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Principles and Practice in Seismic Design

February 24, 2022

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Course Description – Submitted for AIA CE Credit

Principles and Practice in Seismic Design
February 24, 2022

This webinar will provide an essential review of seismic design of structural steel buildings, from the development and codification of the basic concepts to their implementation in practice. This presentation will cover important provisions of ASCE 7 and AISC 341, the fundamentals of capacity design, and the ductile behavior of various seismic force-resisting systems. Several real structures will be presented to demonstrate the concepts. Finally, the concept of performance-based seismic design will be discussed.

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Learning Objectives – Submitted for AIA CE Credit

- Explain the scope for ASCE 7 and AISC 341 related to seismic analysis and design.
- Describe fuse mechanisms in various types of high ductility structural steel seismic force-resisting systems.
- List the considerations that factor into the decision of which type of seismic force-resisting system to use on a building project.
- Identify what types of buildings are good candidates for using a performance-based seismic design approach.

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Principles and Practice in Seismic Design

Michael Engelhardt, PE, PhD
Professor, Civil Engineering
University of Texas at Austin

John Hooper, SE, PE
Senior Principal and Director of Earthquake Engineering
Magnusson Klemencic Associates

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Principles and Practice in Seismic Design

1. Principles of Seismic Design in AISC 341 (Engelhardt)
2. Practical Applications of AISC 341 (Hooper)

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1. Principles of Seismic Design in AISC 341

- Building Code Philosophy for Earthquake-Resistant Design and Importance of Ductility
- Design Earthquake Forces: ASCE-7
- AISC Seismic Provisions: AISC 341

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Building Code Philosophy for Earthquake-Resistant Design and Importance of Ductility

Objective: Prevent collapse in the extreme earthquake likely to occur at a building site.

Objectives are not to:
- limit damage
- maintain function
- provide for easy repair

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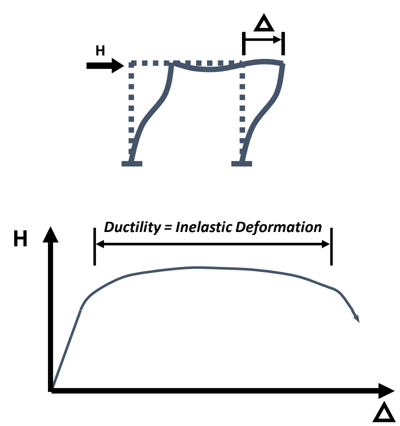
To Survive Strong Earthquake without Collapse: Design for Ductile Behavior



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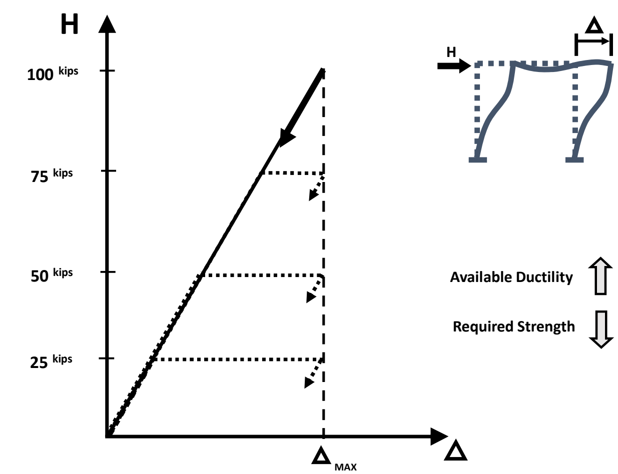

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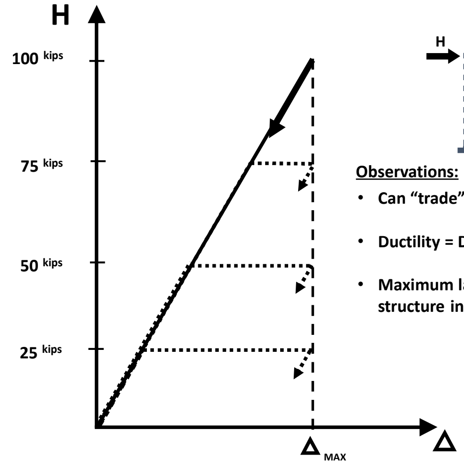
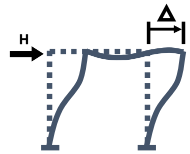


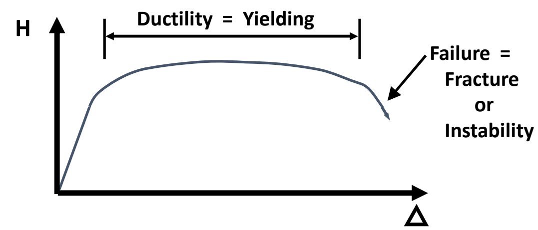


Observations:

- Can "trade" strength for ductility
- Ductility = Damage
- Maximum lateral force experienced by structure in EQ = strength of structure

Ductility in Steel Structures: ***Yielding***

Nonductile Failure Modes: ***Fracture or Instability***



Seismic Resistant Design

Key Elements:

General Seismic Design Requirements and Required Lateral Strength and Stiffness

Specified by ASCE 7-16:
Minimum Design Loads for Buildings and Other Structures

Ductile Detailing Requirements

For steel structures: Specified by AISC 341-16:
Seismic Provisions for Structural Steel Buildings

Design Earthquake Forces: ASCE - 7

Seismic Design Requirements depend on the:

Seismic Design Category (SDC)

SDCs: A
B
C
D
E
F

Increasing seismic risk and Increasingly stringent seismic design and detailing requirements

Seismic Design Category (SDC)

Depends on:

- **Geographic Location**
- **Soil Conditions**
- **Importance of Structure**

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Seismic Design Requirements depend on the:

Seismic Design Category (SDC)

SDCs: A — *Minimal seismic design requirements*

B, C — *Relatively simple approaches possible*

D, E, F — *"High level" seismic design required*

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Analysis Options per ASCE 7-16

- **Equivalent Lateral Force Method**
- **Modal Response Spectrum Analysis**
- **Seismic Response History Analysis**
  - **Linear**
  - **Nonlinear**

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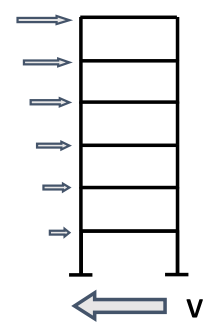
Equivalent Lateral Force Method

$$V = C_S W$$

V = total design lateral force or shear at base of structure

W = effective seismic weight of building

C_S = seismic response coefficient



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$V = C_S W$

$$C_S = \frac{S_{DS}}{\left(\frac{R}{I_e}\right)} \le \begin{cases} \dfrac{S_{D1}}{T\left(\frac{R}{I_e}\right)} & \text{for } T \le T_L \\[2ex] \dfrac{S_{D1}T_L}{T^2\left(\frac{R}{I_e}\right)} & \text{for } T > T_L \end{cases}$$

S_{DS} = design spectral acceleration at short periods

S_{D1} = design spectral acceleration at 1-second period

I_e = importance factor

T = fundamental period of building

T_L = long period transition period

R = response modification coefficient

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R factors for Selected Steel Systems (ASCE 7-16):

SMF	(*Special Moment Resisting Frames*):	R = 8
IMF	(*Intermediate Moment Resisting Frames*):	R = 4.5
OMF	(*Ordinary Moment Resisting Frames*):	R = 3.5
EBF	(*Eccentrically Braced Frames*):	R = 8
SCBF	(*Special Concentrically Braced Frames*):	R = 6
OCBF	(*Ordinary Concentrically Braced Frames*):	R = 3.25
BRBF	(*Buckling Restrained Braced Frame*):	R = 8
SPSW	(*Special Plate Shear Walls*):	R = 7
Undetailed Steel Systems in	Seismic Design Categories B or C (AISC Seismic Provisions not needed)	R = 3

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Seismic Resistant Design

Key Elements:

General Seismic Design Requirements and required Lateral Strength and Stiffness
Specified by ASCE 7-16:
Minimum Design Loads for Buildings and Other Structures

↕

Ductile Detailing Requirements

For steel structures: Specified by AISC 341-16:
Seismic Provisions for Structural Steel Buildings

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AISC Seismic Provisions: AISC 341

AISC 341:

- Design and detailing requirements to achieve appropriate level of ductility.
- Used together with AISC 360 (Specification for Structural Steel Buildings).
- AISC 341 focus is on "systems"
- AISC 341 used when required by the Applicable Building Code

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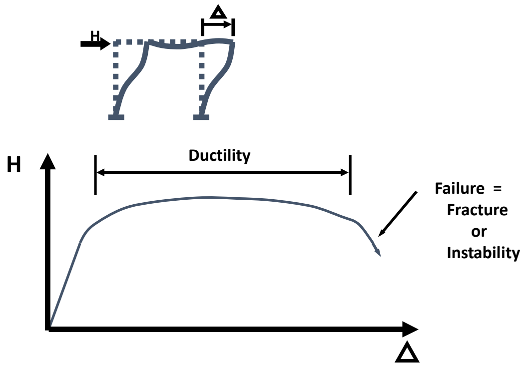

