Buckling



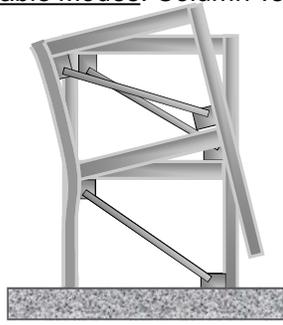
Column buckling must not be the governing limit state.



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Post-Elastic Behavior

Unfavorable Modes: Column Tension Fracture



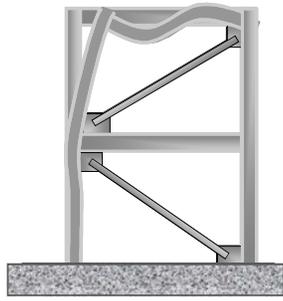
Column tension fracture must not be the governing limit state.



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Post-Elastic Behavior

Unfavorable Modes: Beam Failure



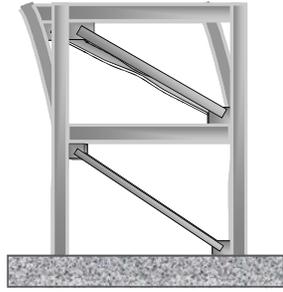
Beam failure must not be the governing limit state.



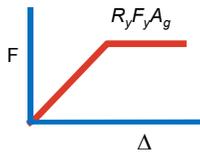
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Post-Elastic Behavior

Preferred Modes: Brace Tension Yielding



Brace yielding should be a governing limit state.



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


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Brace Elongation (Tension Only)

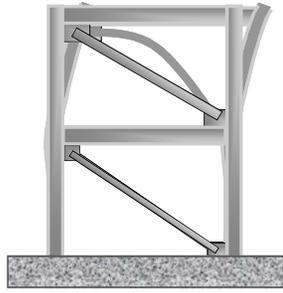


Courtesy of R. Tremblay

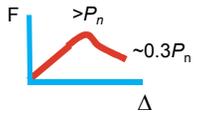

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Post-Elastic Behavior

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



Courtesy of S. Mahin
 U.C. Berkeley, 2004


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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

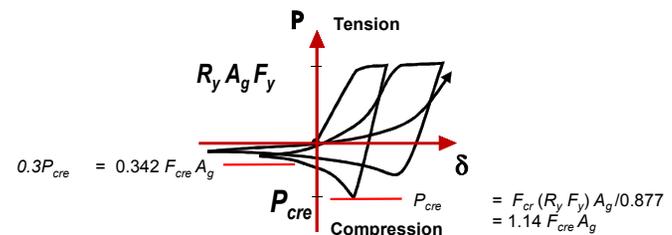
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Design of SCBF

- 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



Design of SCBF braces

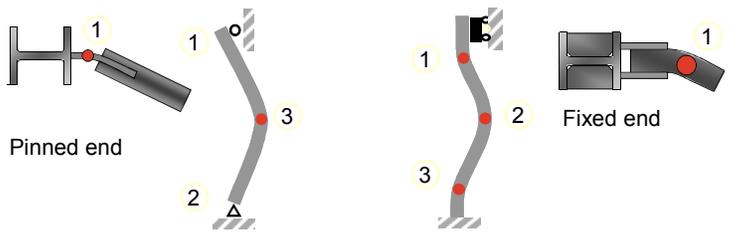
- Limits
 - Compactness limits
 - Slenderness limits
- Pick/determine plane of buckling
 - End fixity in each plane
 - Brace shape (Kl/r in each axis)
- Accommodate buckling in plane of buckling
- Provide fixity in orthogonal plane



Brace Buckling

Flexural buckling (Compression)

Buckling: 3 hinges



Pinned-End Gusset Hinging



Accommodating buckling

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Fixed-End Brace Connection

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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

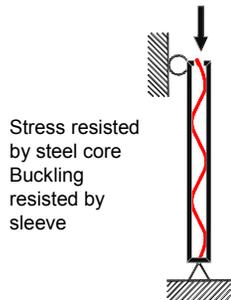
40

There's always a solution in steel.

