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Design Example 5: Eccentrically Braced Frame

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STRUCTURAL ENGINEERS ASSOCIATION OF CALIFORNIA

Acknowledgements

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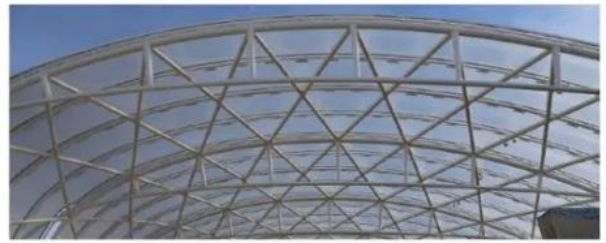

2021 IBC® SEAOC Structural/ Seismic Design Manual

Volume 4 | EXAMPLES FOR STEEL FRAMED BUILDINGS

SEAOC STRUCTURAL ENGINEERS ASSOCIATION OF CALIFORNIA
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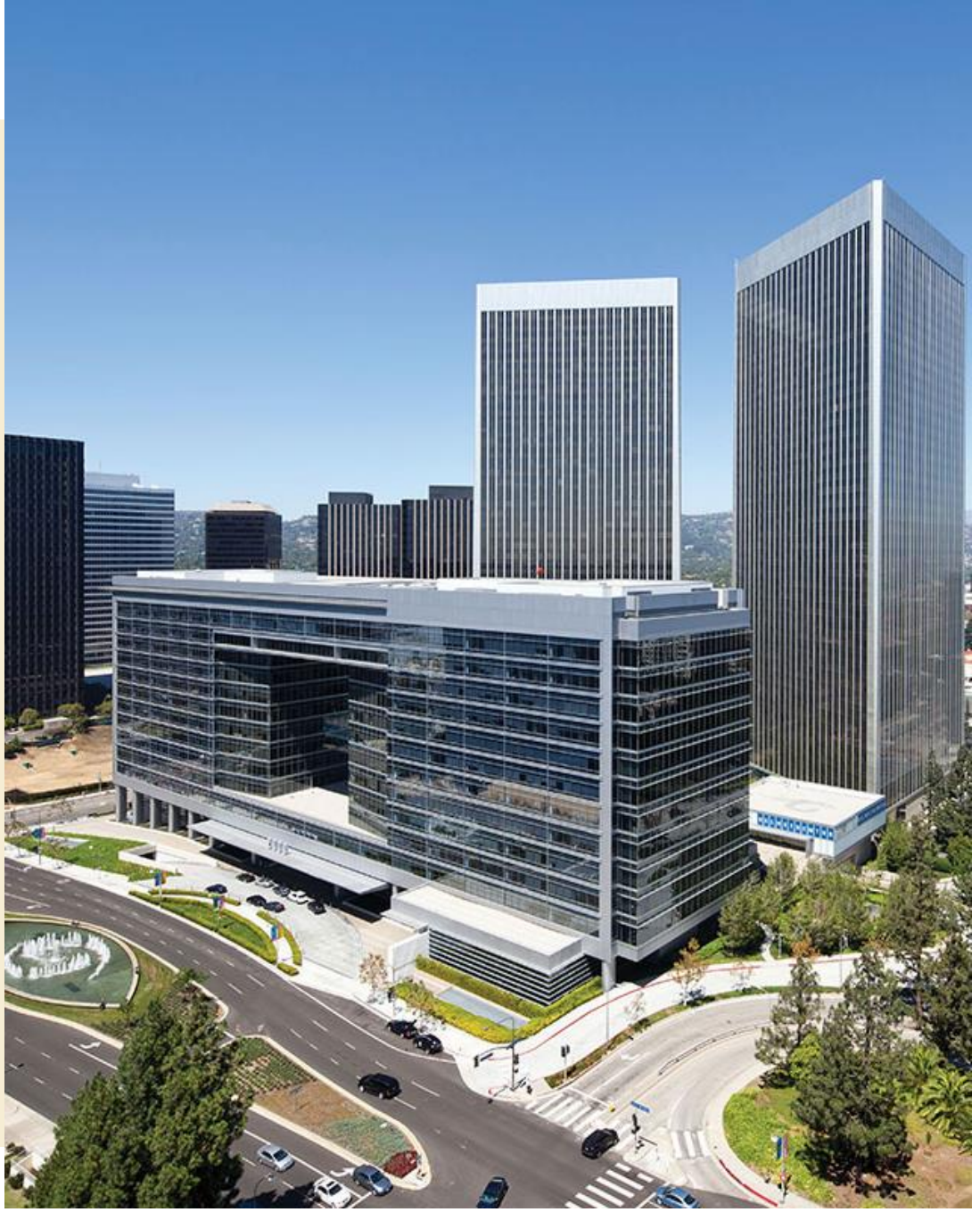
Learning Objectives

1. Understand the design and reference documents associated with EBF construction.
2. Understand EBF concepts, parameters, requirements, and configurations.
3. Application of the earthquake lateral force provisions.
4. Understand the four-step EBF Design process.

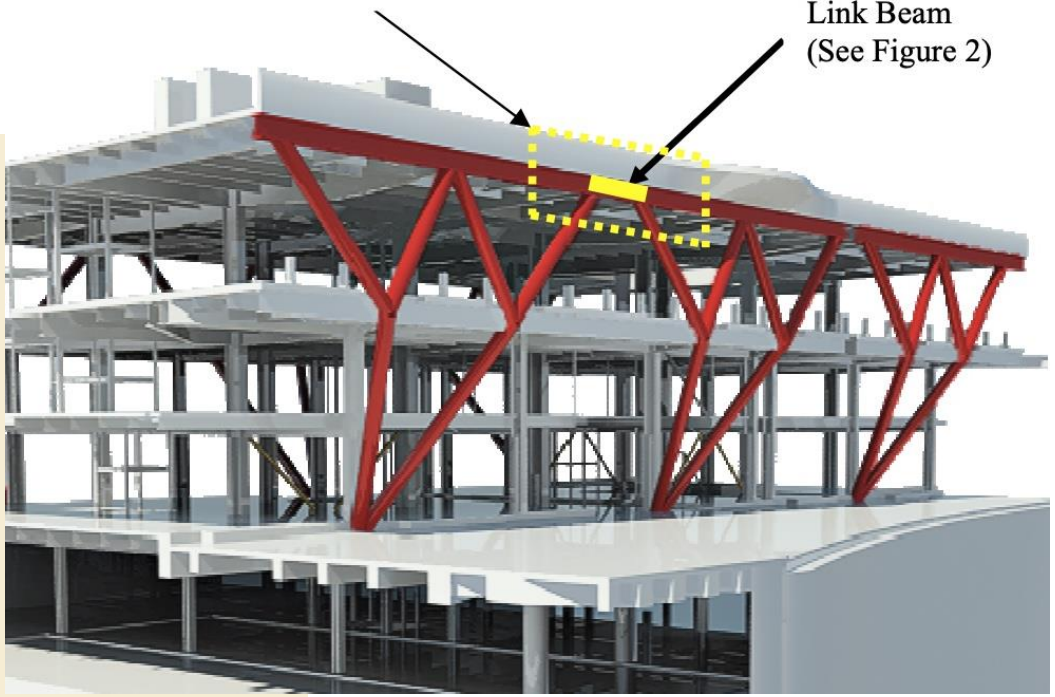


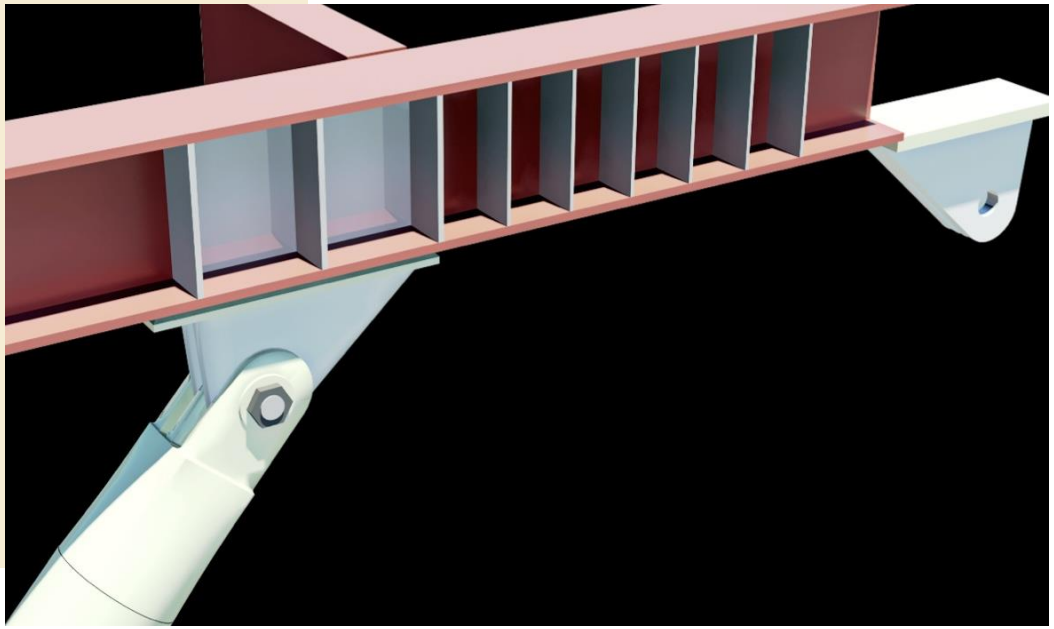
Distinguishing Features

- Substantial Capacity for Inelastic Behavior
- Stiffness of CBF
- 240-feet code allowable height

Distinguishing Features

- Capable of large inelastic deformation
- Ductile fuse
- Energy dissipator





Photos taken from “Full-Scale Testing of Transbay Terminal Center Eccentrically Braced Frame Link Beams,” 2012 SEAOC Convention Proceedings.

Distinguishing Features

- Stable hysteretic behavior
- Ductility and Energy Dissipation of MRF
- Response Modification Coefficient, R = 8

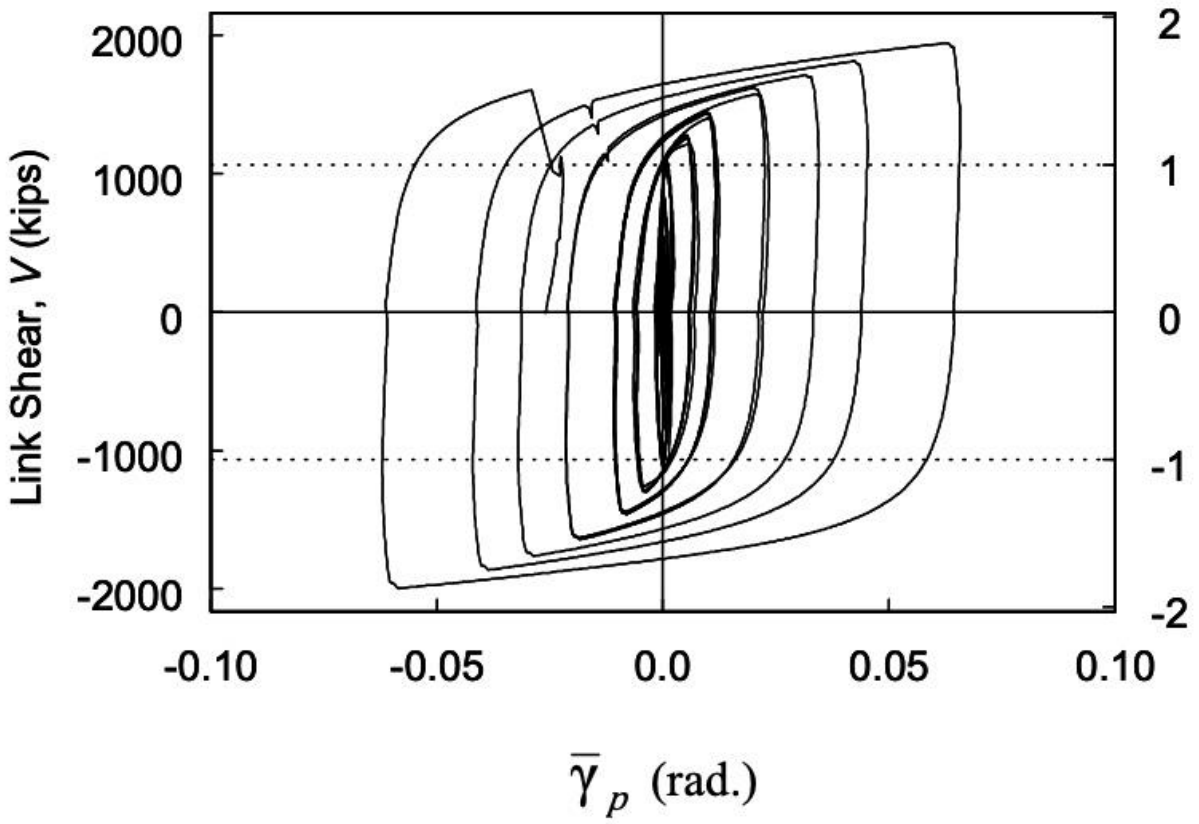


Figure 13 Specimen 1 link global response

Taken from “Full-Scale Testing of Transbay Terminal Center Eccentrically Braced Frame Link Beams,” 2012 SEAOC Convention Proceedings.