Seismic Design: Balance strength with ductility

- Achieving required strength: AISC 360
- Achieving required ductility: AISC 341

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2016 AISC Seismic Provisions for Structural Steel Buildings (AISC 341-16)

Symbols

Glossary

- **A. General Requirements**
- **B. General Design Requirements**
- **C. Analysis**
- **D. General Member and Connection Design Requirements**
- **E. Moment Frame Systems**
- **F. Braced Frames and Shear-Wall Systems**
- **G. Composite Moment Frame Systems**
- **H. Composite Braced Frame and Shear-Wall Systems**
- **I. Fabrication and Erection**
- **J. Quality Control and Quality Assurance**
- **K. Prequalification and Cyclic Qualification Testing Provisions**

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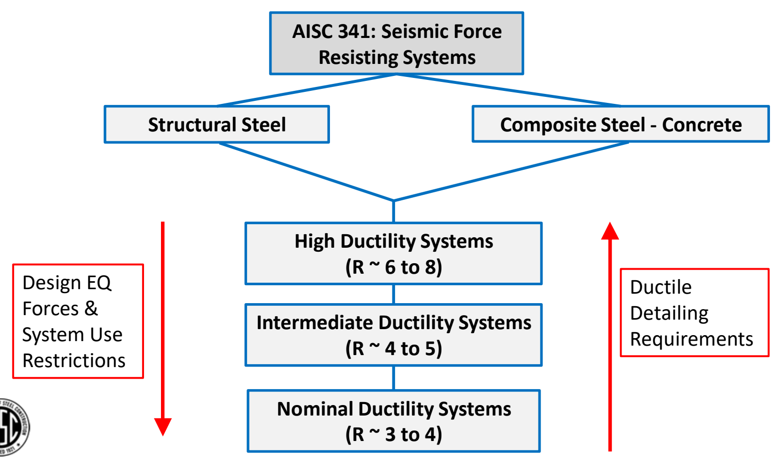

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AISC 341 – Examples of Structural Steel Seismic Force Resisting Systems

High Ductility Systems:

- Special Moment Frames (SMF): R = 8
- Eccentrically Braced Frames (EBF): R = 8
- Buckling Restrained Braced Frames (BRBF): R = 8
- Special Plate Shear Walls (SPSW): R= 7
- Special Truss Moment Frames (STMF): R = 7
- Special Concentrically Braced Frames (SCBF): R = 6

Intermediate Ductility Systems:

- Intermediate Moment Frames (IMF): R = 4.5

Nominal Ductility Systems:

- Ordinary Moment Frames (OMF): R = 3.5
- Ordinary Concentrically Braced Frames (OCBF): R = 3.25

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Guiding Principle for High Ductility Systems: *Capacity Design*

1. **Choose frame elements ("fuses") that will yield in an earthquake; e.g. beams in moment resisting frames, braces in concentrically or buckling restrained braced frames, links in eccentrically braced frames, etc.**

2. **Detail "fuses" to sustain large inelastic deformations prior to the onset of fracture or instability (i.e. detail fuses for ductility).**

3. **Design all other frame elements to be stronger than the fuses, i.e. design all other frame elements to develop the plastic *capacity* of the fuses.**

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Additional Concepts for Developing Ductility

- **Avoid high strength steels in ductile elements.**
- **Use cross-sections with low b/t ratios (delay local buckling).**
- **Provide adequate lateral bracing (delay lateral torsional buckling).**
- **Connections generally stronger than members.**
- **Conservative column design.**
- **Take care in welding and welding quality control.**

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Overview of Selected High Ductility Systems

- **Special Moment Frames (SMF)**
- **Special Concentrically Braced Frames (SCBF)**
- **Eccentrically Braced Frames (EBF)**
- **Buckling Restrained Braced Frames (BRBF)**

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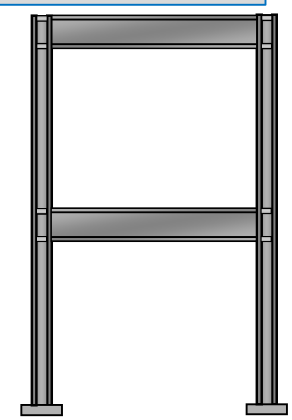
Special Moment Frames (SMF)

Beams and columns with moment resisting connections; resist lateral forces by flexure and shear in beams and columns - i.e. by frame action.

Develop ductility primarily by flexural yielding of the beams.



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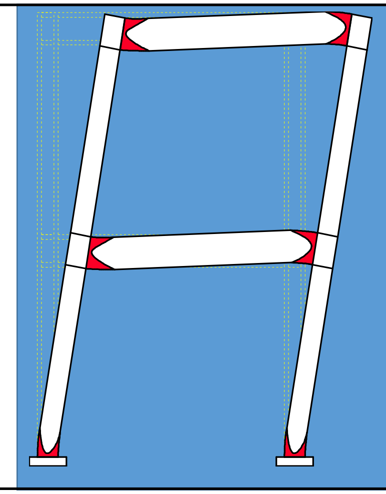
Inelastic Response of SMF



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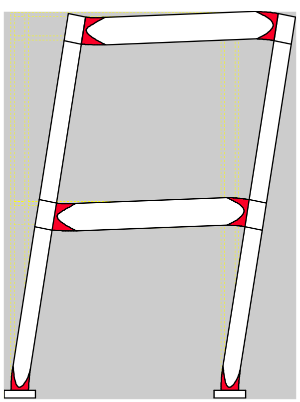
Developing Ductile Behavior in SMF – General Approach



- Design frame so that inelastic behavior is restricted primarily to flexural yielding in the beams, with limited yielding permitted in column panel zones..
- Choose beam section that satisfy highly ductile b/t limits.
- Provide beam lateral bracing that satisfies highly ductile requirements.

- Design beam-column connections to develop strength of beams.
- Choose columns with flexural capacity greater than beams (so plastic hinges form in beams); and choose columns to resist axial forces developed by fully yielded beams.

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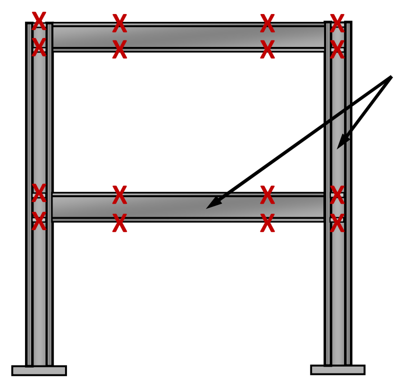
Developing Ductile Behavior in SMF – Additional Details



Beams and Columns:

Satisfy b/t limits for *highly ductile* members

Provide lateral bracing that satisfies requirements *highly ductile* members

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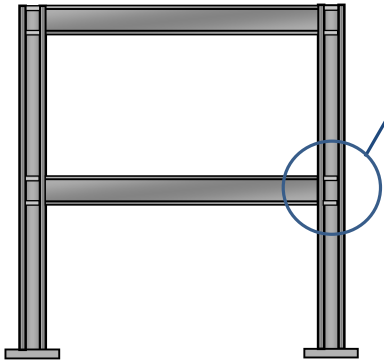

Beam-to-Column Connections:

Capable of ± 0.04 rad. without failure.

Connection qualified by testing (Chapter K) or prequalified per AISC 358-16

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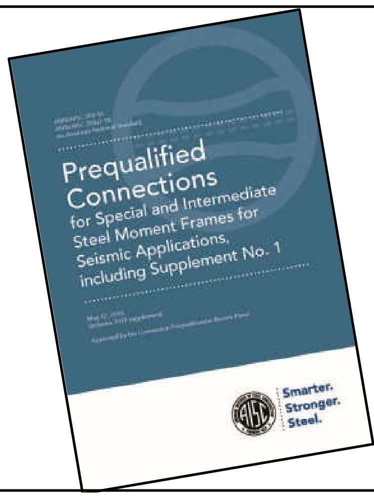

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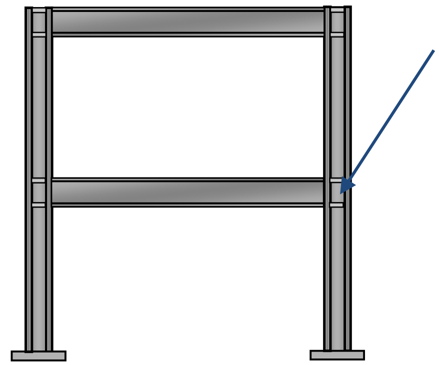

Panel Zone Shear Strength:

Develop flexural strength of beam.

May require doubler plates.