Buckling Restrained Braced Frames

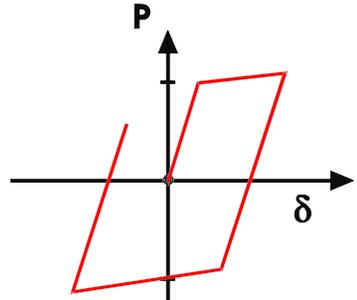


What is a Buckling-restrained Brace? Two Definitions



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



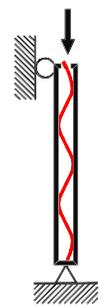
Buckling-Restrained Brace Assembly

Core		
Bond interrupter		
Grout/mortar		
Sleeve		



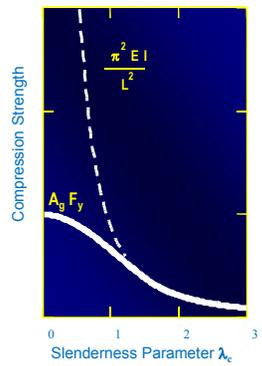
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BRB Definitions Explained: Sleeved Column



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

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



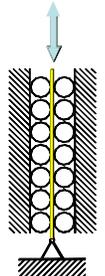
Compression Strength

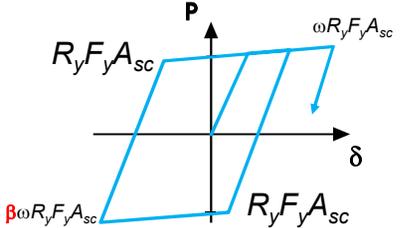
Slenderness Parameter λ_c



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Buckling Restrained Braces

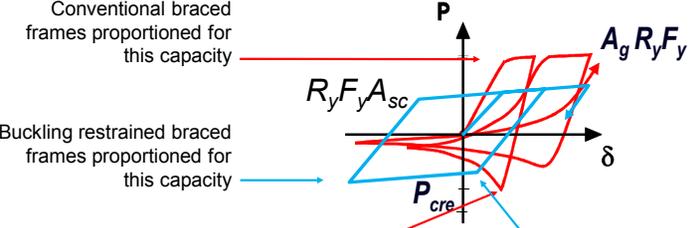




- Balanced Hysteresis
 - Slightly Stronger in Compression (β)
- Hysteretic Energy Dissipation
- Hysteretic Stability
 - Strength
 - Stiffness
- Long Fracture Life


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Capacity design

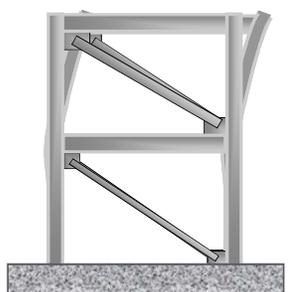


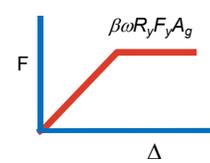
- Conventional braced frames proportioned for this capacity
- Buckling restrained braced frames proportioned for this capacity
- Conventional braces sized for this capacity
- Buckling restrained braces sized for this capacity


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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 STAR Seismic

Courtesy of K.C. Tsai


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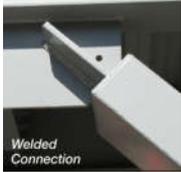
Buckling-Restrained Brace Types



Direct bolting of core
 Courtesy of CoreBrace



Bolted Connection



Welded Connection

Courtesy of STAR Seismic


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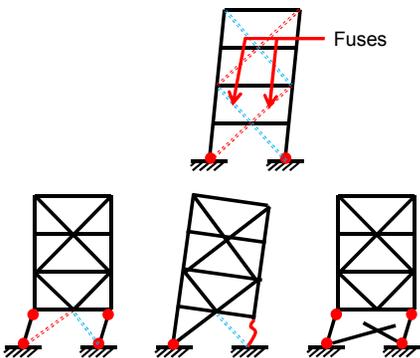
There's always a solution in steel.