Real World Applications

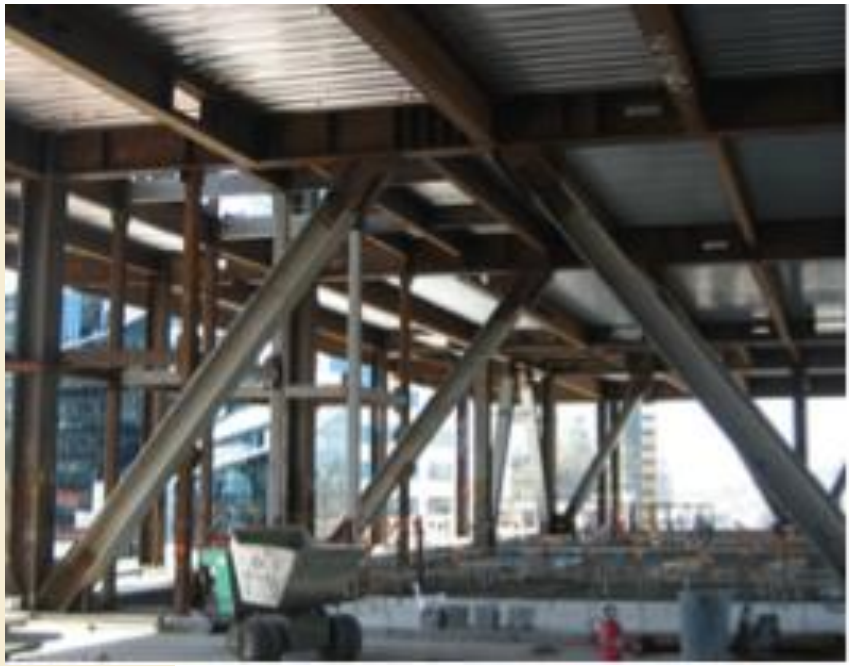
U.S. Courthouse, San Diego

- Built 2013
- $300 Million
- 463,700 square feet
- 16 Stories
- 22-ft floor heights
- 320-ft total height (>240)
- PBSD

Application

U.S. Courthouse, San Diego

- 22-ft floor heights
- 320-ft total height (>240-ft)
- PBSD



Courthouse Photos Courtesy of Tom Sabol

Earthquake Performance

Napa Earthquake, August 24, 2014

- M6.0 6km NW of American Canyon
- Epicenter near West Napa Fault
- PGA: 0.61g
- $1 Billion Estimated Overall Loss

Earthquake Performance

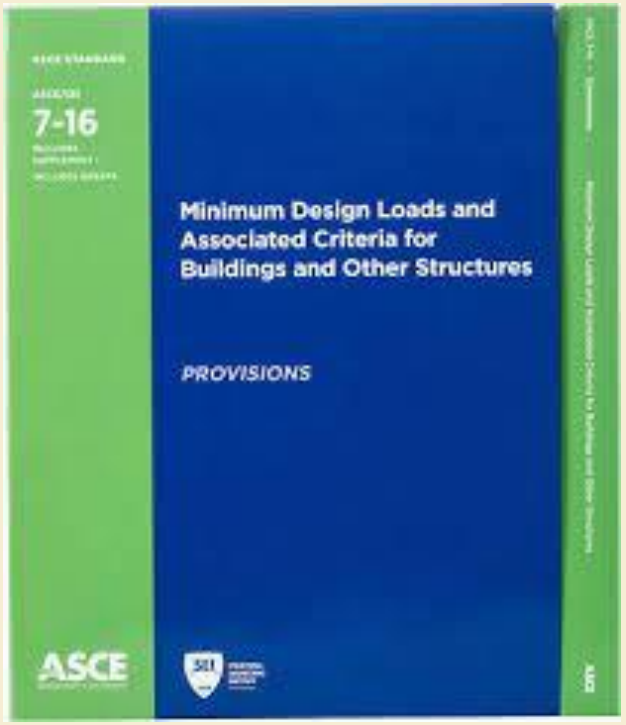
Napa County Criminal Courthouse

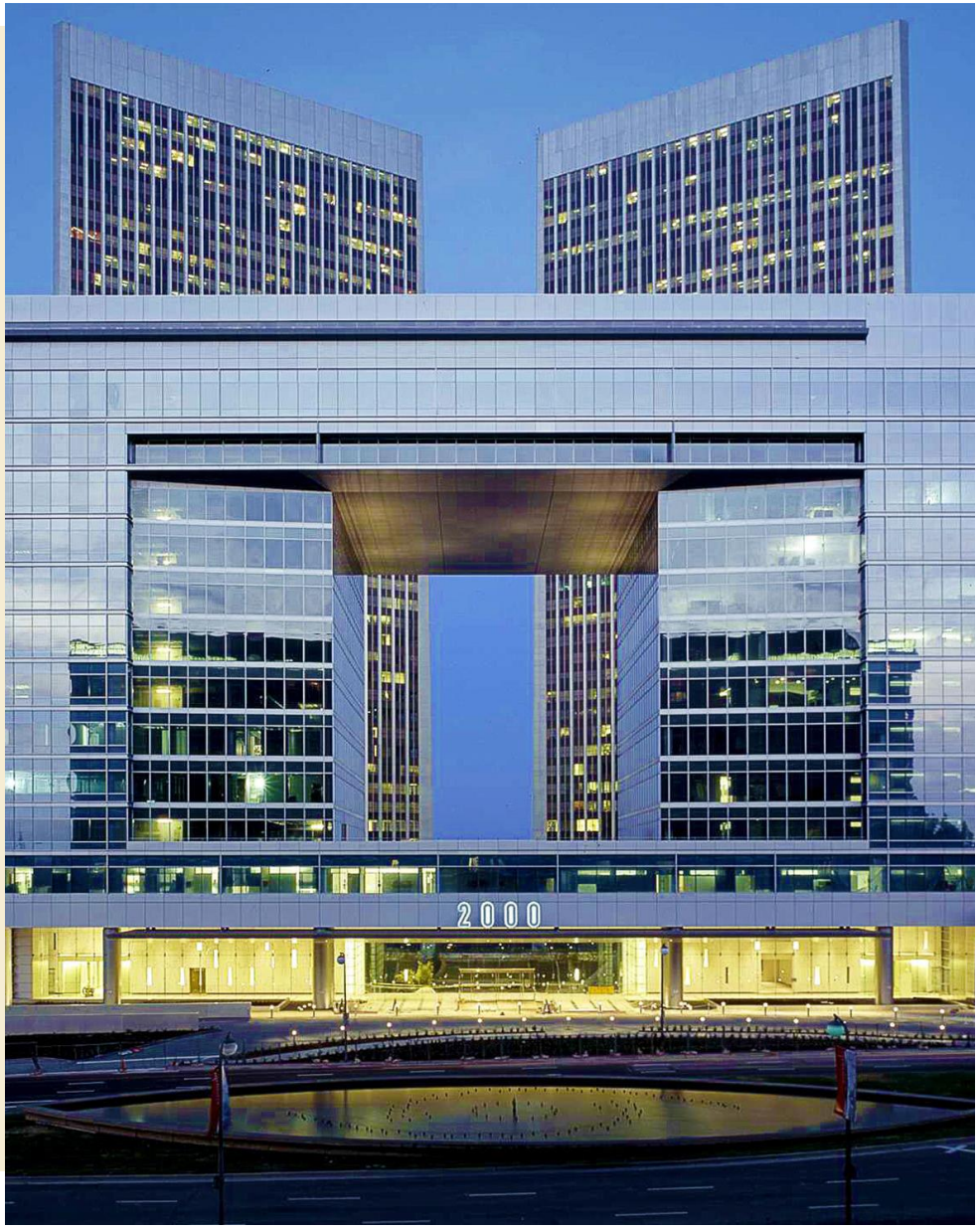
- Year Built: 1996
- Construction: EBF
- Posting: Green
- EOR: Thornton Tomasetti
- PBSD
- Green Tagged

Three-Story, 45,000-Square Foot, Courthouse

Design Standards

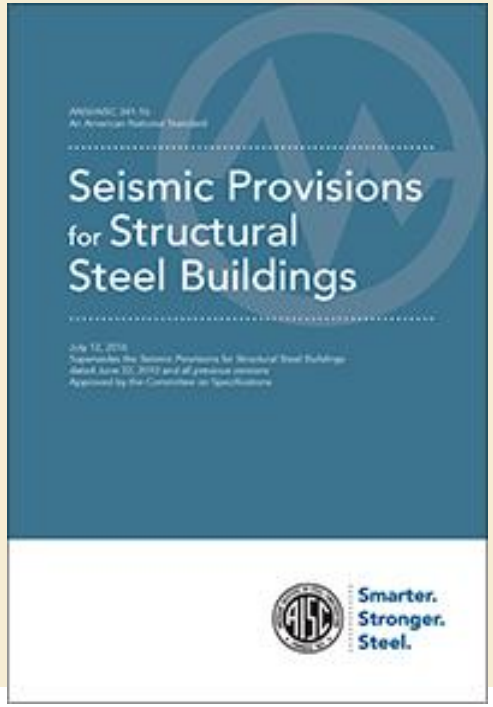
- AISC 7-16 Minimum Loads for Buildings and Other Structures