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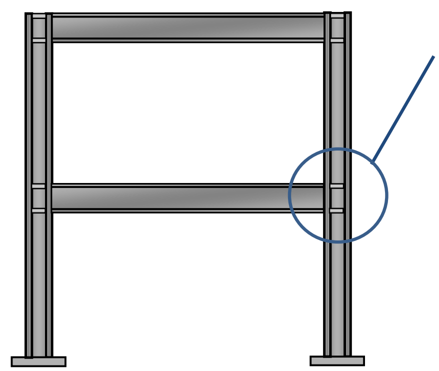

Strong Column – Weak Girder:

$$\frac{\Sigma M_{pc}^{*}}{\Sigma M_{pb}^{*}} > 1.0$$

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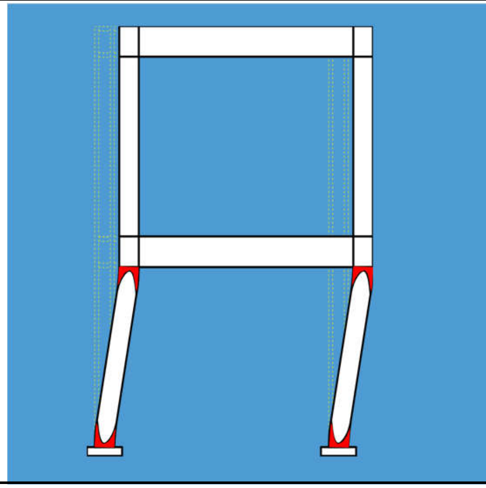

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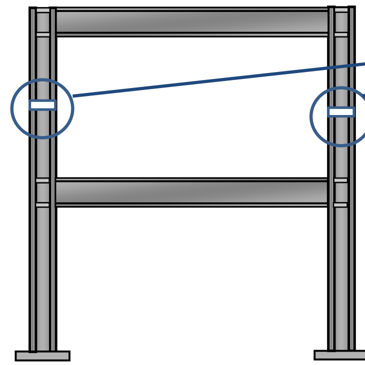

Column Splices:

Splices develop full flexural and shear strength of column.

CJP Groove welds usually required.

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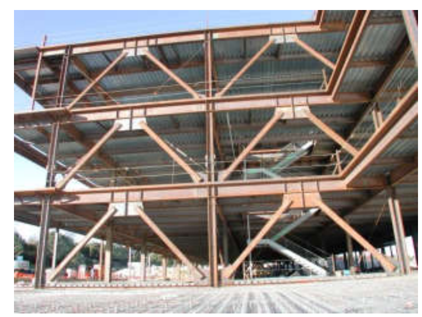
Special Concentrically Braced Frames (SCBF)

Beams, columns and braces arranged to form a vertical truss. Resist lateral earthquake forces by truss action.

Develop ductility through inelastic action in braces.

- braces yield in tension
- braces buckle in compression



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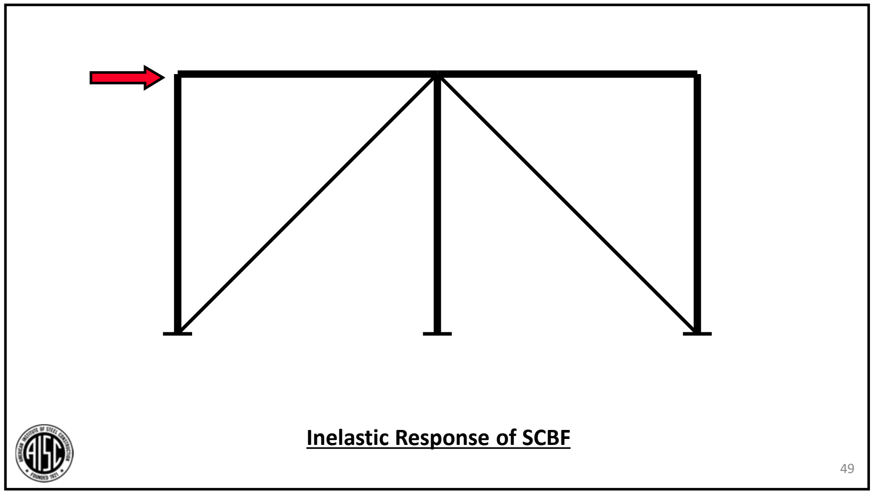
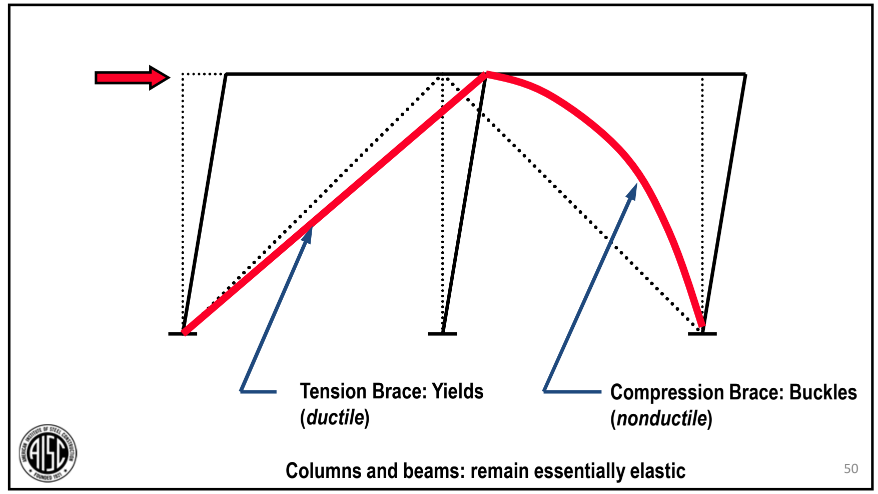
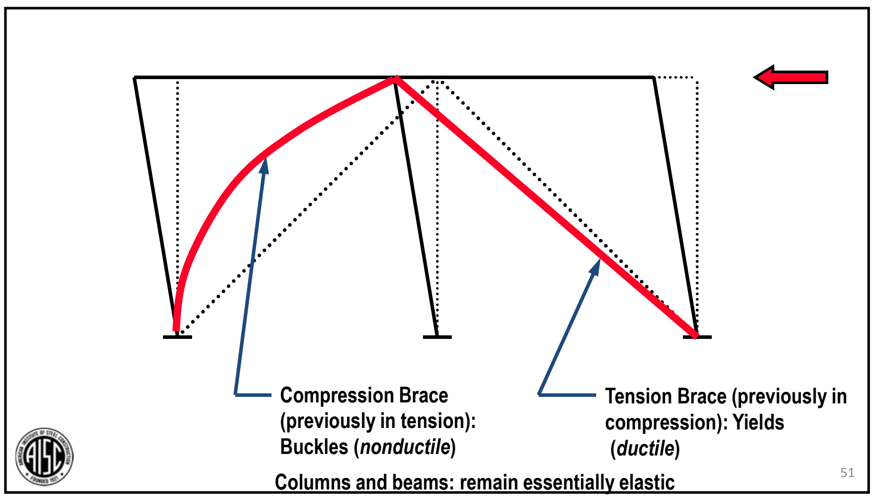
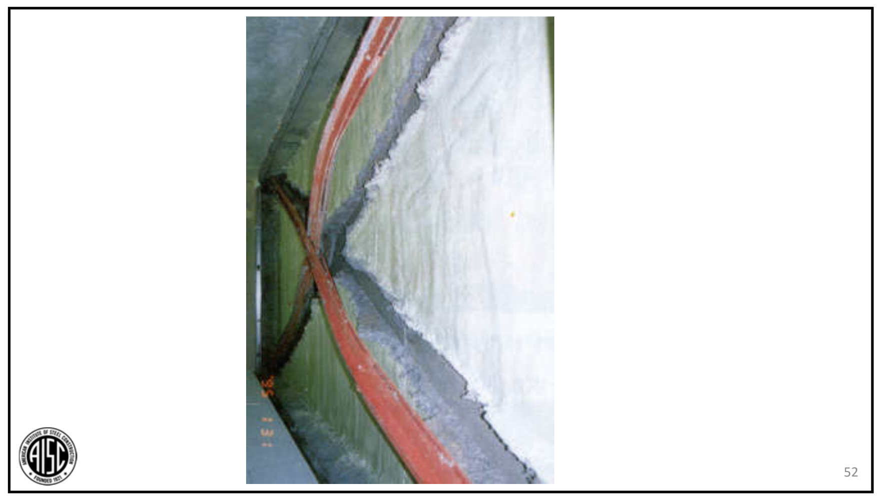

Inelastic Response of SCBF
49


Tension Brace: Yields
(ductile)
Compression Brace: Buckles
(nonductile)
Columns and beams: remain essentially elastic
50


Compression Brace
(previously in tension):
Buckles (nonductile)
Tension Brace (previously in
compression): Yields
(ductile)
Columns and beams: remain essentially elastic
51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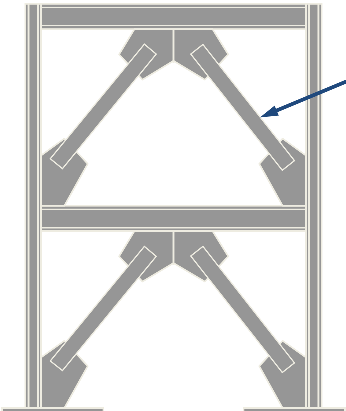
Developing Ductile Behavior in SCBF



- Design frame so that inelastic behavior is restricted to braces.
  - Braces are "fuse" elements of frame.
  - Braces are weakest element of frame.
- Balance tension and compression braces (so reasonable number of braces are in tension for each direction of loading).
- Choose brace members with good energy dissipation capacity and fracture life (limit kL/r and b/t).

