Underlying Concepts in Seismic Design Codes

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Recorded video at http://www.aisc.org/content.aspx?id=26268
Seismic Loadings Codes

- 1985 UBC ($K$ Factor)
- 1988 UBC ($R_w$ Factor)
- 1997 UBC ($R$ Factor)
- ASCE 7, IBC ($R$ Factor)
Steel Materials Codes

- 1985 UBC
- 1988 UBC
  
  <1994 Northridge Earthquake>
- 1997 UBC
- FEMA 350
- Seismic Provisions (AISC 341)
- Prequalified Connections (AISC 358)
- AWS D1.8
Objective of Presentation

- Fundamental Concepts Underlying the Seismic Provisions
- Why and How These Concepts Are Implemented in AISC Seismic Provisions
- Not to Elaborate Detailed Design Provisions of any Particular System
- Some Popular Systems Will be Used to Demonstrate the Concepts
Basic Load Combinations (ASCE 7-10)

1. $1.4D$
2. $1.2D + 1.6L + 0.5(Lr \text{ or } S \text{ or } R)$
3. $1.2D + 1.6(Lr \text{ or } S \text{ or } R) + (L \text{ or } 0.5W)$
4. $1.2D + 1.0W + L + 0.5(Lr \text{ or } S \text{ or } R)$
5. $1.2D + 1.0E + L + 0.2S$
6. $0.9D + 1.0W$
7. $0.9D + 1.0E$
Earthquake “Load”

- Earthquake-Induced Inertia Effect on Structures
Elastic Response Spectra

\[ S_a = \left( \frac{2\pi}{T} \right)^2 S_d \]

Max. Member Force = \( M \times S_a \)
Design Basis Earthquake (ASCE 7)

\[ S_a = \frac{S_{D1}}{T} \]

\[ S_a = \frac{S_{D1}T_L}{T^2} \]
“1g” Building

\[ V_b = 1g \times \bar{M} \]
Resort to DUCTILITY
(or Trade Ductility for Strength)
Ductility Factor

Base Shear, $V$

$V_e = W(S_a) \times 1/R_{\mu}$

\[ \mu = \frac{\Delta_m}{\Delta_y} \]

$\Delta_y$, $\Delta_e$, $\Delta_m$
Newmark-Hall Ductility Reduction Rule

Base Shear, $V$

$V_e \times \frac{1}{R_\mu}$

$V_y$

$\Delta_y$  $\Delta_m$  $\Delta$

Equal Displacement Rule

Ductility Reduction Factor:

$R_\mu = \mu$
Seismic Design Concept 1—Ductility Design

- A Reduced Design Seismic Force Can Be Used **IF** Sufficient Ductility Is Built into the Structure
- But Only a Certain Elements Are Strategically Designated to Serve as Structural Fuses, i.e., Deformation-Controlled Elements (DCE)
Example

• Diagonal Braces as Structural Fuse
• Braces to Buckle Out of Plane
• To Achieve This, More Effort Is Needed to Make It Happen!
Seismic Design Concept 2—"Capacity Design"

- Remaining Part of the Structure Is Designed to Remain Elastic, i.e., Designed These Elements as Force-Controlled Elements (FCE)
Two Key Concepts in AISC Seismic Provisions (AISC 341)

Ductility Design Provisions
+
Capacity Design Provisions

Seismic Provisions for Structural Steel Buildings

June 22, 2010
# Ductility vs. Capacity Design

<table>
<thead>
<tr>
<th>Research Effort</th>
<th>Ductility Design (Deformation-Controlled Elements)</th>
<th>Capacity Design (Force-Controlled Elements)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>More</td>
<td></td>
</tr>
<tr>
<td>Design Effort</td>
<td>Easier (Straightforward)</td>
<td>Requires Understanding/Judgment</td>
</tr>
</tbody>
</table>
SCBF Design Provisions (AISC 341-05)

13.2. Members

13.2a. Slenderness

Bracing members shall have $\frac{E}{F_{y}} \geq 24$.

Exception: Braces with $\frac{E}{F_{y}} < 24$ may be permitted in frames in which the available strength of the column is at least equal to the maximum load transferred to the column consisting of $F_{y}$ (LRFD) or $1.5L_{1}S_{7}$ (ASD), as appropriate, times the nominal strength of the connecting brace elements of the building. Column forces shall not exceed those determined by seismic analysis, nor the maximum load effect that can be developed by the system.