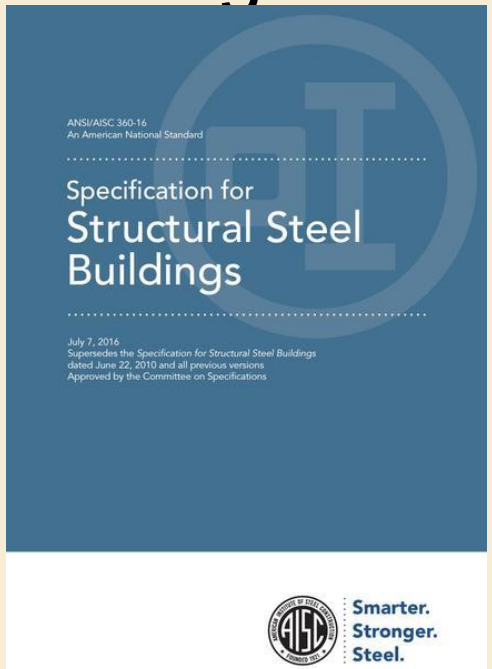


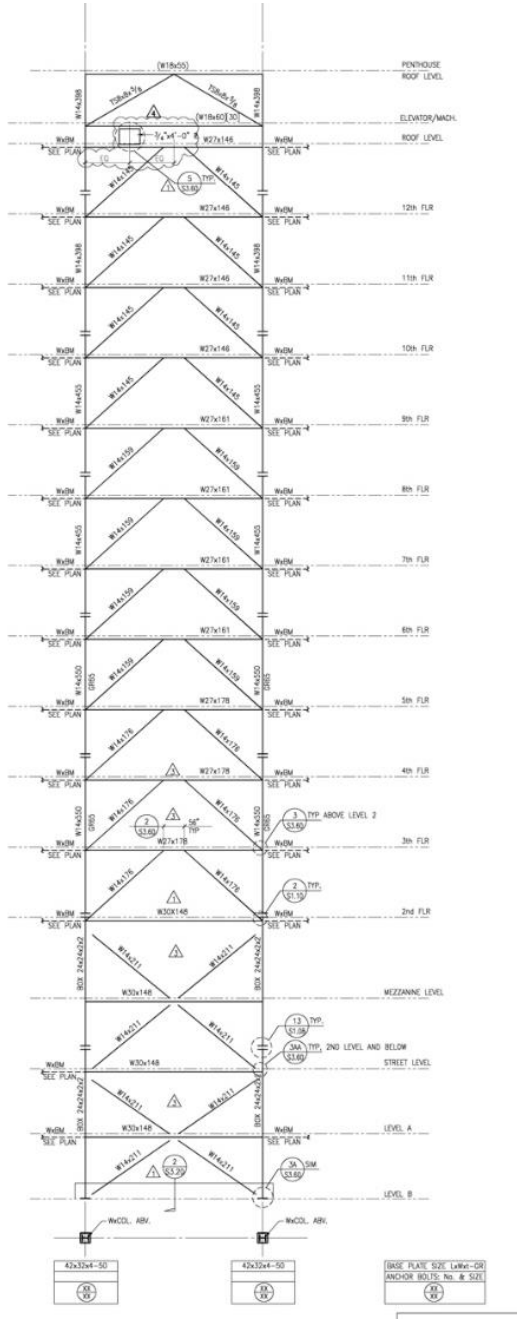


Design Standards

- ANSI/AISC 341-16 Seismic Provisions for Structural Steel Buildings
- ANSI/AISC 360-16 Specification for Structural Steel Buildings

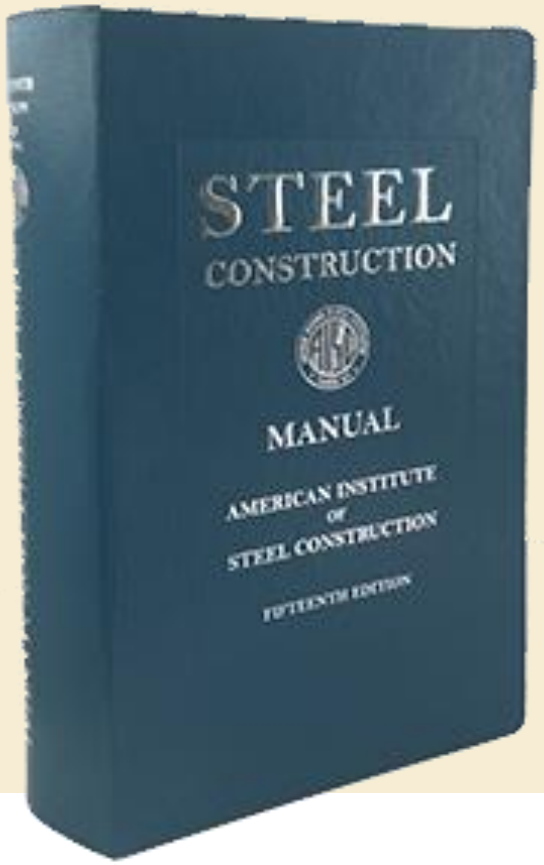


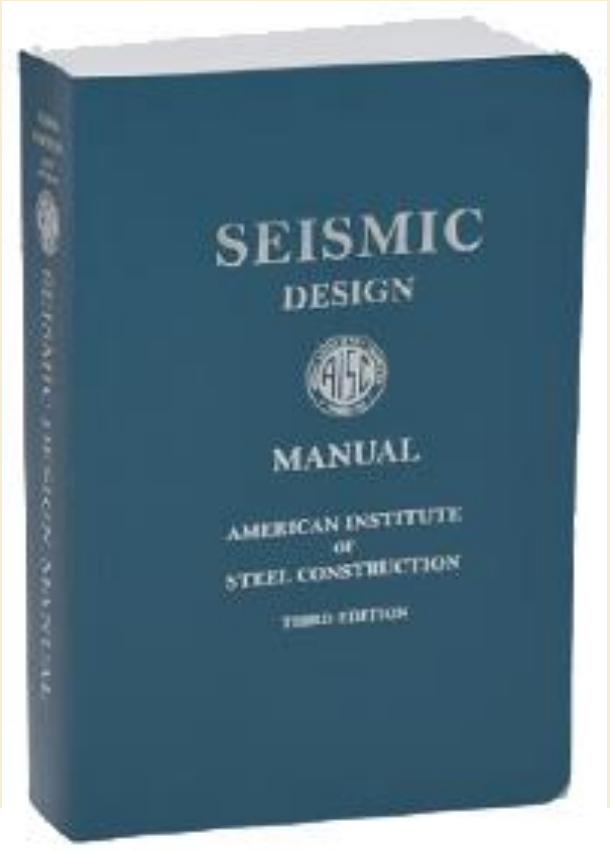


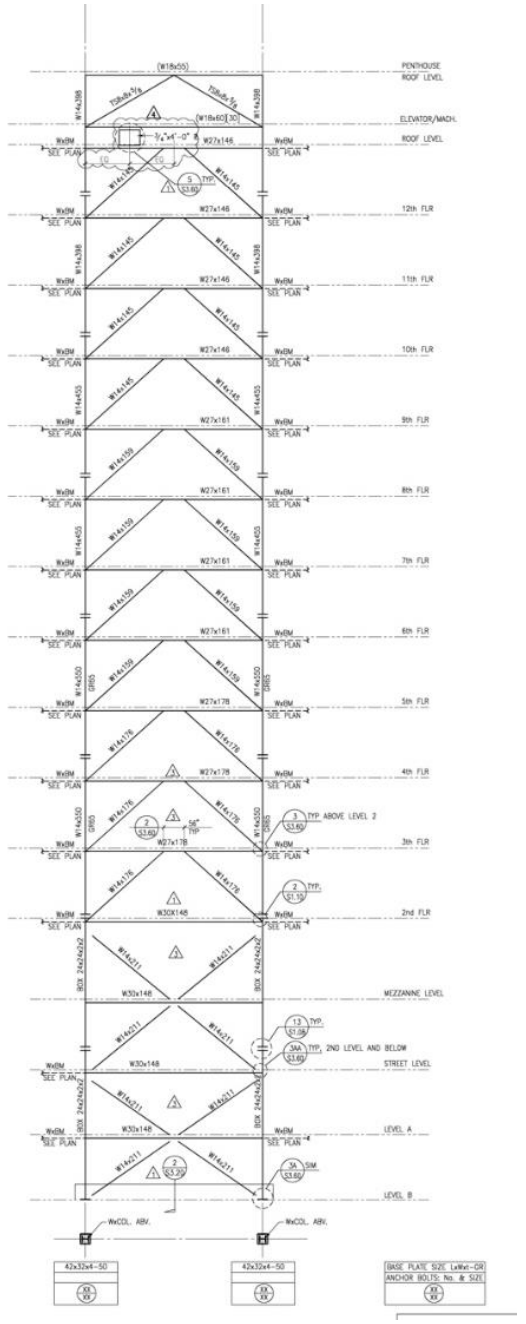


Reference Documents

- AISC Steel Construction Manual
- AISC Seismic Design Manual



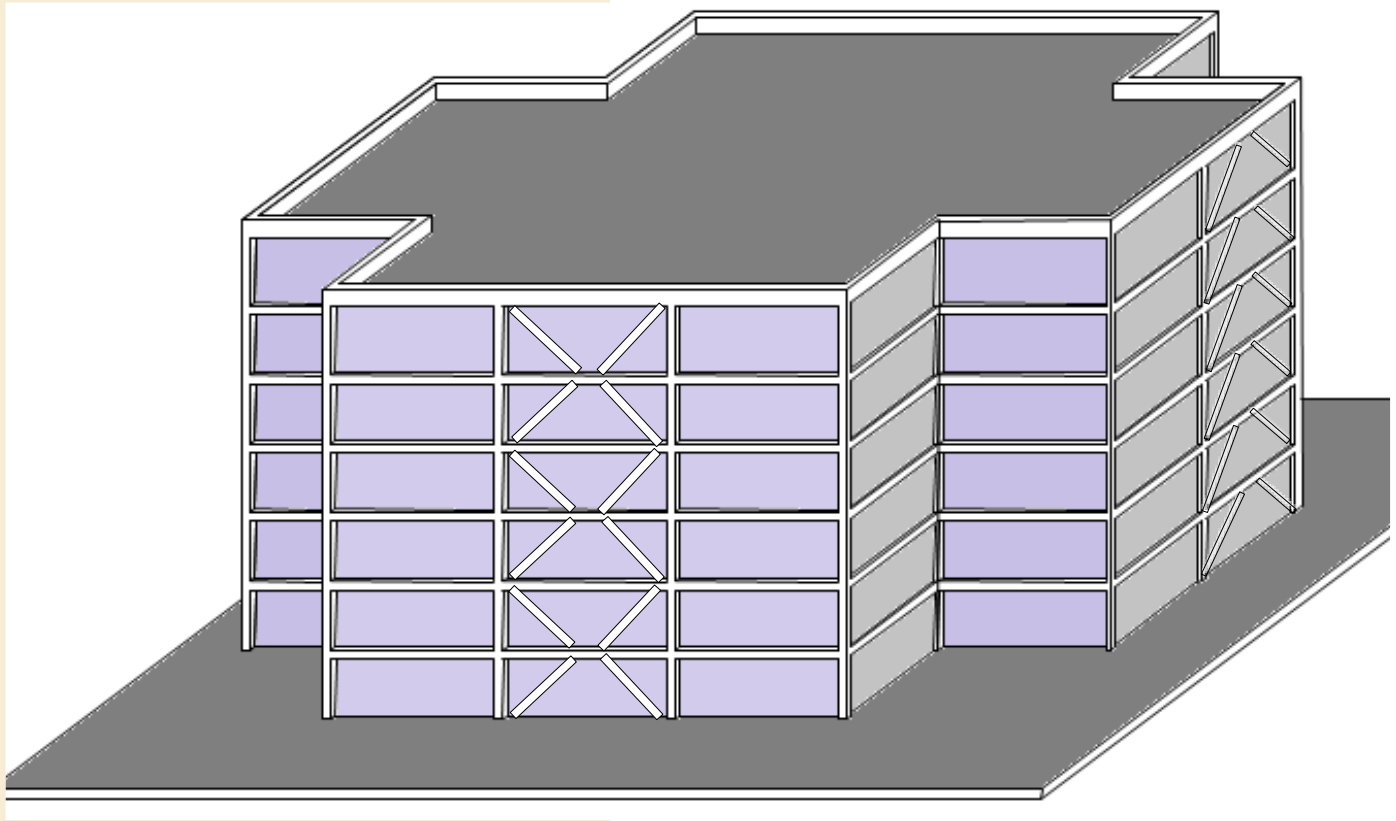




Volume 4 – Sample Building

Distinguishing Features

- Six-story
- Office Occupancy
- San Francisco
- Site Class D
- Risk Category II
- S_s = 1.5g
- S_1= 0.6g