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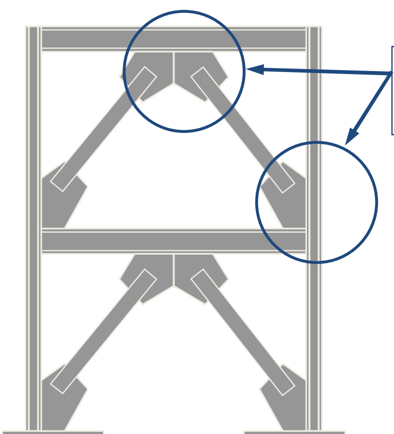

- **Design brace connections for maximum forces and deformations imposed by brace during cyclic yielding/buckling**

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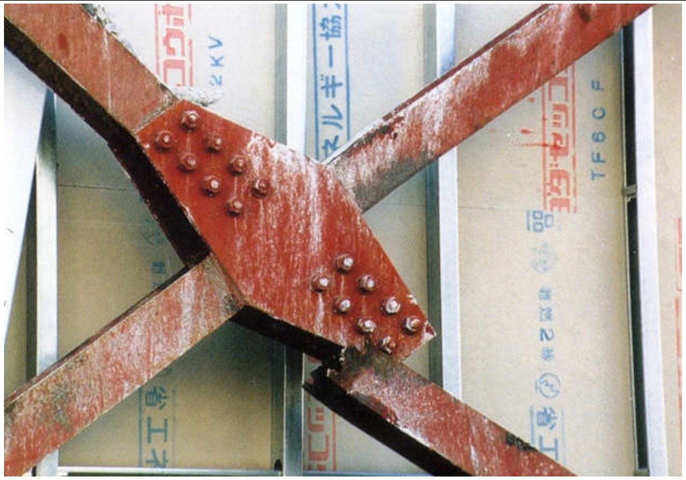

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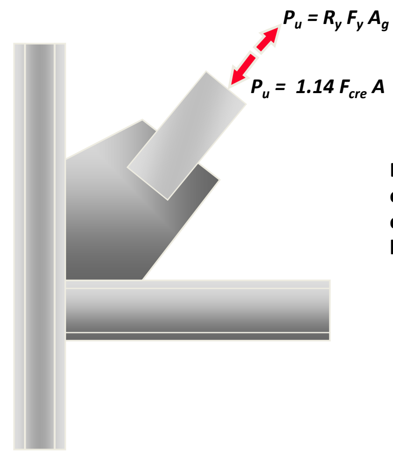

Design brace connection for expected tension and compression strength of brace

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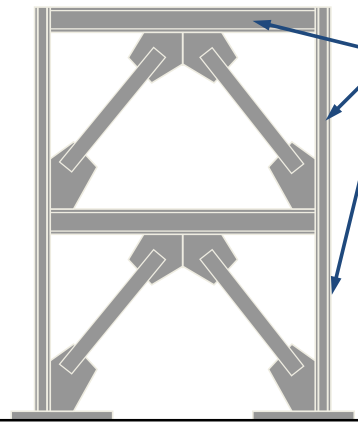

- Design beams and columns (and column splices and column bases) for maximum forces imposed by braces

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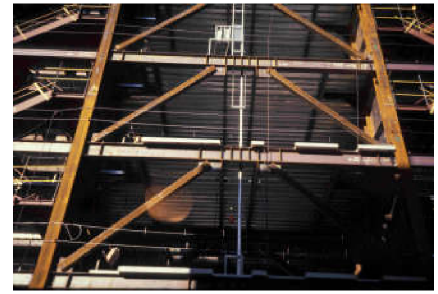
Eccentrically Braced Frames (EBF)

Framing system with beam, columns and braces. At least one end of every brace is connected to isolate a segment of the beam called a *link.*

Develop ductility through inelastic action in the links.



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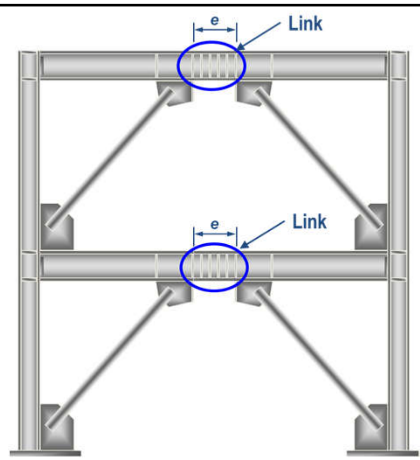

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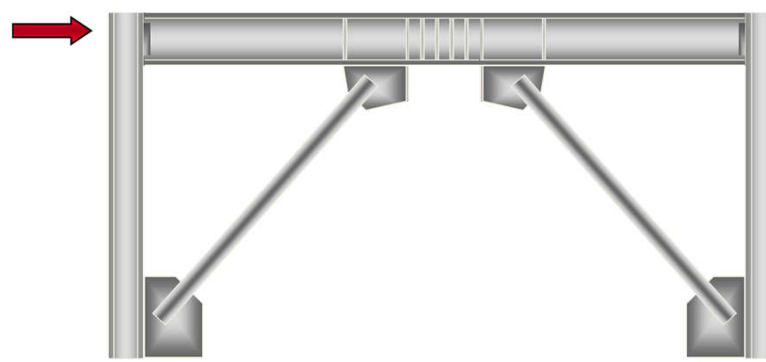

Inelastic Response of EBF

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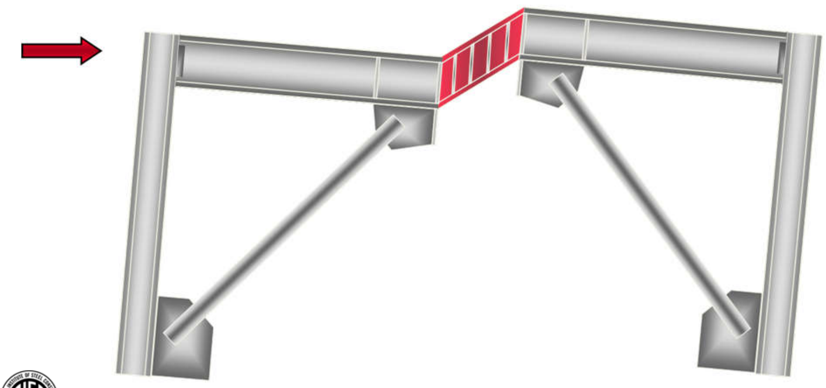

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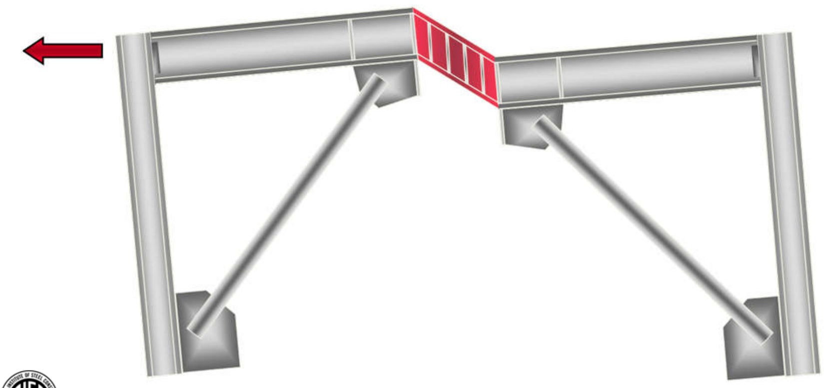

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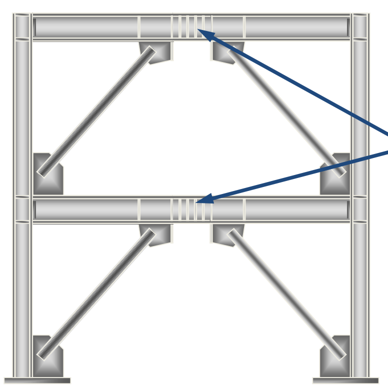
Developing Ductile Behavior in EBF



- Design frame so that inelastic behavior is restricted to links.
  - Links are "fuse" elements of frame.
  - Links are weakest element of frame.
- Detail links to provide high ductility (stiffeners, lateral bracing).