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

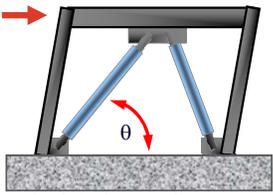

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Force-based design

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

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

- Assume braces resist 100% of story shear F



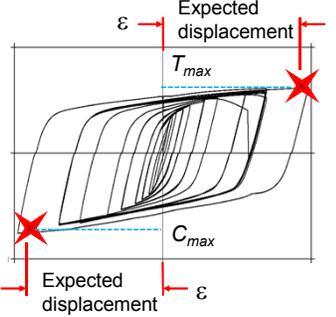
Design braces precisely to calculated capacity
 $(P_u = \phi P_n = \phi F_y A_{sc})$

Do not include gravity load


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Brace demands on frame

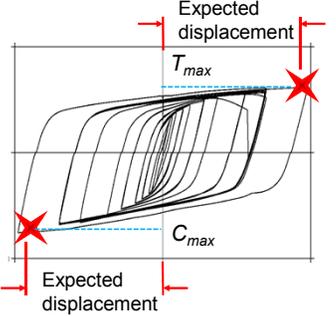
- Estimate fuse capacity
 - Expected material strength
 - Strain hardening
- Based on testing
 - Calculate deformation
 - $\Delta_{bm} = \Delta \cos(\theta)$
 - $\Delta = 2\% h$
 - $\epsilon = \Delta_{bm} / L_y$




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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
 - 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

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

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

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Plastic mechanism analysis

There's always a solution in steel.