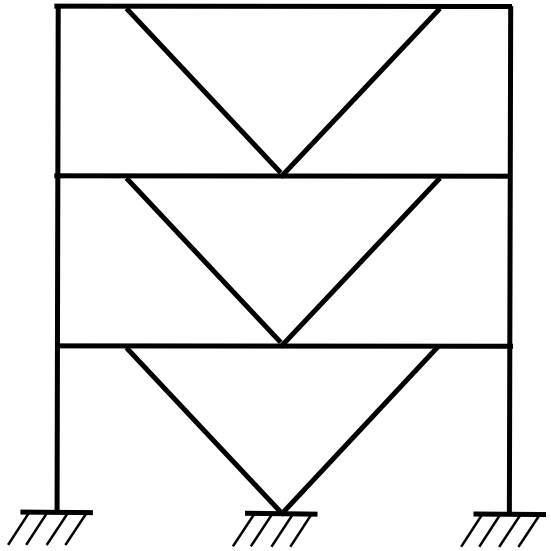


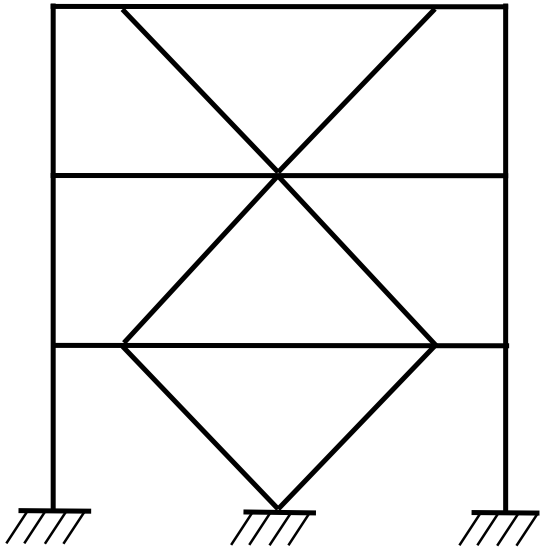
Irregular, cruciform, X, inverted V

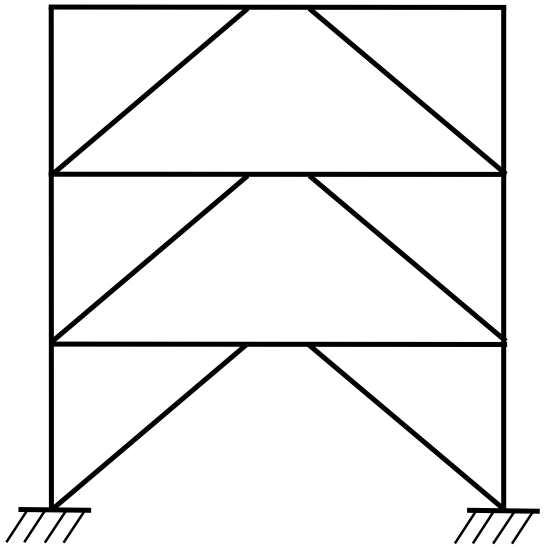
Potential Configurations

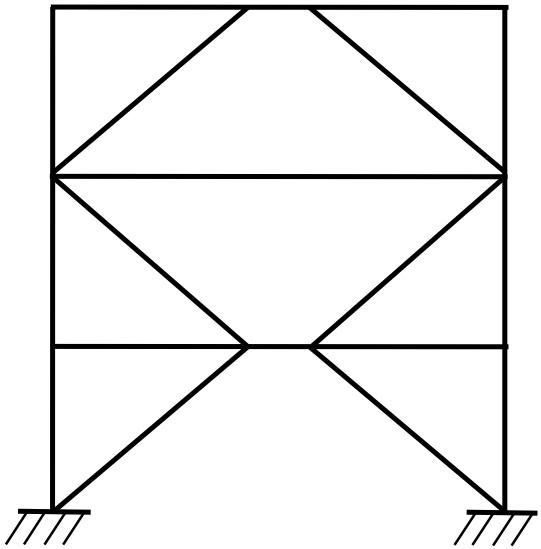
Configurations

- End-link V
- End-link two-story X (AISC 341 F3.6e)
- Center-link inverted-V
- Center-link two-story X





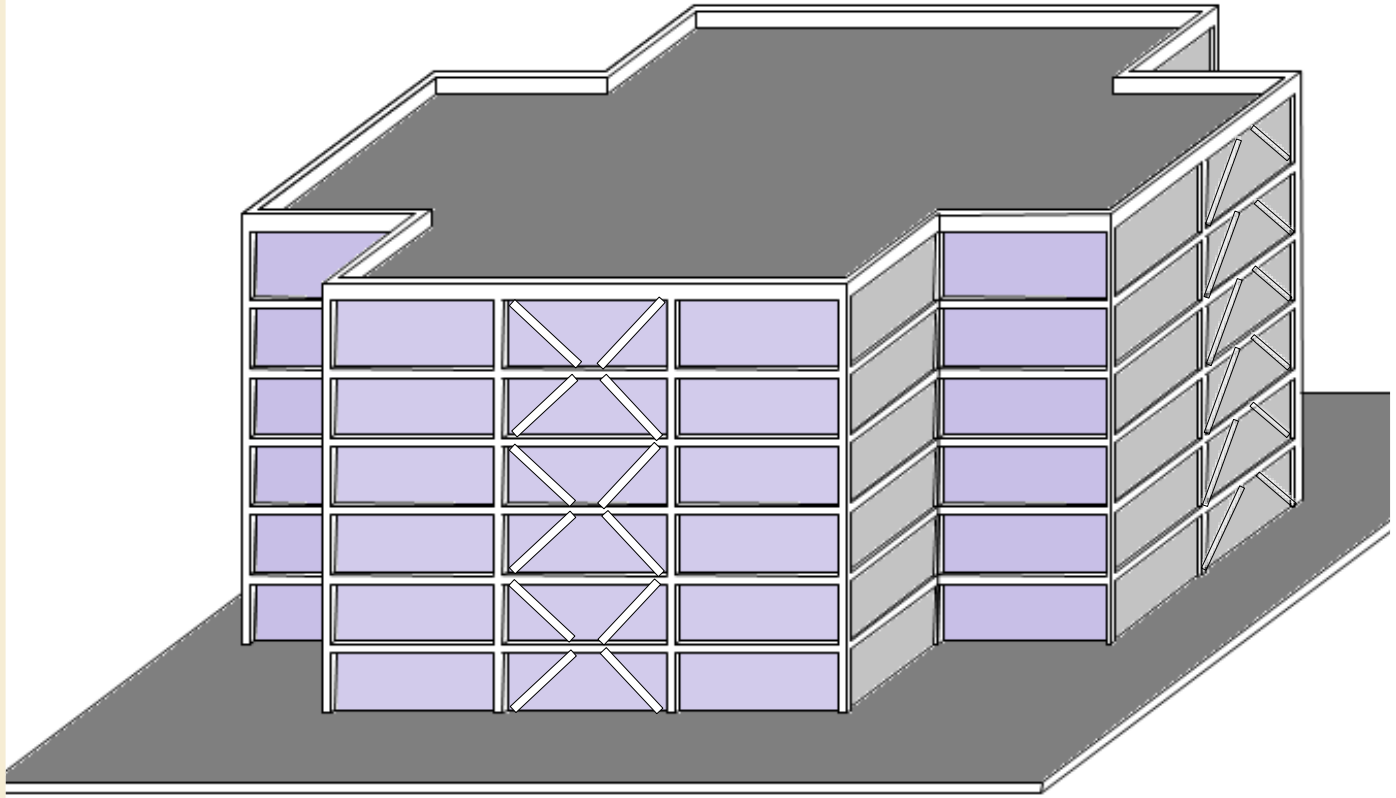




Volume 4 – Sample Building

Design Parameters

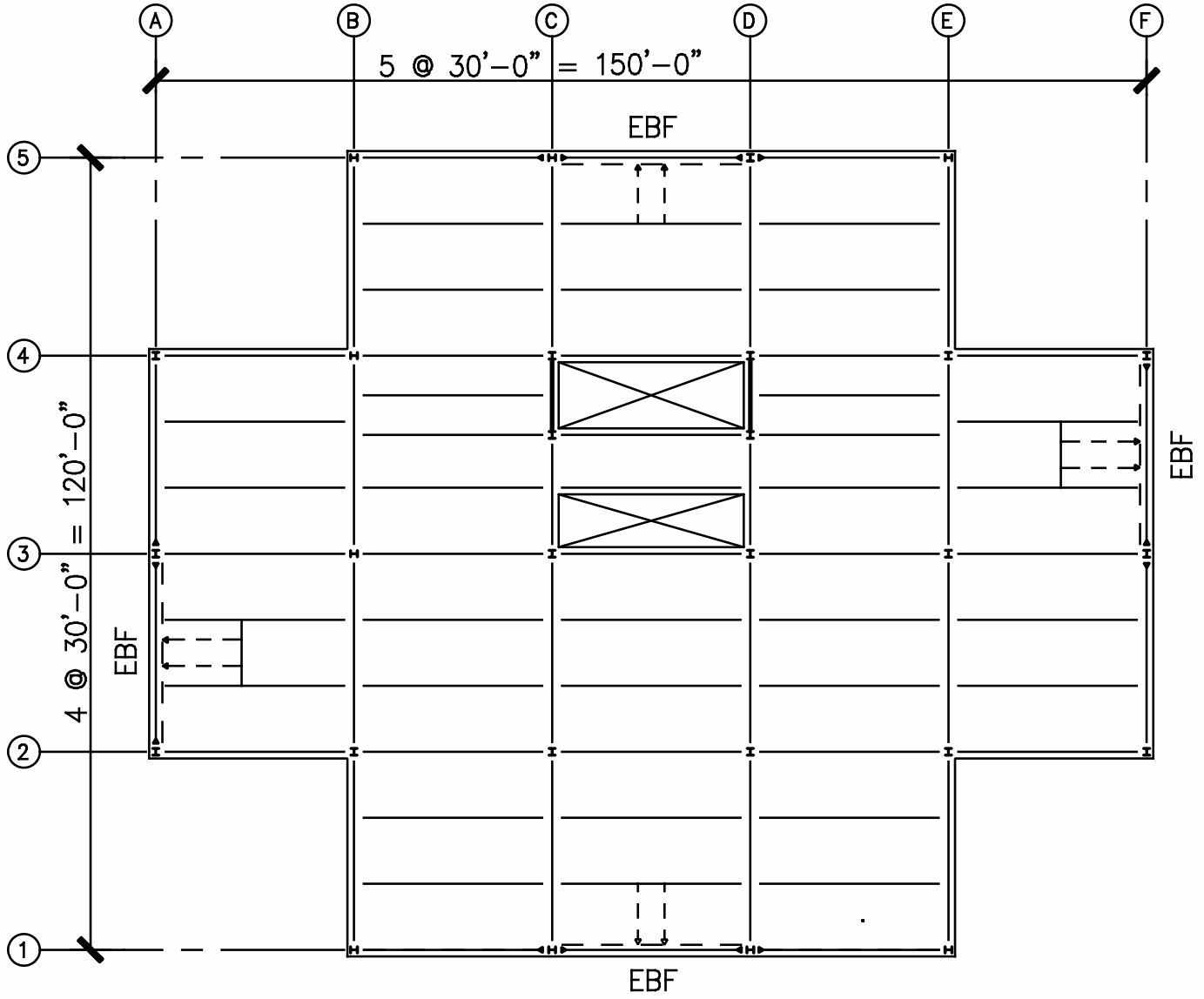
- Gravity 67.7 psf
- Seismic 77.7 psf
- R = 8.0
- Ω_o = 2.0
- C_d = 4.0 ASCE 7 Table 12.2-1