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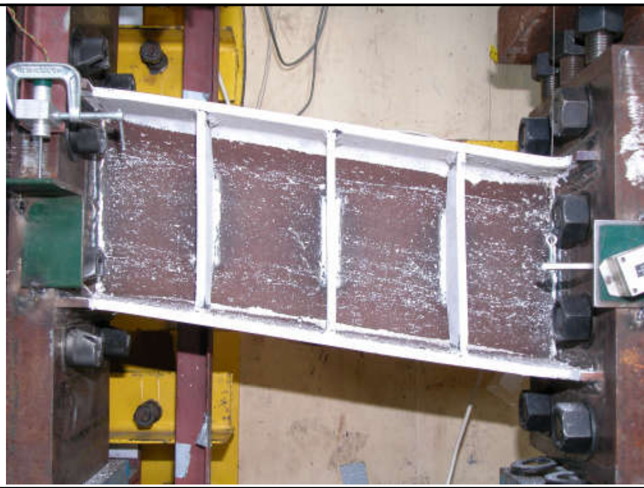

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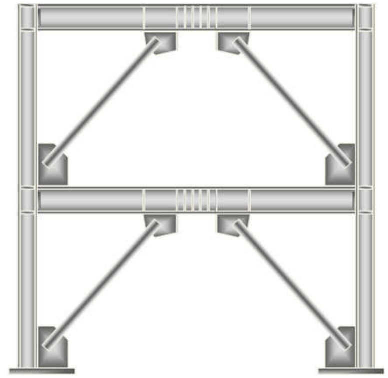

- Design all other frame elements (braces, column, beam segments outside of links) and connections to develop full strength of links

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Buckling Restrained Braced Frames (BRBF)

Type of concentrically braced frame.

Beams, columns and braces arranged to form a vertical truss. Resist lateral earthquake forces by truss action.

Special type of brace members used: *Buckling-Restrained Braces (BRBs)*. BRBs yield both in tension and compression - *no buckling !!*

Develop ductility through inelastic action (cyclic tension and compression yielding) in BRBs.

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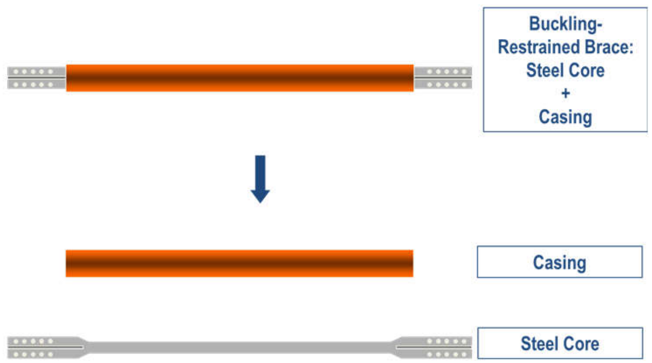
Buckling-Restrained Brace



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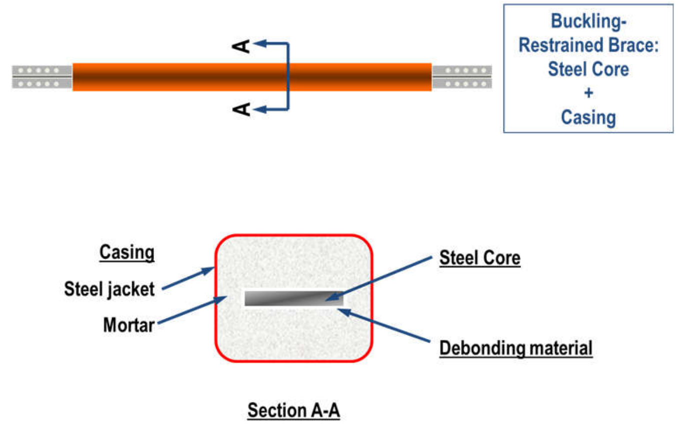

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Steel core resists entire axial force P

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

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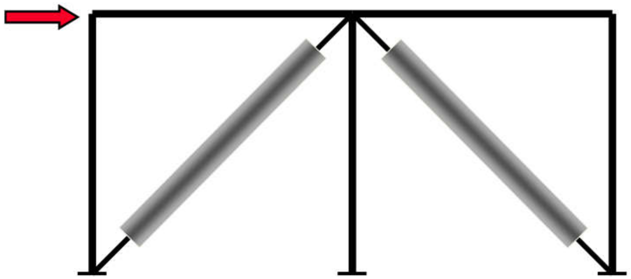

Inelastic Response of BRBF

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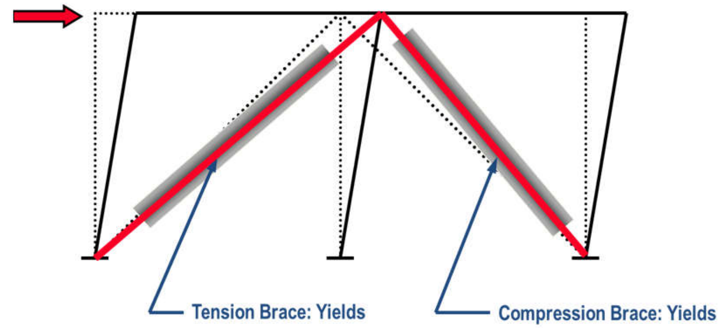

Columns and beams: remain essentially elastic

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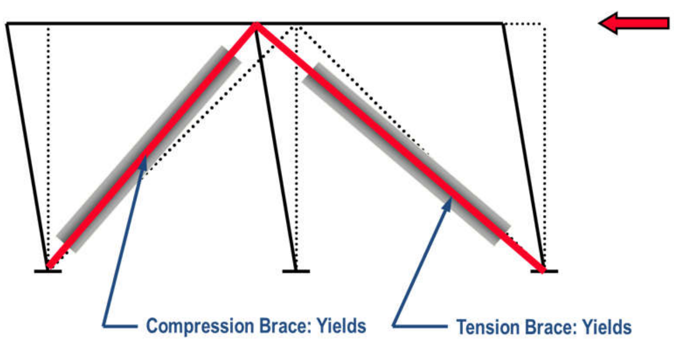

Columns and beams: remain essentially elastic

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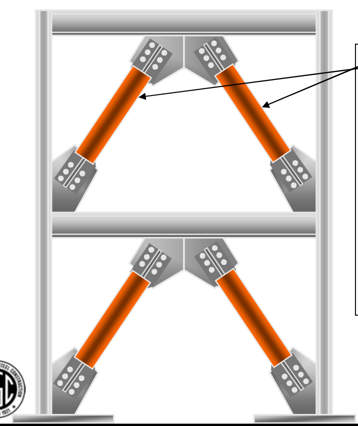
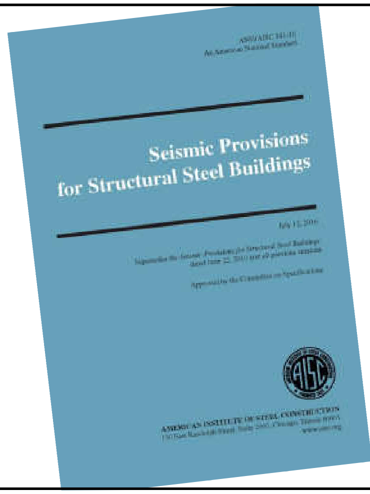
Developing Ductile Behavior in BRBF



- BRBs are "fuse" elements.
- Choose BRB design with performance verified by testing
- Design all other frame elements (beams, columns, brace connections, column bases) for maximum forces that can be generated by fully yielded and strain hardened BRBs

80



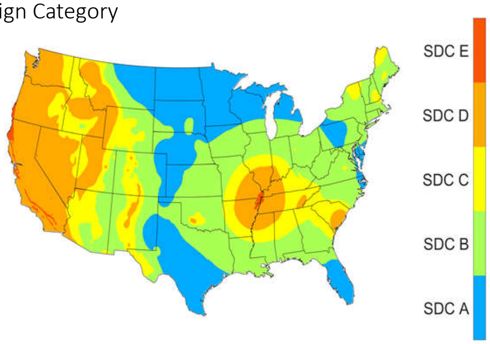
81

2. Practical Applications of AISC 341

82

ASCE 7-16 SDC Map for Default Site Class

SDC: Seismic Design Category



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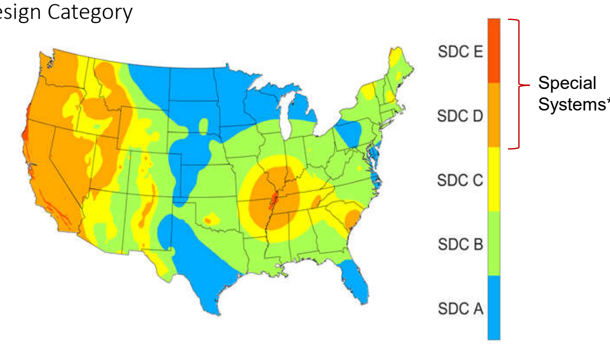
ASCE 7-16 SDC Map for Default Site Class