What elastic analysis misses

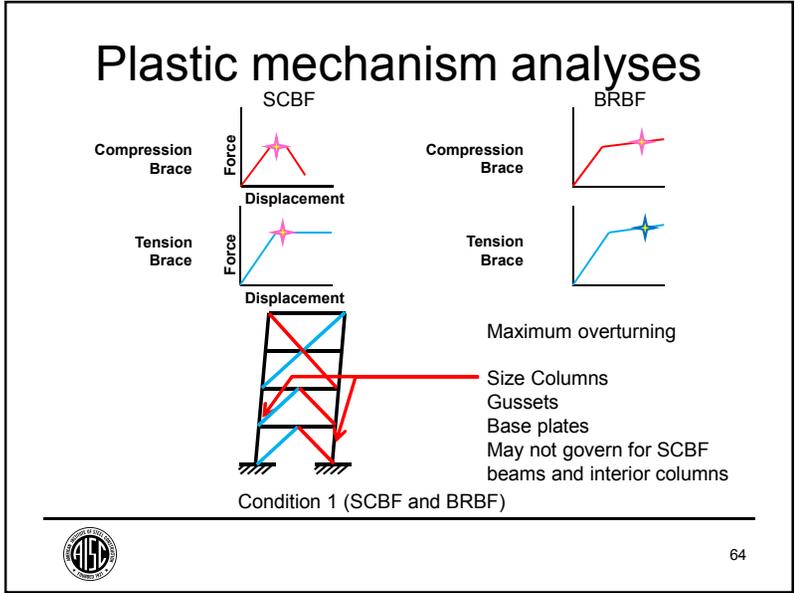
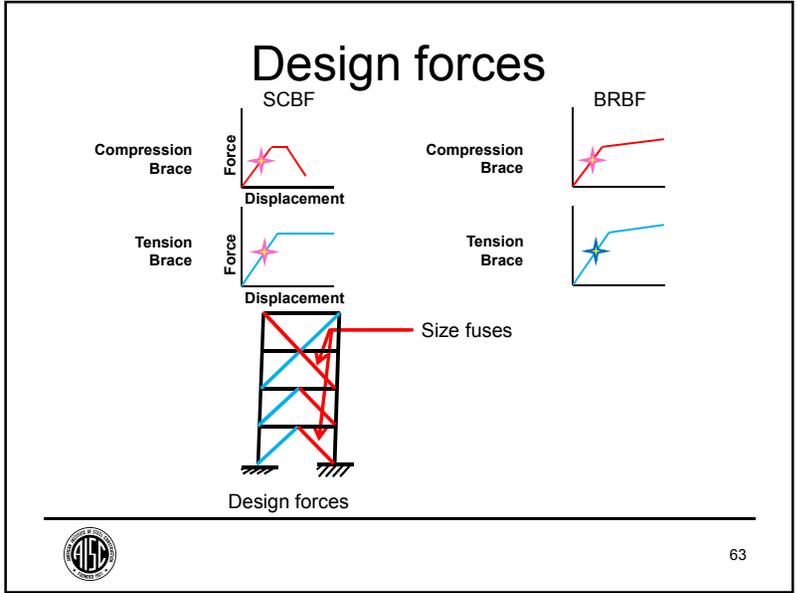
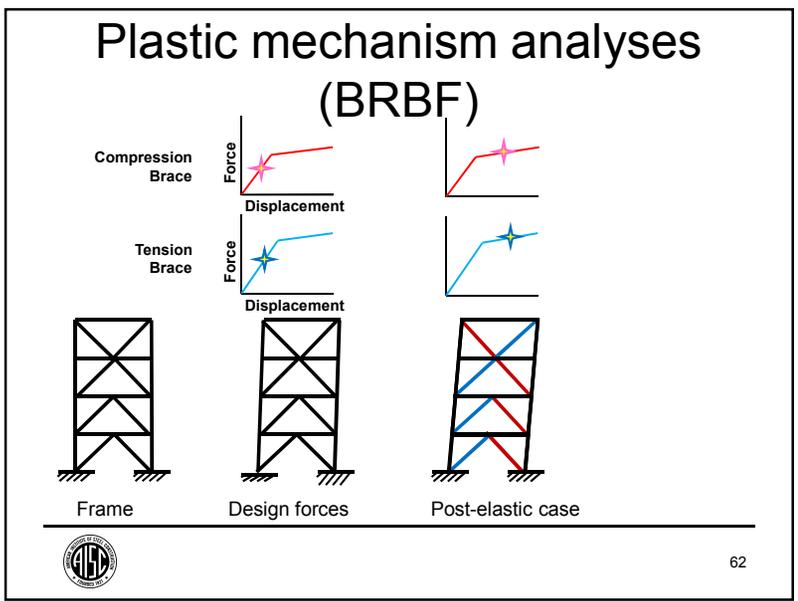
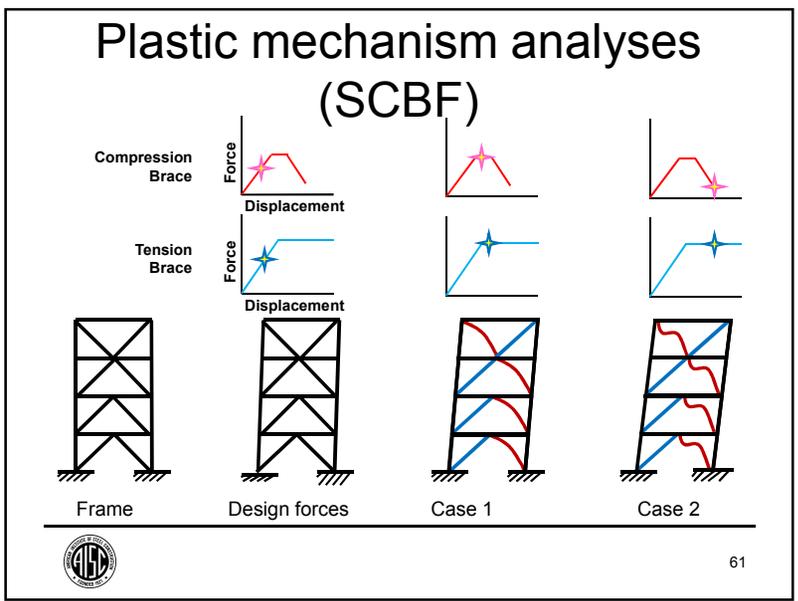
Tension
 W14x370
 HSS3x3x1/4
 W14x370
 Compression
 Interior column seismic axial load effect is zero