Volume 4 – Sample Building

Irregularities

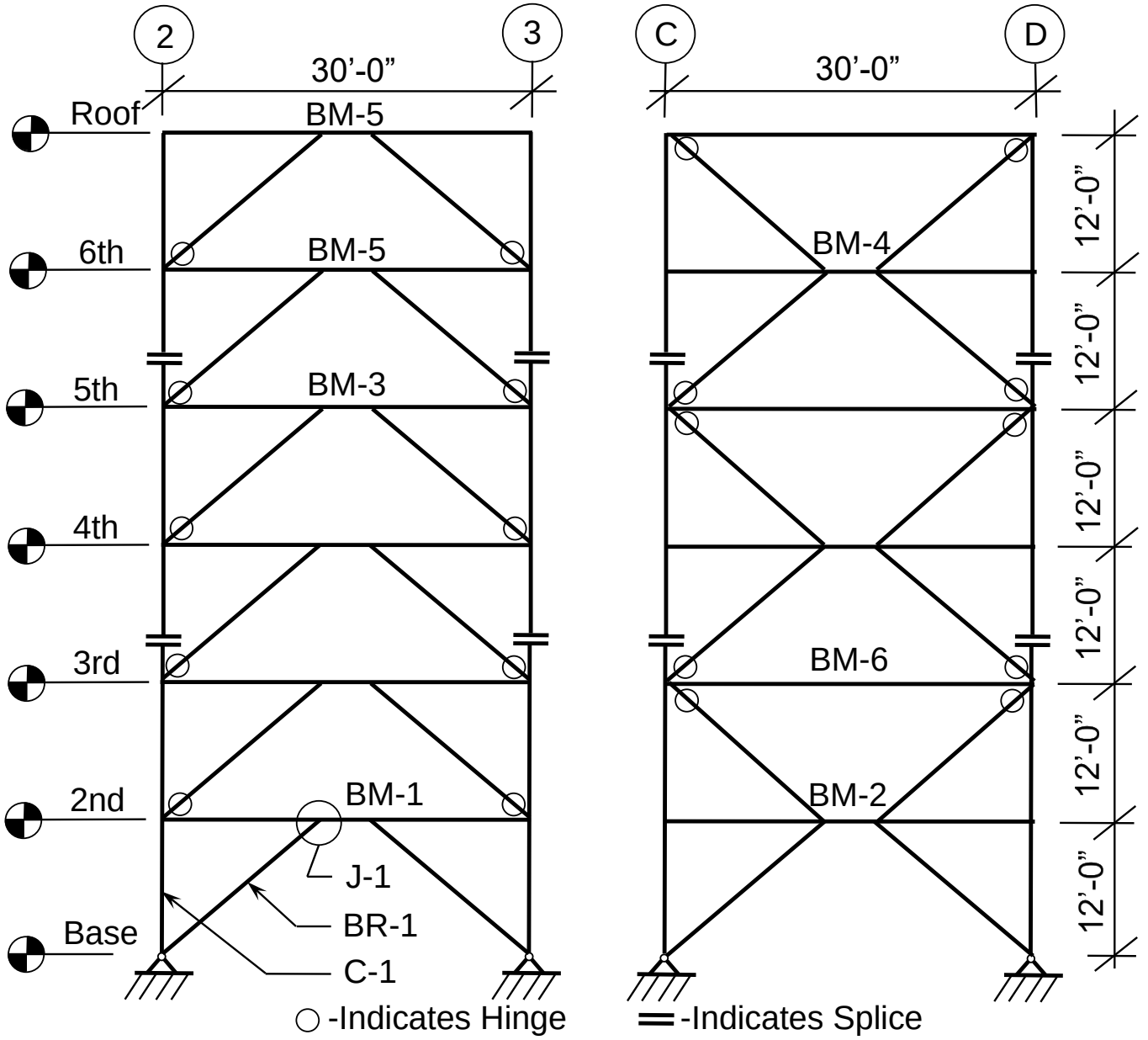
- Reentrant Corners
- Diaphragm Discontinuity ASCE 7 Section 12.3.2.1 and 2



Volume 4 – Sample Building

Configurations

- 6 vs. 3 Links
- 12 vs. 8 Brace Connections
- Pin Base
- Brace-to-Link
- Beam-to-Column
- Splices
- Material A992 / A572

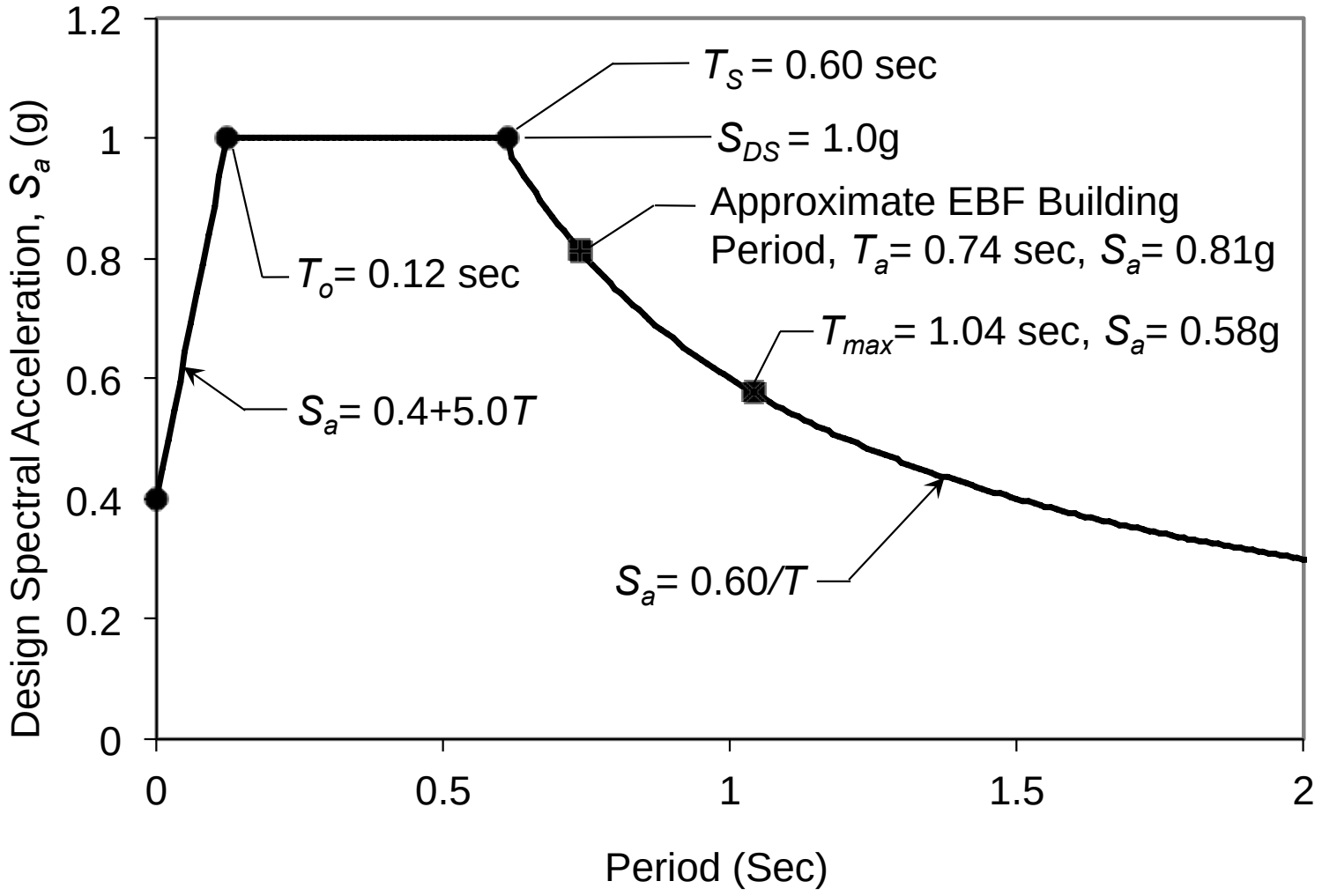


Design Response Spectra

Considerations

ASCE 7 Section 12.6, Table 12.6-1

- < 160 feet
- SDC-D
- Nominal Irregularities
- ELF
- $T > T_{max}$



Seismic Response

Considerations

- Response Coefficient, C_s = 0.072 ASCE 7 Section 12.8.1.1
- Base Shear, V = 521 kips ASCE 7 Section 12.8.1
- Vertical Distribution ASCE 7 Section 12.8.3

Level	w_i (kips)	h_i (ft)	$w_i h_i^k$	C_{vx}	F_x (kips)
Roof	656	72	149,870	0.188	98
6th	1,315	60	238,330	0.299	156
5th	1,315	48	179,516	0.225	117
4th	1,315	36	124,575	0.156	81
3rd	1,315	24	74,438	0.093	49
2nd	1,315	12	30,866	0.039	20
Total	7,231		797,595	1.000	521

- Horizontal Distribution ASCE 7 Section 12.8.4

Seismic Response

Horizontal Distribution ASCE 7 Section 12.8.4

- Rigid Diaphragm ASCE 7 Section 12.3.2
- 5% Offset ASCE 7 Section 12.8.4.2

Grid	Direction	d_i	Rd_i	Rd_i^2	V_i	V_{tai}	V_{xi}
A	X	-75	-75 R	5625 R	0.50 F_i	-0.024 F_i	0.48 F_i
F	X	75	75 R	5625 R	0.50 F_i	0.024 F_i	0.52 F_i
1	Y	-60	-60 R	3600 R	0.50 F_i	-0.024 F_i	0.48 F_i
5	Y	60	60 R	3600 R	0.50 F_i	0.024 F_i	0.52 F_i

Level	Design Story Shear, V_{xi}, (kips)	Cumulative Shear, (kips)
Roof	51	51
6^{th}	81	132
5^{th}	61	193
4^{th}	42	235
3^{rd}	26	261
2^{nd}	10	271
1^{st}	0	271

Design Procedure

Four Step Process:

1. **Preliminary Member Design (Link, Column and Brace)**
2. Analytical Analysis and Evaluation
3. Final Member Design
4. Connection Design