13.2b. Required Strength

Where the effective area of bracing members is less than the gross area, the required axial strength of the brace based upon the limiting state of fracture in the net section shall be greater than the lesser of the following:

(a) The expected yield strength, in tension, of the bracing member, determined as $F_{y}A_{n}$ (LRFD) or $F_{y}A_{n}/1.5$ (ASD), as appropriate.

(b) The maximum load effect, indicated by analysis that can be transferred to the brace by the system.

User Note: This provision applies to bracing members where the section is reduced. A typical case is a skewed brace at the gusset plate connections.

13.2c. Lateral Force Distribution

Along any line of bracing, braces shall be deployed in alternate directions such that, for either direction of force parallel to the bracing, at least 50% but no more than 70% of the total horizontal force along that line is resisted by braces in tension, unless the available strength of such braces in compression is larger than the required strength resulting from the application of the appropriate load combinations stipulated by the applicable building code including the amplified seismic load. For the purposes of this provision, a line of bracing is defined as a single line or parallel lines with a pitch of 10 or less of the building distance perpendicular to the line of bracing.

13.2d. Width-Thickness Limitations

Columns and brace members shall meet the requirements of Section 8.2.

User Note: User Note: Sections 13.2a should be used for the design of tension-only bracing.

13.3. Required Strength of Bracing Connections

13.3a. Required Tensile Strength

The required tensile strength of bracing connections (including brace-to-column connections if part of the bracing system) shall be the lesser of the following:

(a) The expected yield strength, in tension, of the bracing member, determined as $F_{y}A_{n}$ (LRFD) or $F_{y}A_{n}/1.5$ (ASD), as appropriate.

(b) The maximum load effect, indicated by analysis that can be transferred to the brace by the system.

13.3b. Required Flexural Strength

The required flexural strength of bracing connections shall be equal to $1.1R_{f}M_{f}$ (LRFD) or $1.1L_{1}S_{7}R_{f}M_{c}$ (ASD), as appropriate, of the brace about the critical buckling axis.

Exception: Braces connections that meet the requirements of Section 13.3a can accommodate the kinetic forces associated with brace post-buckling deformations under this requirement.

13.4. Special Bracing Configuration Requirements

13.4a. V-Type and Inverted V-Type Bracing

V-type and inverted V-type SCBF shall meet the following requirements:

1. The required strength of braces integrated by braces, their connections, and supporting members shall be determined based on the load combinations of the applicable building code ensuring that the braces provide no support for dead and live loads. For load combinations that include earthquake forces, the earthquake effect on the braces shall be determined as follows:

(a) The forces in all braces in tension shall be assumed to be equal to $F_{y}A_{n}$

(b) The forces in all braces in compression shall be assumed to be equal to $0.55F_{y}$

2. Braces shall contain the same brace components. Both braces of the braces shall be laterally braced, with a minimum spacing of $L_{1} = L_{2}$ as specified by Equation 3.1-7 of the Specification. Lateral braces shall meet the provisions of Appendix E-A.6 and A-A.6-3 of the Specification, where $R_{f} = M_{f}$, and $L_{1}, L_{2}$, $S_{7}$ (ASD), as appropriate, of the brace and $C_{1} = 1.0$.

As a minimum, one set of lateral braces is required at the point of intersection of the V-type (or inverted V-type) bracing, unless the brace has sufficient out-of-plane strength and stiffness to assure stability between adjacent brace points.

User Note: One method of demonstrating sufficient out-of-plane strength and stiffness of the braces is to apply the bracing force defined in Equation 3.1-7 of the Specification to each brace, as to form a triangular couple; this leading should be in conjunction with the lumped forces defined in item (1) above. The stiffness of the brace (and its restraint) with respect to this torsional loading should be sufficient to satisfy Equation 3.1-6.

13.4b. K-Type Bracing

K-type braced frames are not permitted for SCBF.

13.5. Column Splices

In addition to the requirements in Section 8.4, column splices in SCBF shall be designed to avoid 50% of the net available flexural strength of the connected members. The required shear strength shall be $2M_{f} / (1-L_{1}S_{7})$ (ASD), as appropriate, where $L_{1}$ is the sum of the nominal plastic flexural strength of the column above and below the splice.