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What elastic analysis misses

Tension
 T_{max}
 C_{min}
 Compression
 Interior column seismic axial load effect significant

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Plastic mechanism analyses

Case 1

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

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Plastic mechanism analyses

Condition 2 (SCBF only)

Force redistribution:
 Compression braces participate less
 Force zig-zags
 Size beams &
 Interior columns

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Plastic mechanism analyses

Case 2 (SCBF)

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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

$$\alpha = 1^{in}/_{in}/8F$$

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

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

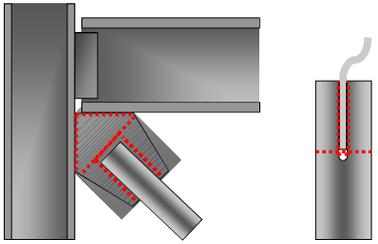
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Connections

There's always a solution in steel.

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 DOWNSWELL ENGINEERING JOURNAL / THIRD QUARTER / 2012










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

^a Table 7 from Downsweil (2008) 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

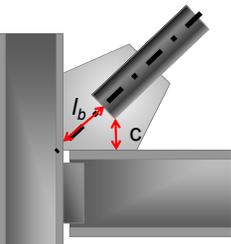


Courtesy of R. Tremblay



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Connections: Compression

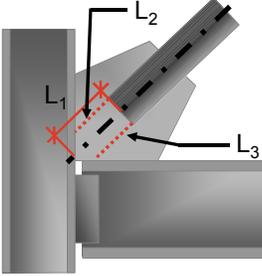


if $t_b < t_g$, the gusset will yield before it buckle (Dowswell, 2006)

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



Connections: Compression



if $t_b > t_g$, $K = 0.6$ (Dowswell, 2006) for conventional braces
 Dowswell (2006)

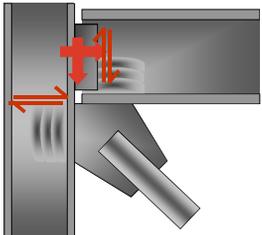
3 Options (all reasonably reliable)
 $L = \text{Ave } (L)?$
 $L = \text{Max } (L)?$
 $L = \phi (L)?$

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, crippling, shear
- Beam-column connection, shear
- Beam-column connection, axial



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Beam Instability



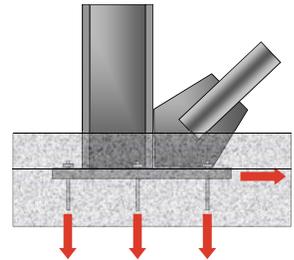
Courtesy of R. Tremblay



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Base-plates

Connections: Base Plate



Shear
 Tension

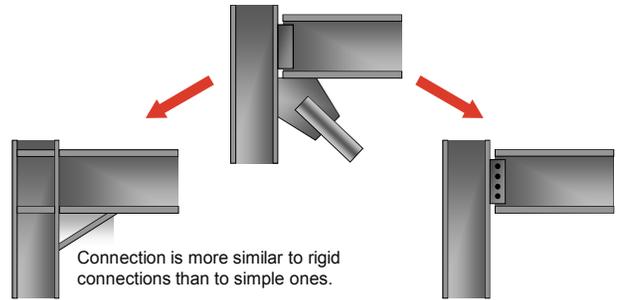
Resistance to horizontal and vertical force components must be provided. Different mechanisms (with different limit states) can be used.