Preliminary Member Design

Link Requirements AISC 341.F3.5b

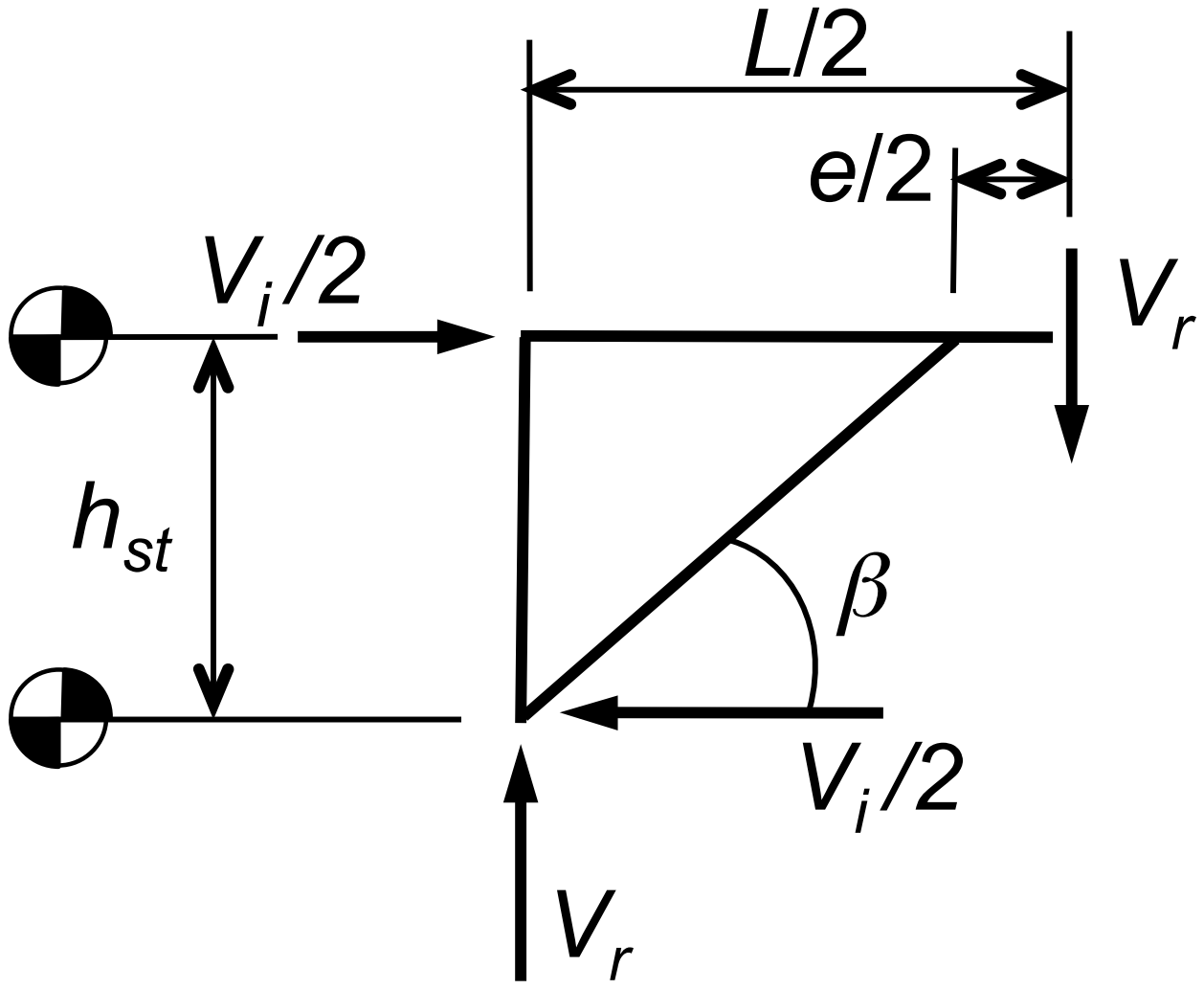
- I-Shaped (Rolled or Built-up) AISC 341.F3.5b(1)
- Box (Built-up no HSS) AISC 341.F3.5b(1)
- Highly Ductile per AISC 341.D1.1
- I-Shape Flange Exception AISC 341.F3.5b(1)
- Shear Yielding $e<1.6\ M_p/V_p$
- Flexural Yielding $e>2.6\ M_p/V_p$
- Shear Yielding Estimate: $e<1.3\ M_p/V_p$

Preliminary Member Design

Link Size and Length

- $V_r = V_2 h_{st} / L$ = 108 kips
- Equation F3-2
- $A_{tw} = V_r / \phi_v 0.6 F_y$
  $= 4.0$ in.^{2}
- W10x68

  $V_p = 0.6 F_y A_{tw}$ = 125 kips Eq. F3-2
  $M_p = F_y Z$ = 4265 kip-in. Eq. F3-8
- $e = 1.3\, M_p / V_p$ = 44 in.
- Say 48 in.



Preliminary Member Design

Link Optimization

- Elements Other Than Link Intended to Remain Elastic
- AISC 341 Section F3.3 Requires Link Strength “Adjustment”
- 1.25 for I-Shaped Links, 1.4 for Box
- Adjusted Shear Strength, V_{mh}
- $V_{mh} = 1.25\ R_y V_p = 172$ kips

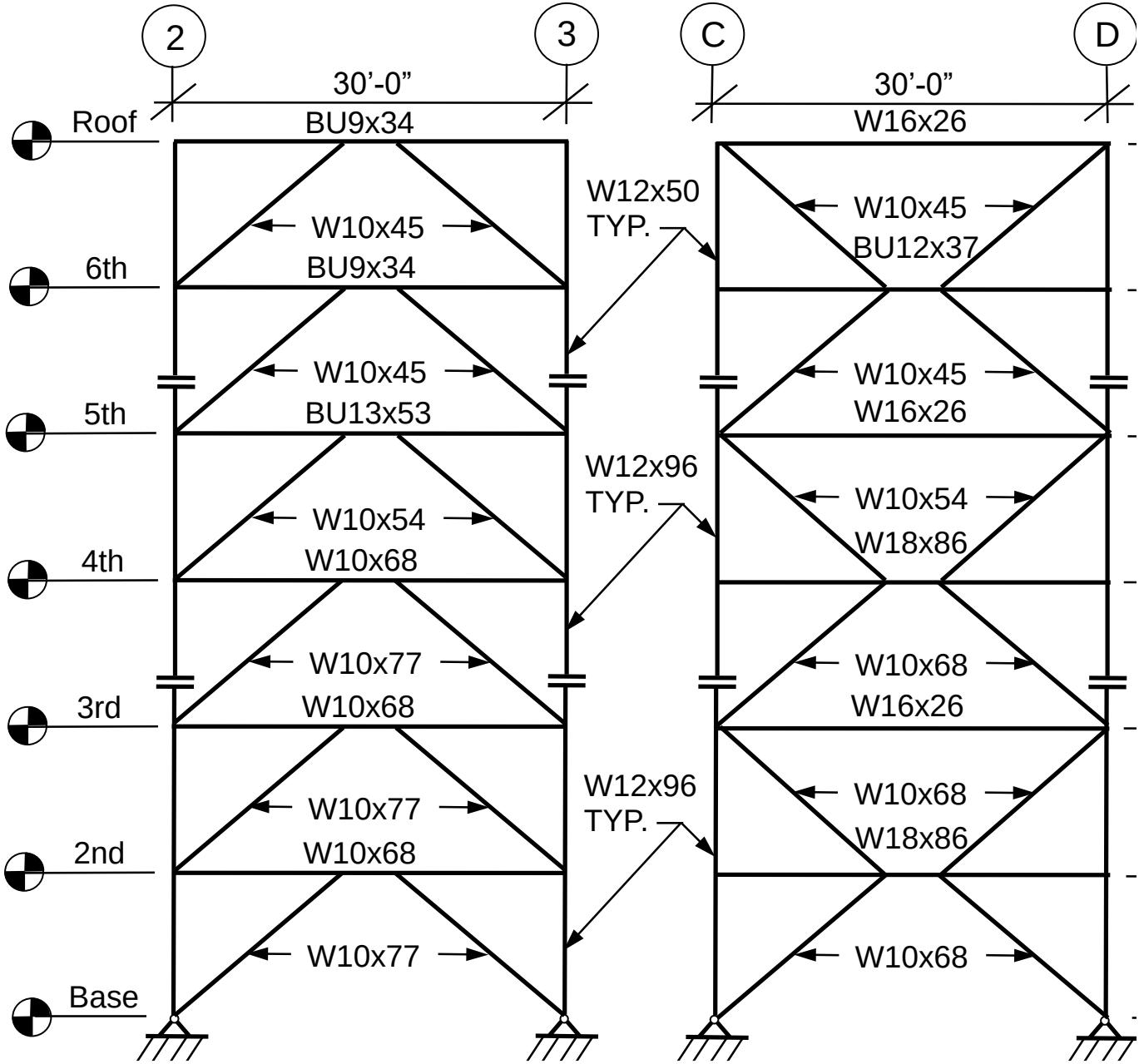
Preliminary Member Design

Link Built Up Sections

- W10x68 Too Large For Upper Floors
- Web to Flange CJP AISC 341.F3.5b(1)
- CJP Demand Critical AISC 341.F3.5b(1)
- Plate Material and Fabrication
- 3-4 Times Cost of Rolled Section (B. Manning)

Preliminary Member Design

Preliminary Link Beam Sizes:

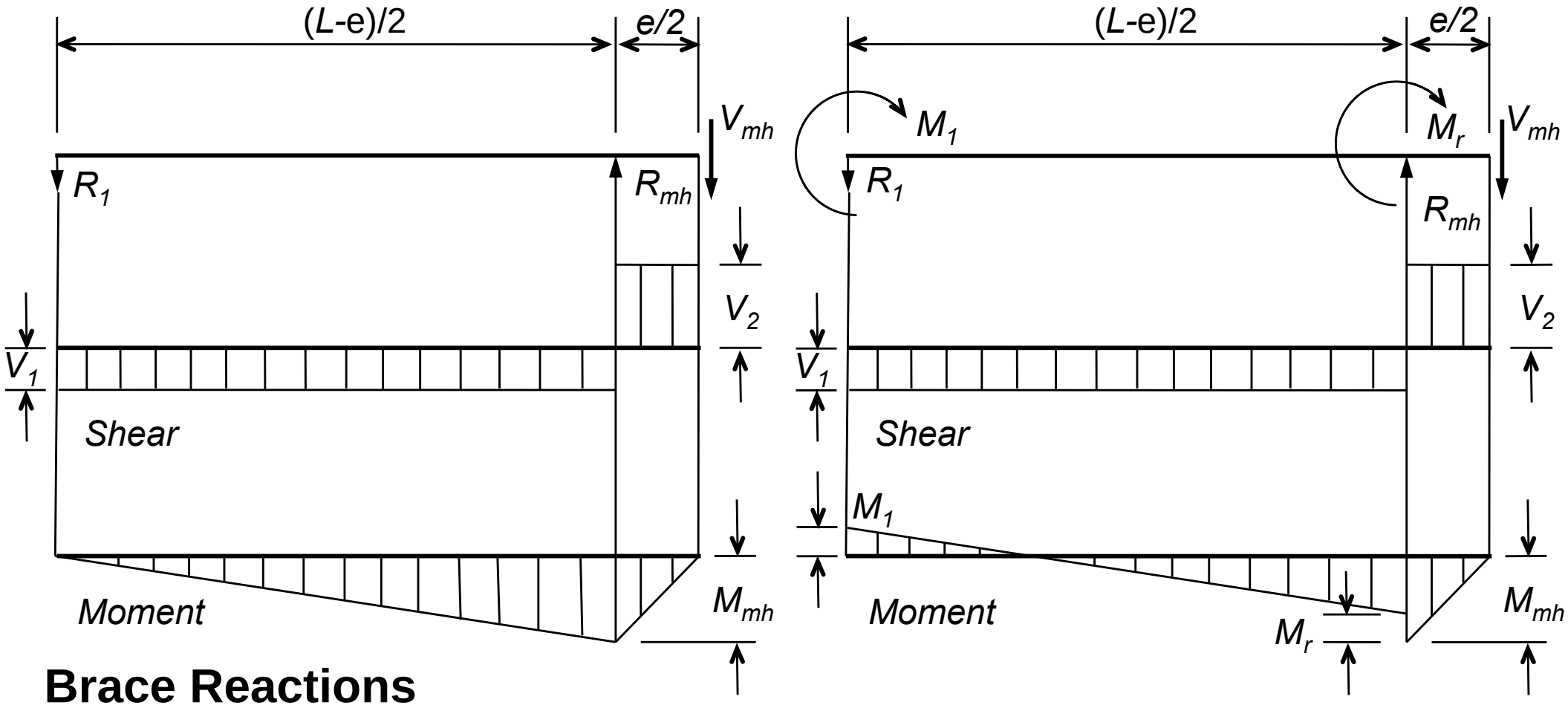


Preliminary Member Design

Brace Size AISC 341.5b

- Adjusted Shear Strength, V_{mh}
  AISC 341.F3.3
- Moderately Ductile
- Beam-Column Design Estimate (Pin vs Fixed)

Preliminary Member Design



Brace Reactions

- $V_{mh} = V_{mh}\ (L\ /\ L\text{-}\ e)$ = 198 kips
- $M_{mh} = V_{mh}$ (e / 2) = 344 kip-ft

Preliminary Member Design

Brace Size

- Axial, $P_r = R_{mh} / \phi_c(\sin \beta) = 324$ kips
- Moment, $M_r = 0.50\, M_{mh} / \phi_c = 191$ kip-ft
- AISC Manual Table 6-1, $L_b = 17$ ft
- AISC SDM Table 1-3
- W10x77

Preliminary Member Design

Column Size AISC 341.5a

- Highly Ductile
- Three link reduction, 0.88 AISC 341.F3.3(1)(b)
- No Simultaneous Strain Hardening
- $R_{mh} = V_{mh}\,(e\,/\,L - e) = 26.5$ kips