13.6. Protected Zone

The protected zone of bracing members in SCBF shall include the center one-quarter of the brace length, and a zone adjacent to each connection equal to the brace depth in the plane of buckling. The protected zone of SCBF shall include...
# SCBF Design Provisions (AISC 341-10)

**F2. Special Concentrically Braced Frames (SCBF)**  
9.1–217

1. **Scope**  
   ... 9.1–217

2. **Basis of Design**  
   ... 9.1–217

3. **Analysis**  
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4. **System Requirements**  
   ... 9.1–222
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   ... 9.1–222
   4b. **V- and Inverted V-Braced Frames**  
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   ... 9.1–223

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   ... 9.1–223
   5a. **Basic Requirements**  
   ... 9.1–223
   5b. **Diagonal Braces**  
   ... 9.1–224
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   ... 9.1–225

6. **Connections**  
   ... 9.1–225
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   ... 9.1–228
   6d. **Column Splices**  
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AISC 341-05

• Moment Frames (Sections 9, 10, 11)
• Special Truss Moment Frames (Section 12)
• Concentrically Braced Frames (Sections 13, 14)
• Eccentrically Braced Frames (Section 15)
• Buckling-Restrained Braced Frames (Section 16)
• Special Plate-Shear Walls (Section 17)
E. MOMENT-FRAME SYSTEMS

E1. Ordinary Moment Frames (OMF)
E2. Intermediate Moment Frames (IMF)
E3. Special Moment Frames (SMF)
E4. Special Truss Moment Frames (STMF)
E5. Ordinary Cantilever Column Systems (OCCS)
E6. Special Cantilever Column Systems (SCCS)
F. BRACED-FRAME AND SHEAR-WALL SYSTEMS

F1. Ordinary Concentrically Braced Frames (OCBF)
F2. Special Concentrically Braced Frames (SCBF)
F3. Eccentrically Braced Frames (EBF)
F4. Buckling-Restrained Braced Frames (BRBF)
F5. Special Plate Shear Walls (SPSW)
Ductility Design Concept
Target Yield Mechanism

Moment Frame

Concentrically Braced Frame

Eccentrically Braced Frame

$F$

Flexural Yielding

Tensile Yielding/Buckling

Shear Yielding
Ductility Requirements

Code Implementation Example 1: Special Moment Frame (SMF) Design

(Courtesy: M.D. Engelhardt)
Steel Moment Connections
RBS Moment Connection
RBS Moment Connection

Specimen 1
0.018 rad inelastic
Dynamic Testing of Pre-Northridge Moment Connection
RBS Moment Connection Response
Local Buckling Control
### TABLE I-8-1
Limiting Width-Thickness Ratios for Compression Elements

<table>
<thead>
<tr>
<th>Description of Element</th>
<th>Width-Thickness Ratio</th>
<th>Limiting Width-Thickness Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexure in flanges of rolled or built-up I-shaped sections [a], [c], [e], [g], [h]</td>
<td>b/t</td>
<td>$\lambda_{ps}$ (seismically compact) 0.30 $\sqrt{E/F_y}$</td>
</tr>
<tr>
<td>Uniform compression in flanges of rolled or built-up I-shaped sections [b], [h]</td>
<td>b/t</td>
<td>$\lambda_{ps}$ (seismically compact) 0.30 $\sqrt{E/F_y}$</td>
</tr>
<tr>
<td>Uniform compression in flanges of rolled or built-up I-shaped sections [d]</td>
<td>b/t</td>
<td>$\lambda_{ps}$ (seismically compact) 0.38 $\sqrt{E/F_y}$</td>
</tr>
<tr>
<td>Uniform compression in flanges of channels, outstanding legs of pairs of angles in continuous contact, and braces [c], [g]</td>
<td>b/t</td>
<td>$\lambda_{ps}$ (seismically compact) 0.30 $\sqrt{E/F_y}$</td>
</tr>
</tbody>
</table>
### TABLE D1.1

Limiting Width-to-Thickness Ratios for Compression Elements For Moderately Ductile and Highly Ductile Members

<table>
<thead>
<tr>
<th>Description of Element</th>
<th>Width-to-Thickness Ratio</th>
<th>( \lambda_{hd} ) Highly Ductile Members</th>
<th>( \lambda_{md} ) Moderately Ductile Members</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstiffened Elements</td>
<td>( b/t )</td>
<td>( 0.30 \sqrt{E/F_y} )</td>
<td>( 0.38 \sqrt{E/F_y} )</td>
<td></td>
</tr>
</tbody>
</table>
Lateral-Torsional Buckling

AISC SP §9.8:

\[ L_b = 0.086 r_y E / F_y \]
Panel Zone

AISC SP §9.3:

\[ t = \frac{(d_z + w_z)}{90} \]
Protected Zone
(AISC SP §9.3)
Ductility Requirements

Code Implementation Example 2:
Special Concentrically Braced Frame (SCBF) Design
Target Yield Mechanism