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Fixity of gusset connections

Flexure: Connection Fixity

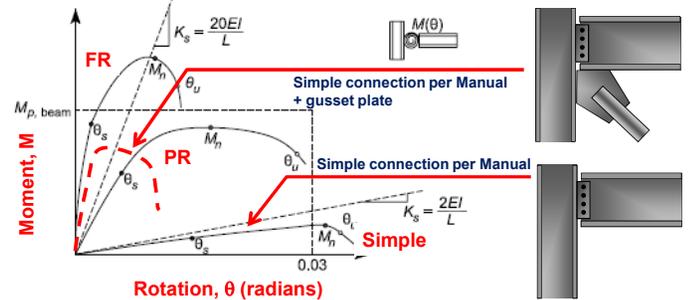


Connection is more similar to rigid connections than to simple ones.



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Rotation in gusseted beam-column connections



FR
 PR
 Simple

Simple connection per Manual + gusset plate
 Simple connection per Manual
 Simple

Rotation, θ (radians)

Equations shown:
 $K_s = \frac{20EI}{L}$
 $K_s = \frac{2EI}{L}$



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Rotation in gusseted beam-column connections

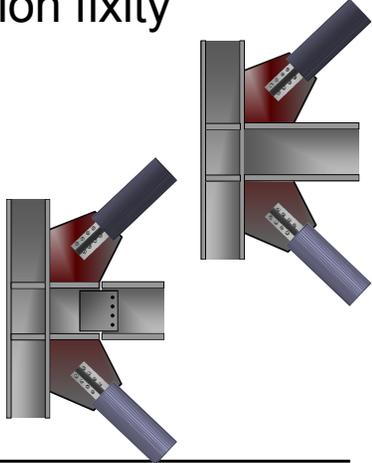
- UC Berkeley testing (and other testing) showed inability of simple+gusset connections to withstand large rotations




85

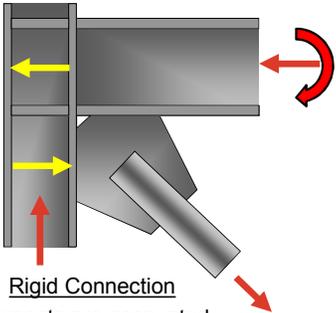
Connection fixity

- 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

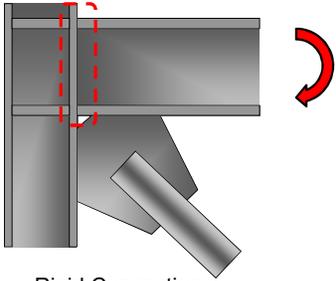


Connection strength exceeds beam strength

Rigid Connection
 Moments are accounted for in design


87

Method of accommodating frame rotations

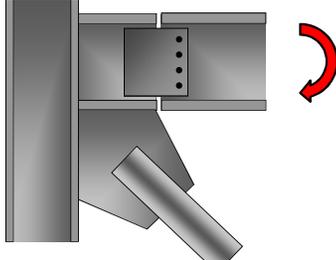


Connection consists of Ordinary Moment Frame (OMF) connection, plus gusset

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

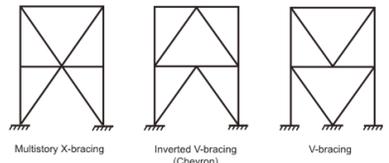
Additional topics

There's always a solution in steel.