SDC: Seismic Design Category



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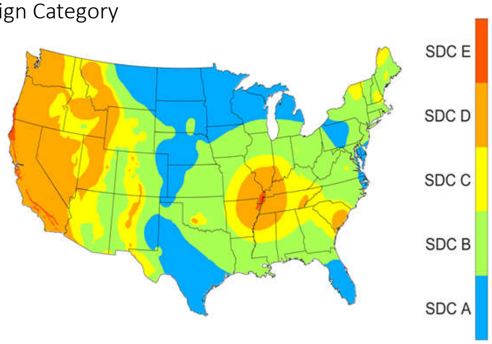
ASCE 7-16 SDC Map for Default Site Class

SDC: Seismic Design Category

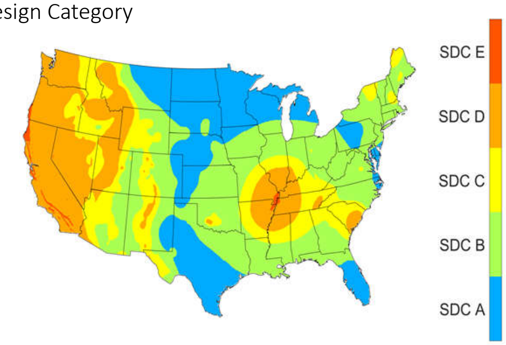


Ordinary, Intermediate and Special Systems
R = 3 Systems

85

ASCE 7-16 SDC Map for Default Site Class

SDC: Seismic Design Category



Designed per Chapter 1 of ASCE 7

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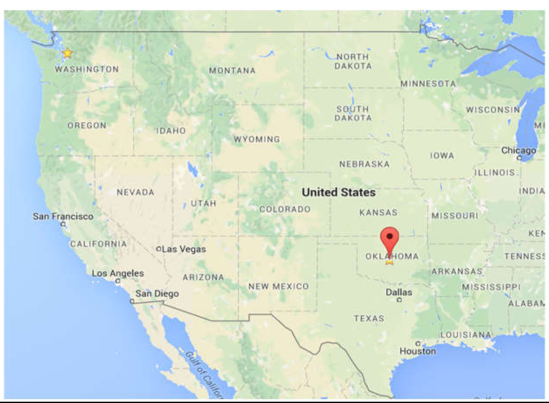
Case Study 1: Oklahoma City Convention Center



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Case Study 1: Oklahoma City Convention Center

88

Case Study 1: Oklahoma City Convention Center

3-story, 550,000-ft²
Convention Center

- Exhibit Hall: 200,000-ft²
- Meeting Room: 45,000-ft²
- Ballroom Space: 30,000-ft²

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Case Study 1: Oklahoma City Convention Center

Architect: Populous
Builder: Flintco
MKA Team:

- Derek Beaman (PIC)
- Chris Lubke (PM)

Delivery Method:

- Conventional Design-Build Contract

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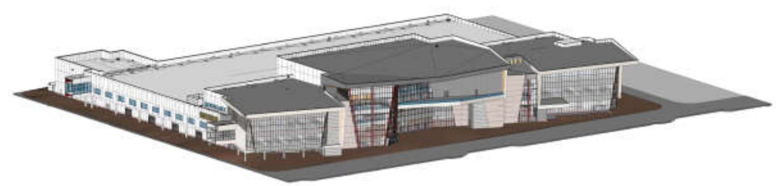
Case Study 1: Oklahoma City Convention Center

91

Case Study 1: Oklahoma City Convention Center



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Case Study 1: Oklahoma City Convention Center

- Seismic Design Parameters:
- Site Class B
- Seismic Design Category B (Low Seismic Hazard Site)
- Risk Category III

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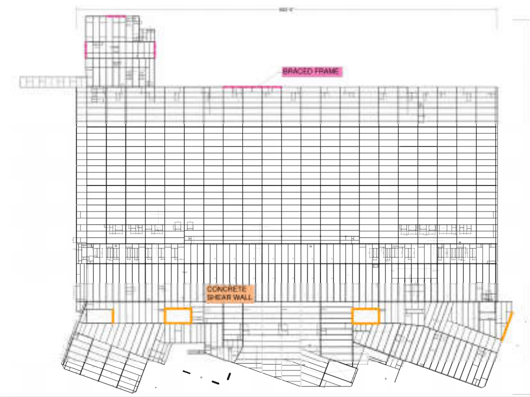
Case Study 1: Oklahoma City Convention Center



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Case Study 1: Oklahoma City Convention Center

- Lateral Force-Resisting System Options:
- R = 3 Steel System
- OCBF (R = 3.25)
- SCBF (R = 6)
- Detailed Plain Concrete Shear Walls (R = 2)
- Ordinary Concrete Shear Walls (R = 5)
- Special Concrete Shear Walls (R = 6)
- Foundation System:
- Drilled Concrete Piers and Shafts

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Case Study 1: Oklahoma City Convention Center

- Lateral Force-Resisting System Options:
- R = 3 Steel System
- OCBF (R = 3.25)
- SCBF (R = 6)
- Detailed Plain Concrete Shear Walls (R = 2)
- Ordinary Concrete Shear Walls (R = 5)
- Special Concrete Shear Walls (R = 6)
- Foundation System:
- Drilled Concrete Piers and Shafts

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Case Study 1: Oklahoma City Convention Center

- Resulting Base Shears (ASCE 7-10)
- Wind
  - X-dir = 903 kips
  - Y-dir = 1453 kips
- Seismic
  - Both Dir = 1200 kips (R = 6)
  - Both Dir = 2400 kips (R = 3)

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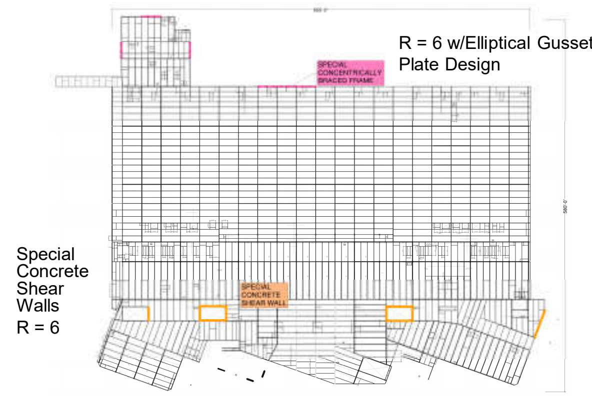
Case Study 1: Oklahoma City Convention Center



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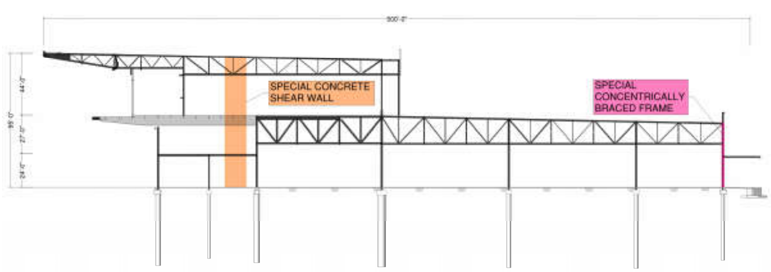
Case Study 1: Oklahoma City Convention Center



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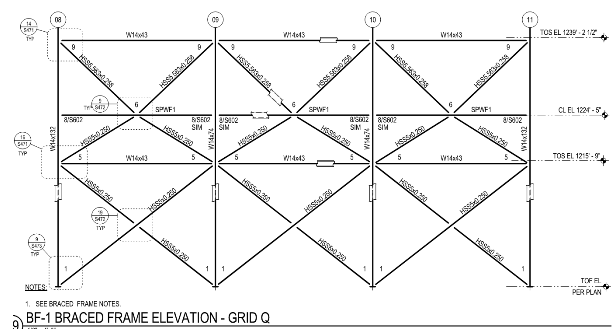
Case Study 1: Oklahoma City Convention Center