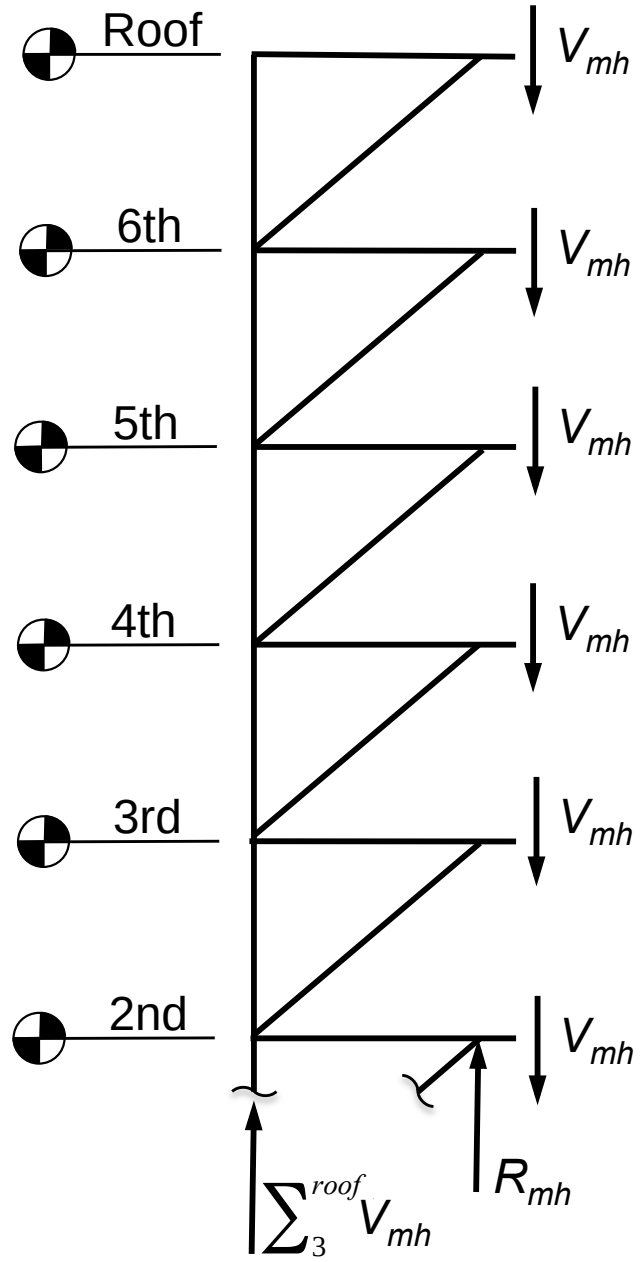
Preliminary Member Design

Column Loading

- $R_{mh} = V_{mh}\,(e\,/\,L - e)$
  $= 26.5$ kips
- $P_{Emh} = 0.88\,(\Sigma\, V_{mh} - R_{mh})$
  $= 531$kips

$P_r = 1.4\,D + 0.5\,L + 1.0\,E$
$= 980$ kips

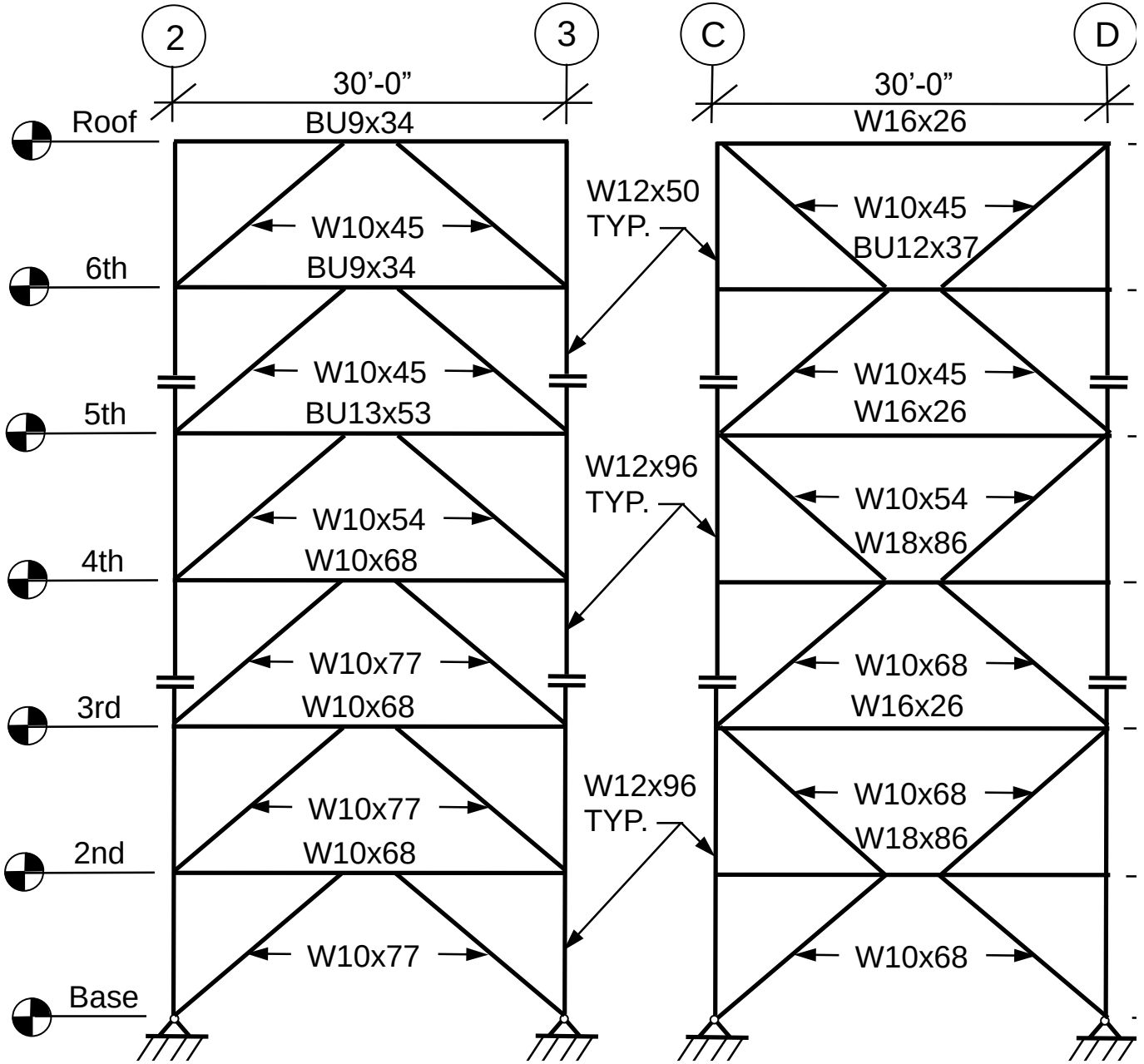
$M_{Emh} = 0.15\,(0.88) M_{mh}\,/\,\phi_b$
$= 50.4$ kip-ft



Preliminary Member Design

Column Size

- AISC Manual Table 6-1, L_b = 11 ft
- AISC SDM Table 1-3
- W12 x 96



Design Procedure

Four Step Process:

1. Preliminary Member Design (Link, Column and Brace)
2. **Analytical Analysis and Evaluation**
3. Final Member Design
4. Connection Design

Analytical Analysis and Evaluation

Analysis Verification

- Drift Limits
- P-Delta Effects
- Link Rotation Angle AISC 341.F3.4a
- Output Member Forces

Analytical Analysis and Evaluation

Computed Period

- T = 1.16s, 1.25s (Invert V, 2SX)

Drift Limits AISC 341.B1

- $\Delta_a = 0.020h_{st}$ = 2.88 in. ASCE 7 Table 12.12-1
- $\delta_x = \Delta_2 - \Delta_1 = C_d\delta_{xe} / I_e$
  = 1.39 in. ASCE 7 Eq 12.8-15

If $\delta_x > \Delta_a$

Ignore T_{max} = 1.05 , Use T ASCE 7 12.8.6.1 & 2

Analytical Analysis and Evaluation

P-Delta Effects ASCE 7 Section 12.8.7

- $\theta = P_x \Delta I_e / V_x h_{sx} C_d \leq 0.10$
  Vertical Load Designs IBC Table 1607.1
- $P_2 = \Sigma D + \Sigma L = 10{,}077$ kips
- $\theta = 0.07 \leq 0.10$