(Courtesy: K.C. Tsai, NCREE)
Bracing Ductility Requirements

- Bracing Buckling (SP §13.2a)

\[
\left( \frac{KL}{r} \right)_{\text{max}} = 4 \sqrt{\frac{E_s}{F_y}}
\]
Bracing Ductility Requirements

- **Local Buckling (SP §8.2b):** Seismically Compact

<table>
<thead>
<tr>
<th>Stiffen</th>
<th>(\frac{D}{t})</th>
<th>(1.12 \sqrt{\frac{F_y}{2.33 - c_a}} \leq 1.49 \sqrt{\frac{F_y}{E/F_y}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round HSS in axial and/or flexural compression ([c], [g])</td>
<td>(\frac{D}{t})</td>
<td>(0.044 \frac{E}{F_y})</td>
</tr>
<tr>
<td>Rectangular HSS in axial and/or flexural compression ([c], [g])</td>
<td>(\frac{b}{t}) or (\frac{h}{t_w})</td>
<td>(0.64 \sqrt{\frac{E}{F_y}})</td>
</tr>
</tbody>
</table>

(Courtesy: K.C. Tsai)
Gusset “2t” Requirement

(Courtesy: K.C. Tsai)
Gusset “2t” Requirement
Ductility Requirements

Code Implementation Example 3: Eccentrically Braced Frame (EBF) Design
EBF Configuration

Structural Fuse: Links
Link Ductility Requirement

Plastic Deformation Demand

\[ \gamma_p = \frac{L}{e} \left( \frac{\Delta_p}{h} \right) \]
Link Ductility Requirements

• Link Deformation Capacity Depends on
  ♦ (Seismically) Compactness
  ♦ Length
  ♦ Link Stiffeners
Link Length Effect

(AISC SP §15.2c)

\[ \gamma_a = 0.176 - 0.06V_p e/M_p \]

\[ e = 1.6\frac{M_p}{V_p}, \quad e = 2.6\frac{M_p}{V_p}, \quad \text{Link Length, } e \]
Capacity Design Concept
# Ductility vs. Capacity Design

<table>
<thead>
<tr>
<th>Research Effort</th>
<th>Ductility Design (Deformation-Controlled Elements)</th>
<th>Capacity Design (Force-Controlled Elements)</th>
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<tr>
<td>Design Effort</td>
<td>Easier (Straightforward)</td>
<td>Requires Understanding/Judgment</td>
</tr>
</tbody>
</table>
ASCE 7 Seismic Performance Factors

3 Mysterious Factors: $R$, $C_d$, and $\Omega_o$

<table>
<thead>
<tr>
<th>Seismic Force–Resisting System</th>
<th>ASCE 7 Section where Detailing Requirements are Specified</th>
<th>Response Modification Coefficient, $R^a$</th>
<th>System Overstrength Factor, $\Omega_0^g$</th>
<th>Deflection Amplification Factor, $C_d^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. BEARING WALL SYSTEMS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Special reinforced concrete shear walls</td>
<td>14.2 and 14.2.3.6</td>
<td>5</td>
<td>$2^{1/2}$</td>
<td>5</td>
</tr>
<tr>
<td>2. Ordinary reinforced concrete shear walls</td>
<td>14.2 and 14.2.3.4</td>
<td>4</td>
<td>$2^{1/2}$</td>
<td>4</td>
</tr>
<tr>
<td>3. Detailed plain concrete shear walls</td>
<td>14.2 and 14.2.3.2</td>
<td>2</td>
<td>$2^{1/2}$</td>
<td>2</td>
</tr>
<tr>
<td>4. Ordinary plain concrete shear walls</td>
<td>14.2 and 14.2.3.1</td>
<td>$1^{1/2}$</td>
<td>$2^{1/2}$</td>
<td>$1^{1/2}$</td>
</tr>
<tr>
<td>5. Intermediate precast shear walls</td>
<td>14.2 and 14.2.3.5</td>
<td>4</td>
<td>$2^{1/3}$</td>
<td>4</td>
</tr>
</tbody>
</table>
Newmark-Hall Ductility Reduction Rule

Equal Displacement Rule

Ductility Reduction Factor:

$$R_\mu = \mu$$
Multistory Frames

\[ V_b = \sum F_i \]

Pushover Analysis
Multistory Frames

\[ R = R_\mu \times \Omega_o \]
Capacity Design Seismic Forces

\[ \frac{V_S}{R} \]

\[ \begin{align*} & V_b \\ & V_e \\ & V_e \times \Omega_o \\ & \Delta S \\ & \Delta \end{align*} \]
Seismic Load Combinations (IBC)