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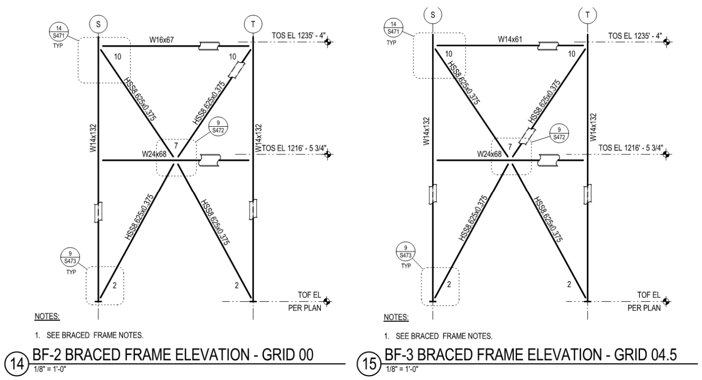
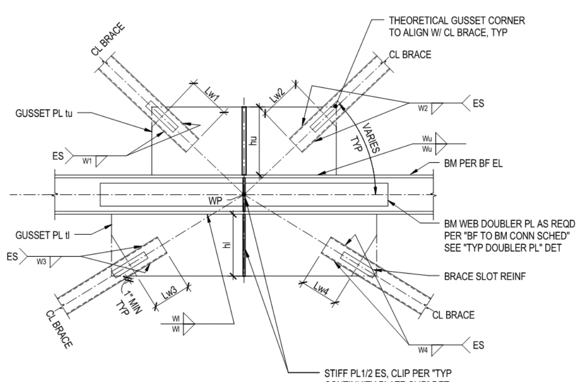
Case Study 1: Oklahoma City Convention Center



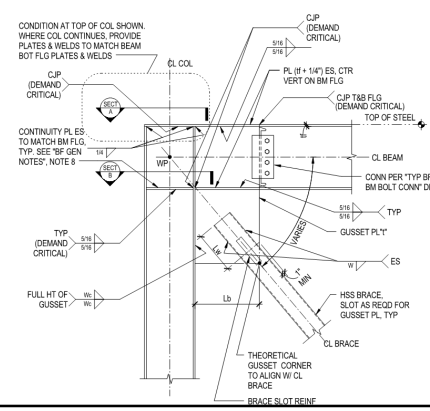
Case Study 1: Oklahoma City Convention Center

- Resulting Connection Demands:
- SCBF R = 6
  - Brace Size Based on Compression Capacity
  - Connection Design Based on Brace Tension Capacity ($R_yF_yA_g$)
- R = 3 Braced Frame
  - Connection Design Based on Analysis Results
- SCBF Connection Factor Ranged from 1.5 to 2.5

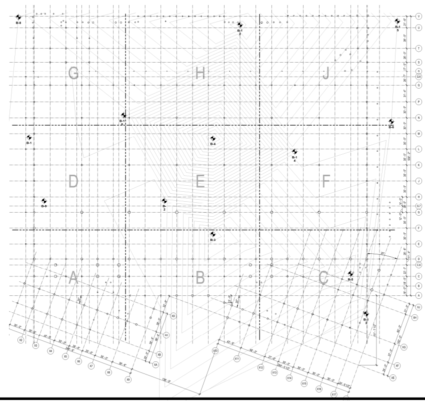
Case Study 1: Oklahoma City Convention Center



Case Study 1: Oklahoma City Convention Center



Case Study 1: Oklahoma City Convention Center



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Case Study 1: Oklahoma City Convention Center

- Foundation Considerations
- Lateral Resistance Provided Primarily by Drilled Concrete Piers and Shafts
- Correlation Between Lateral Base Shear and Number of Piles → Foundation Costs

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Case Study 2: Gateway of Pacific Phase 3

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Case Study 2: Gateway of Pacific Phase 3

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Case Study 2: Gateway of Pacific Phase 3

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Case Study 2: Gateway of Pacific Phase 3

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Case Study 2: Gateway of Pacific Phase 3

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Case Study 2: Gateway of Pacific Phase 3

- Seismic Design Parameters:
- Site Class B
- Seismic Design Category E (Very High Seismic Hazard Site)
  - S_{DS} = 1.267
  - S_{D1} = 0.592
- Risk Category II

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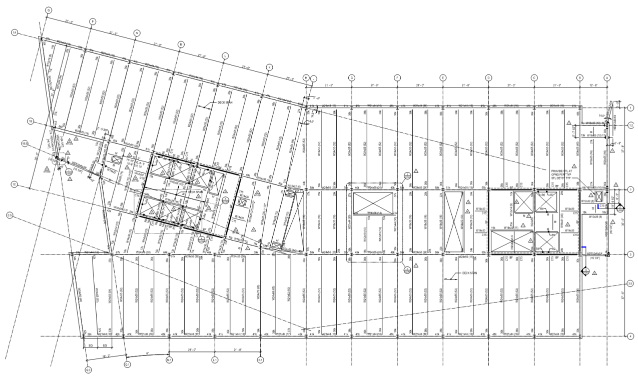
Case Study 2: Gateway of Pacific Phase 3



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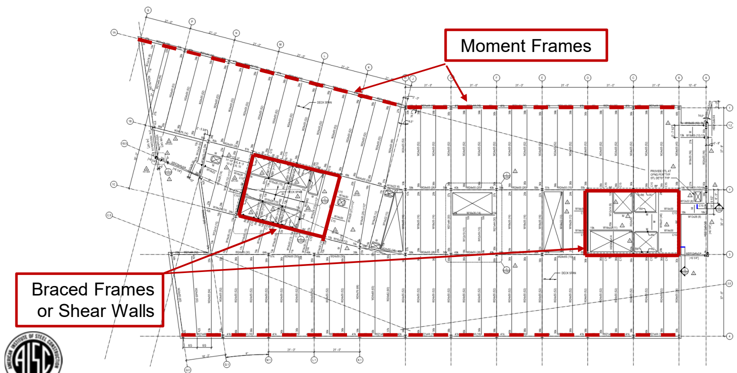
Case Study 2: Gateway of Pacific Phase 3



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Case Study 2: Gateway of Pacific Phase 3

- Lateral Force-Resisting System Options:
- Special Concrete Shear Walls (R = 6)
- SCBF (R = 6)
- SMF (R = 8)
- BRBF (R = 8)
- Foundation System:
- Mat/Spread Footings (Fp = 10,000 psf)

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Case Study 2: Gateway of Pacific

- Resulting Base Shears (CBC 2016 / ASCE 7-16)
- Wind
  - X-Dir = 1040 kips
  - Y-Dir = 2100 kips
- Seismic
  - Both Dir = 1690 kips (R = 8)
  - Both Dir = 2260 kips (R = 6)

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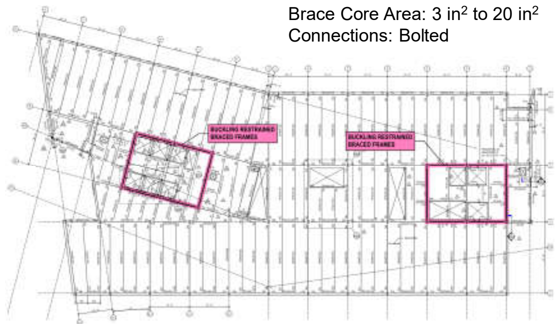
Case Study 2: Gateway of Pacific Phase 3



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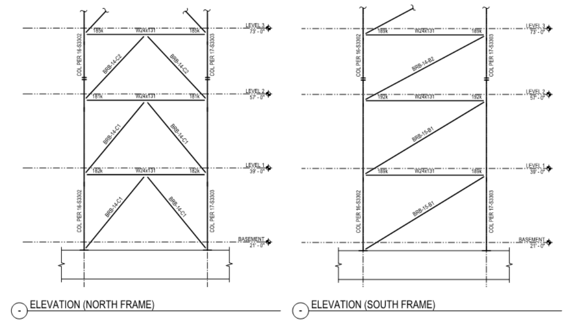
Case Study 2: Gateway of Pacific Phase 3



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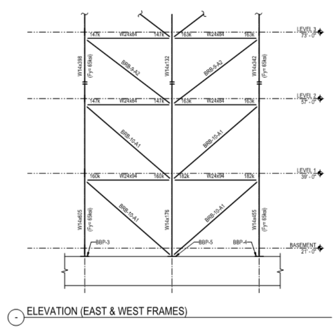
Case Study 2: Gateway of Pacific Phase 3



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Case Study 2: Gateway of Pacific Phase 3

- Resulting Connection Demands:
- Brace Core Area Sized Using Loading from Analysis
- Connection Design Based on Expected Brace Strength
  - Compression: $\omega\beta R_y P_{ysc}$
  - Tension: $\omega R_y P_{ysc}$