Configuration

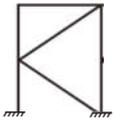
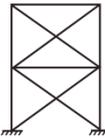
- Chevron
 - V or inverted-V
 - Formerly known as "K"
 - Until 1970s.
 - Two-story X
 - Post-elastic vertical forces on beams




91

Configuration

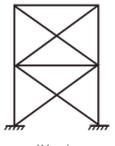
- K
 - Post-elastic horizontal forces on columns
 - Prohibited
- Tension-only braces
 - Only allowed in OCBF

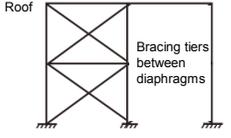

92

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



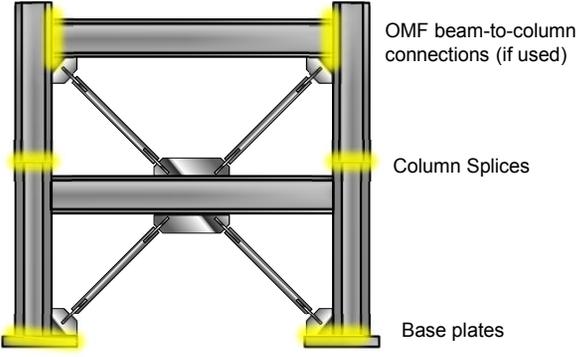
X-bracing



Roof
Bracing tiers between diaphragms


93

Demand critical welds




94

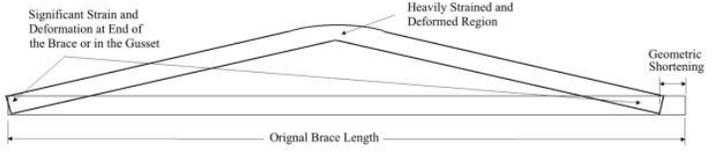
Detailing & Constructability

- 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
 - 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



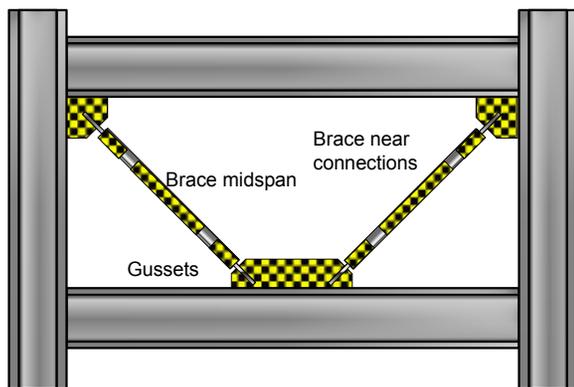
Courtesy of R. Tremblay



SCBF

98

Protected zones (SCBF)



SCBF

99

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
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 <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(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
 - Provide load path for brace-buckling fixed-end moments
- Investigate all geometrical conditions



SCBF

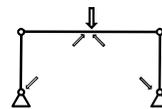
105

Gravity forces in BRBs

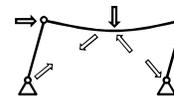
Gravity Forces in Braces

Neglect

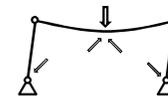
Effective tension and compression strength will be equal for subsequent cycles



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

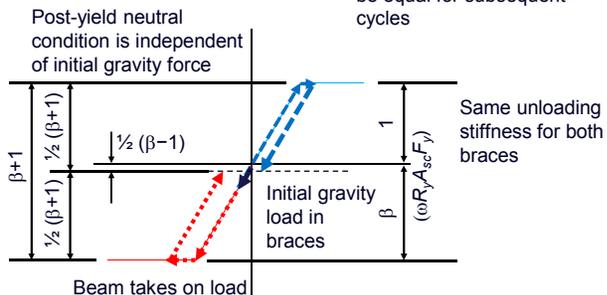
106

Gravity forces in BRBs

Gravity Forces in Braces

Neglect

Effective tension and compression strength will be equal for subsequent cycles



BRBF

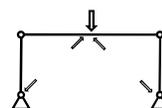
107

Gravity forces in BRBs

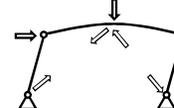
Gravity Forces in Braces

Neglect

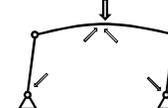
Effective tension and compression strength will be equal for subsequent cycles