- §16.5.2.1 Basic Seismic Load Combination:
  \[ 1.2D + f_1L + f_2S + 1.0E \]

- §1605.4 Special Seismic Load Combination:
  \[ 1.2D + f_1L + 1.0E_m \]

Seismic Force Level II Force for Deformation-Controlled Elements (Ductility Design Needed)

Seismic Force Level III Force for Force-Controlled Elements (Capacity Design Needed)
Internal Force Distribution

- At Seismic Force Level II (Basic Load Combination) – Use Elastic Structural Analysis to Determine Internal Force Distribution
- At Seismic Force Level III (Basic Load Combination) – Internal Force Re-distribution Occurs due to Nonlinear Response
Example

- Check as Compressive Member
- Check as Beam-Column

(a) Seismic Force Level II
(b) Seismic Force Level III
Capacity Design

• Think **beyond Elastic** Response Mentality
• Use **Expected Material Strength** for Estimate Maximum Force Developed in Structural Fuse (Note: Structural Fuse Material Strength too High Is not Desirable for Seismic Design)
• **Two Methods** to Calculate Seismic Force Level III for Capacity Design
Expected Material Strength

- AISC 341-10 §A3.2
- Expected Yield Stress, \( F_{ye} = R_y F_y \)

### TABLE A3.1
**R_y** and **R_t** Values for Steel and Steel Reinforcement Materials

<table>
<thead>
<tr>
<th>Application</th>
<th>( R_y )</th>
<th>( R_t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot-rolled structural shapes and bars:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• ASTM A36/A36M</td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>• ASTM A1043/1043M Gr. 36 (250)</td>
<td>1.3</td>
<td>1.1</td>
</tr>
<tr>
<td>• ASTM A572/572M Gr. 50 (345) or 55 (380),</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>ASTM A913/A913M Gr. 50 (345), 60 (415), or 65 (450),</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Capacity Design—Method 1

• When the Structural Fuse Is Next to Force-Controlled Element
• Apply Statics at “Local” Level
• Seismic Force Level II not Needed
• An Upper-Bound Estimate of Seismic Force Level III
Example 1: SCBF Bracing Connection

- Bracing is Structural Fuse
- AISC 341-10 §F2.6 Bracing Connection Design

\[
\begin{align*}
T &= R_y F_y A_g \\
C &= 1.1 R_y P_n
\end{align*}
\]

Don’t Oversize Structural Fuse!
Example 1: SCBF Beam Design

Check as Beam-Column

- AISC 341-10
  §F2.3: Beam Design for V-Type Bracing

\[
\begin{align*}
T &= R_y F_y A_g \\
C &= 0.3 P_n
\end{align*}
\]
Example 2: EBF Column Design

- Links Are Structural Fuse
- AISC 341-10 § F3.3 for Column Design

\[ 1.1R_y V_n \]
\[ P_{br} \]
\[ P_u \]
Example 2: EBF Brace Design

- Links Are Structural Fuse
- AISC 341-10 § F3.3 for Beam/Bracing Design

Don’t Oversize Links
Example 3: SMF

- AISC 358-10 (CPRP)

\[ M_{pr} = C_{pr} R_y F_y Z_e \]

\[ M^*_pb \]

\[ M_f \]

\[ w = \text{uniform beam gravity load} \]

\[ L' = \text{distance between centers of RBS cuts} \]

\[ L = \text{distance between column centerlines} \]
Capacity Design—Method 2

• An Approximate (or “Lazy”) Method:
  \[ \Omega_o \times (\text{Seismic Force Level II}) \]
• Use It When Method 1 Cannot Be Applied Easily
• Usually Applied at the “Global” (or System) Level
• Can Be Dangerous If Not Properly Applied
Example 1–SCBF Column Design

Method 1

\[ 0.3P_n \]

\[ P_u = ? \]

Method 2

\[ \Omega_oF_3 \]
\[ \Omega_oF_2 \]
\[ \Omega_oF_1 \]

\[ P_u = ? \]
Example 1–SCBF Column Design

\[ \Omega_o F_3 \]

\[ \Omega_o F_2 \]

\[ \Omega_o F_1 \]

\[ P_u \approx 0! \]

Method 2
Example–SCBF

Check as Compressive Member

Check as Beam-Column

(a) Seismic Force Level II

(b) Seismic Force Level III

(Method 2 Will not Work)