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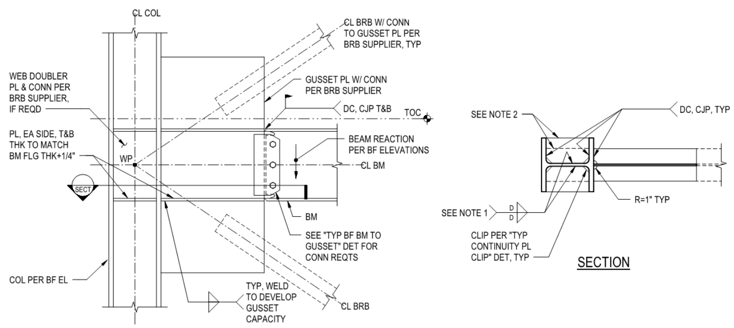
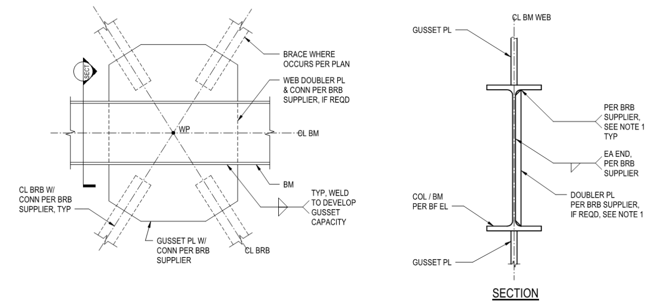
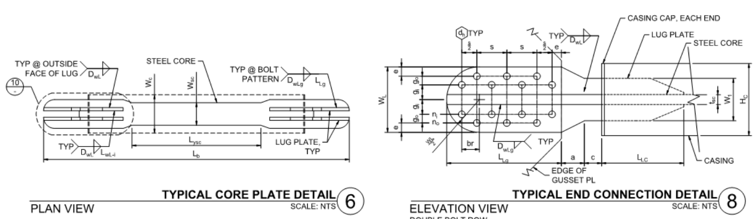
Case Study 2: Gateway of Pacific Phase 3



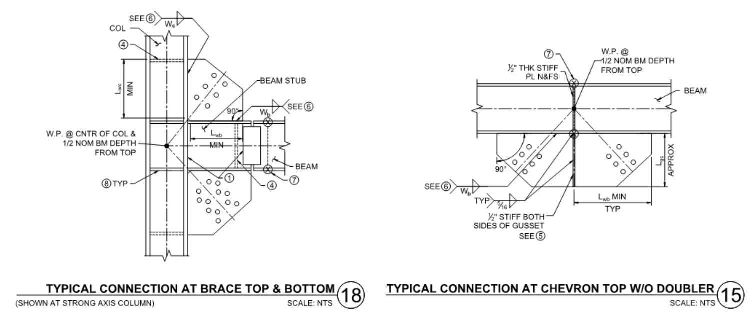
Case Study 2: Gateway of Pacific Phase 3



Case Study 2: Gateway of Pacific Phase 3



Case Study 2: Gateway of Pacific Phase 3



Case Study 2: Gateway of Pacific Phase 3

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Performance-Based Seismic Design (NLRHA)

- High Seismic Hazard Locations (SDC D or E)
  - New Systems
  - Buildings With Structural Height > 240′
    - Exceeds System Height Limit
  - Buildings With Structural Height > ~160′
    - Column Axial Demands Become "Excessive"
      - Capacity-limit Design Requirements
      - Intersecting Frame Effects Requirements

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Performance-Based Seismic Design (NLRHA)

Section D1.4a

For columns that are common to intersecting frames, determination of the required axial strength, including the overstrength seismic load or the capacity-limited seismic load, as applicable, shall consider the potential for simultaneous inelasticity from all such frames. The direction of application of the load in each such frame shall be selected to produce the most severe load effect on the column.

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Performance-Based Seismic Design (NLRHA)

Section D1.4a

Exceptions:

(a) It is permitted to limit the required axial strength for such columns based on a three-dimensional nonlinear analysis in which ground motion is simultaneously applied in two orthogonal directions, in accordance with Section C3.

(b) Columns common to intersecting frames that are part of Sections E1, F1, G1, H1, H4 or combinations thereof need not be designed for these loads.

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Performance-Based Seismic Design (NLRHA)

C3. Nonlinear Analysis

When nonlinear analysis is used to satisfy the requirements of these Provisions, it shall be performed in accordance with the applicable building code.

User Note: ASCE/SEI 7 permits nonlinear analysis by a response history procedure. Material and geometric nonlinearities are to be included in the analytical model. The main purpose is to determine expected member inelastic deformations and story drifts under representative ground motions. The analysis results also provide values of maximum expected internal forces at locations such as column splices, which can be used as upper limits on required strength for design.

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Performance-Based Seismic Design (NLRHA)

C3. Nonlinear Analysis

When nonlinear analysis is used to satisfy the requirements of these Provisions, it shall be performed in accordance with the applicable building code.

User Note: ASCE/SEI 7 permits nonlinear analysis by a response history procedure. Material and geometric nonlinearities are to be included in the analytical model. The main purpose is to determine expected member inelastic deformations and story drifts under representative ground motions. The analysis results also provide values of maximum expected internal forces at locations such as column splices, which can be used as upper limits on required strength for design.

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Performance-Based Seismic Design — "New System"

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Performance-Based Seismic Design — Rainier Square

1.4 Million sf
850-feet Tall
58-story Office + Residential
7 Levels Below-grade Parking
722,000 sf Office Space
200 Apartment Units
1000 Parking Stalls

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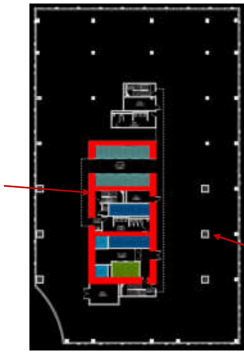
Performance-Based Seismic Design — Rainier Square

Typical Low-Rise Office



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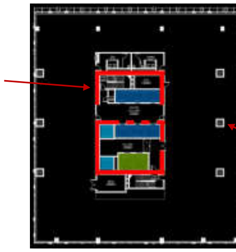
Performance-Based Seismic Design — Rainier Square

Typical High-Rise Office



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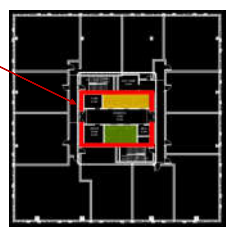
Performance-Based Seismic Design — Rainier Square

Typical Residential



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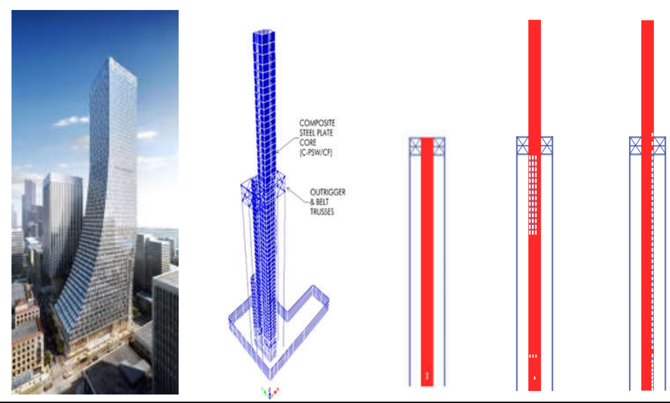
Performance-Base Seismic Design — Rainier Square



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Performance-Based Seismic Design — Rainier Square

137

Performance-Based Seismic Design — Rainier Square

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Performance-Based Seismic Design — Buildings > 240′

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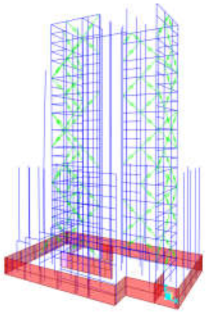
Performance-Based Seismic Design — 5MH1



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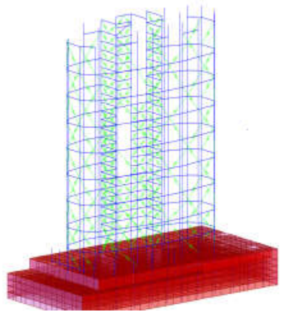
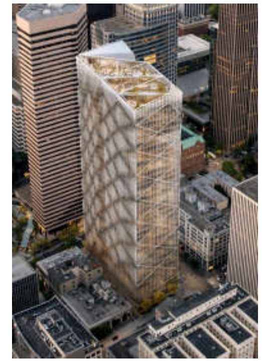
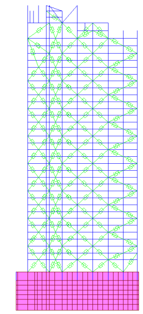
Performance-Based Seismic Design — NE8



141

Performance-Based Seismic Design — Marion Tower





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Summary

- Seismic Design Category → Lateral Force-Resisting System
  - But Not Always
  - Overall Building Cost is Primary Driver
- Use of PBSD (NLRHA) is Becoming More Commonplace in High Seismic Hazard Regions
  - Buildings with Structural Height > 160′

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AISC | Questions?

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CEU / PDH Certificates

For those participating at their own connection…

- Reporting attendance is not necessary.
- Certificates will be issued based on AISC's attendance record.
- You will be receiving certificates via email from registration@aisc.org.

Smarter.
Stronger.
Steel.

CEU / PDH Certificates

For those participating at one connection with a group…

- Main registrant will report attendance via an online form. (The link will be provided in an email from registration@aisc.org.)
  - Username: Same as AISC website username.
  - Password: Same as AISC website password.
- Once attendance has been reported, each group member will be receiving certificates via email from registration@aisc.org.

Smarter.
Stronger.
Steel.

AISC | Thank you

Smarter.
Stronger.
Steel.