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
 $\frac{1}{2}(\beta-1) \omega R_y A_{sc} F_y$

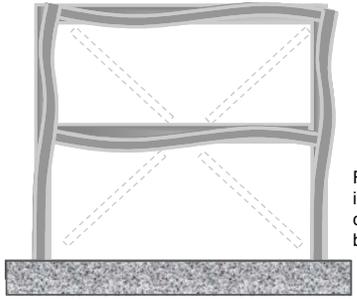


BRBF

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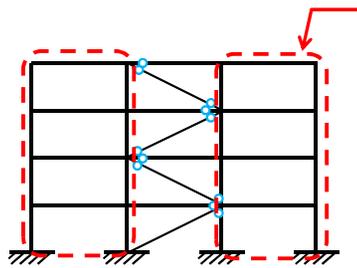
Frame Participation



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



Summary

There's always a solution in steel.



- 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



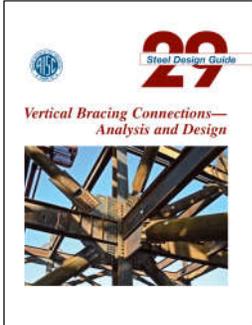
There's always a solution in steel.

End of session 2

Next:
Seismic design of buildings




Additional resources




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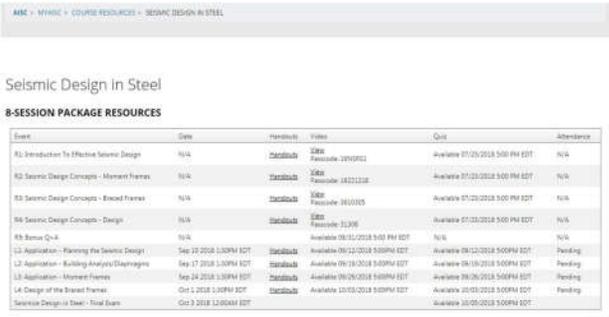
There's always a solution in steel.

Question time



8-Session Package Registrants Course Resources

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



Event	Date	Handouts	Video	Quiz	Attendance
R1 Introduction to Effective Seismic Design	N/A	Completed	Done	Available 07/23/2018 5:00 PM EDT	N/A
R2 Seismic Design Concepts - Moment Frames	N/A	Completed	Done	Available 07/23/2018 5:00 PM EDT	N/A
R3 Seismic Design Concepts - Braced Frames	N/A	Completed	Done	Available 07/23/2018 5:00 PM EDT	N/A
R4 Seismic Design Concepts - Design	N/A	Completed	Done	Available 07/23/2018 5:00 PM EDT	N/A
R5 Bonus Q&A	N/A	Completed	Available 08/15/2018 9:00 PM EDT	N/A	N/A
L2 Application - Planning For Seismic Design	Aug 15 2018 1:00PM EDT	Completed	Available 08/15/2018 9:00PM EDT	Available 08/15/2018 9:00PM EDT	Pending
L3 Application - Building Analysis/Designs	Aug 17 2018 1:00PM EDT	Completed	Available 08/17/2018 9:00PM EDT	Available 08/18/2018 9:00PM EDT	Pending
L4 Application - Moment Frames	Aug 24 2018 1:00PM EDT	Completed	Available 08/24/2018 9:00PM EDT	Available 08/26/2018 9:00PM EDT	Pending
L4 Design of the Braced Frames	Oct 1 2018 1:00PM EDT	Completed	Available 10/01/2018 9:00PM EDT	Available 10/01/2018 9:00PM EDT	Pending
Seismic Design in Steel - Final Exam	Oct 3 2018 12:00AM EDT	Completed	Available 10/03/2018 9:00PM EDT	Available 10/03/2018 9:00PM EDT	Pending



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.