Analytical Analysis and Evaluation

Link Rotation Angle

AISC 341.F3.4a, Figure C-F3.4

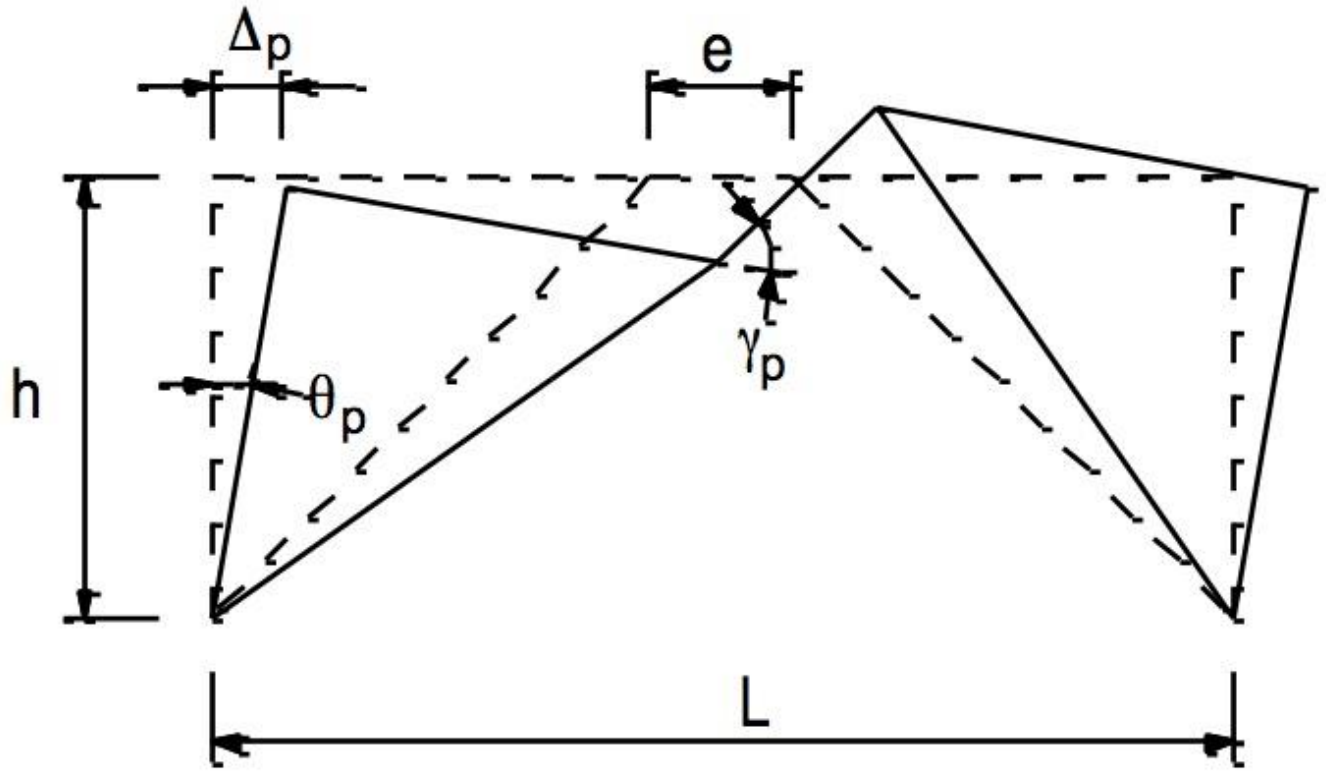
Plastic Story Drift Angle

- $\theta_p = \Delta_p / h_{st} = 0.007$

Link Rotation Angle

- $\gamma_p = (L / e)\, \theta_p$

  $= 0.05 < 0.08$



$$\gamma_p = \frac{L}{e}\theta_p$$

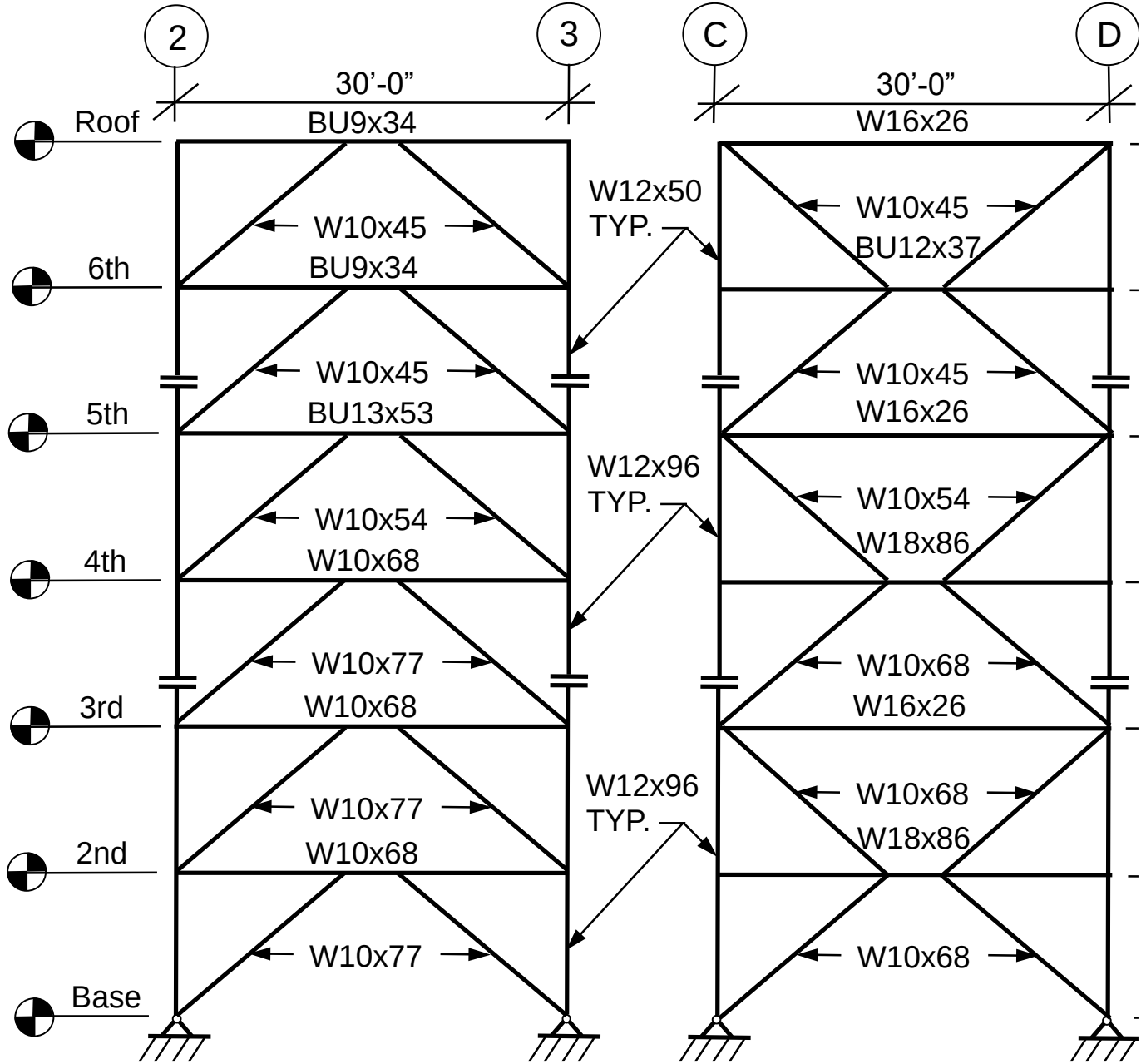
Design Procedure

Four Step Process:

1. Preliminary Member Design (Link, Column and Brace)
2. Analytical Analysis and Evaluation
3. **Final Member Design**
4. Connection Design

Preliminary Member Design

Final Sizes



Design Procedure

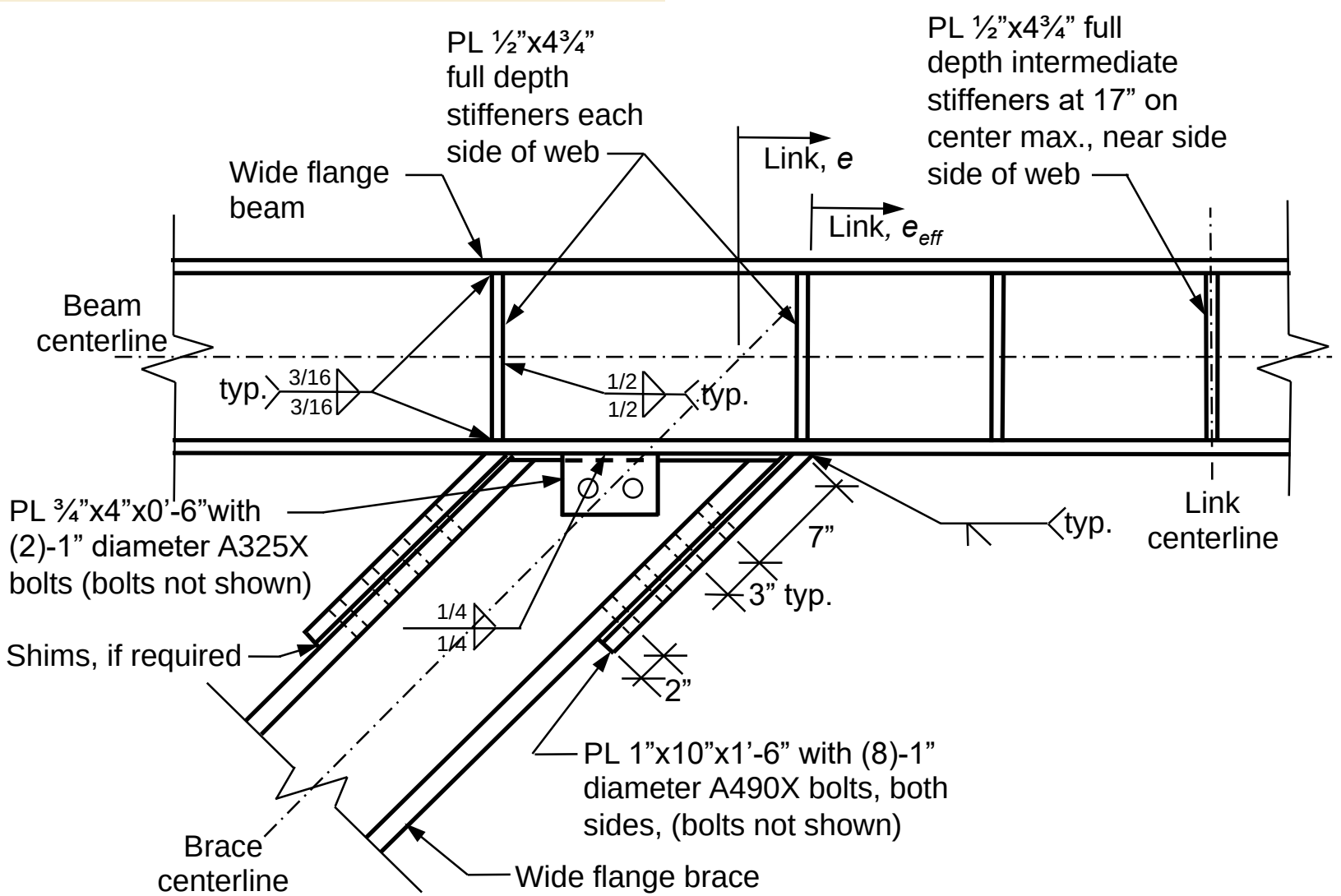
Four Step Process:

1. Preliminary Member Design (Link, Column and Brace)
2. Analytical Analysis and Evaluation
3. Final Member Design
4. **Connection Design**

Connection Design

Considerations AISC 341.F3.5b(4)

- Link End Stiffeners
- Link Intermediate Stiffeners
- Stiffener Weld Requirements
- Brace-To-Link
- Final Link Design Check



Connection Design

Link End Stiffener AISC 341.F3.5b(4)

- $w_{min} = (b_f - 2t_w) / 2 = 4.6$ in
- $t_{min} = 0.75\, t_w \geq 3/8$ in $= 0.35$ in

Link Intermediate Stiffener AISC 341.F3.5b(4)

Given $e < 1.6\, M_p/V_p$

For $\gamma_p = 0.08$,

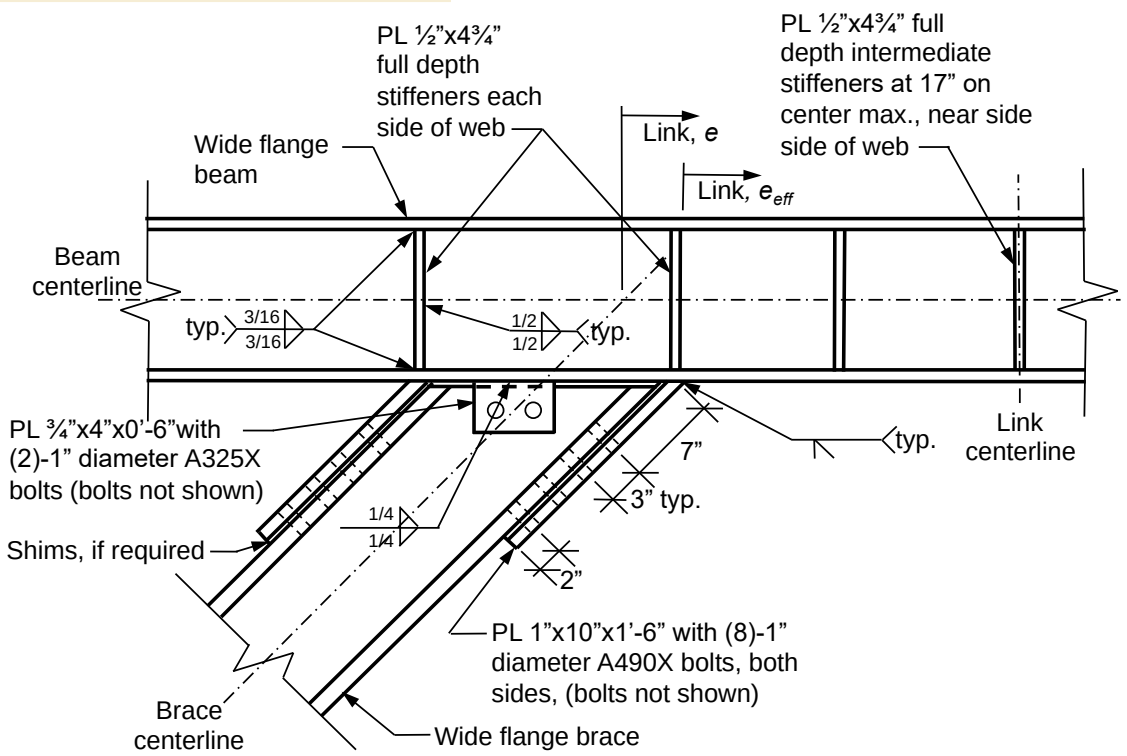
$s = (30t_w - d/5) = 12.0$ in

For $\gamma_p \leq 0.02$,

$s = (52t_w - d/5) = 22.4$ in

Therefore, for $\gamma_p = 0.05$,

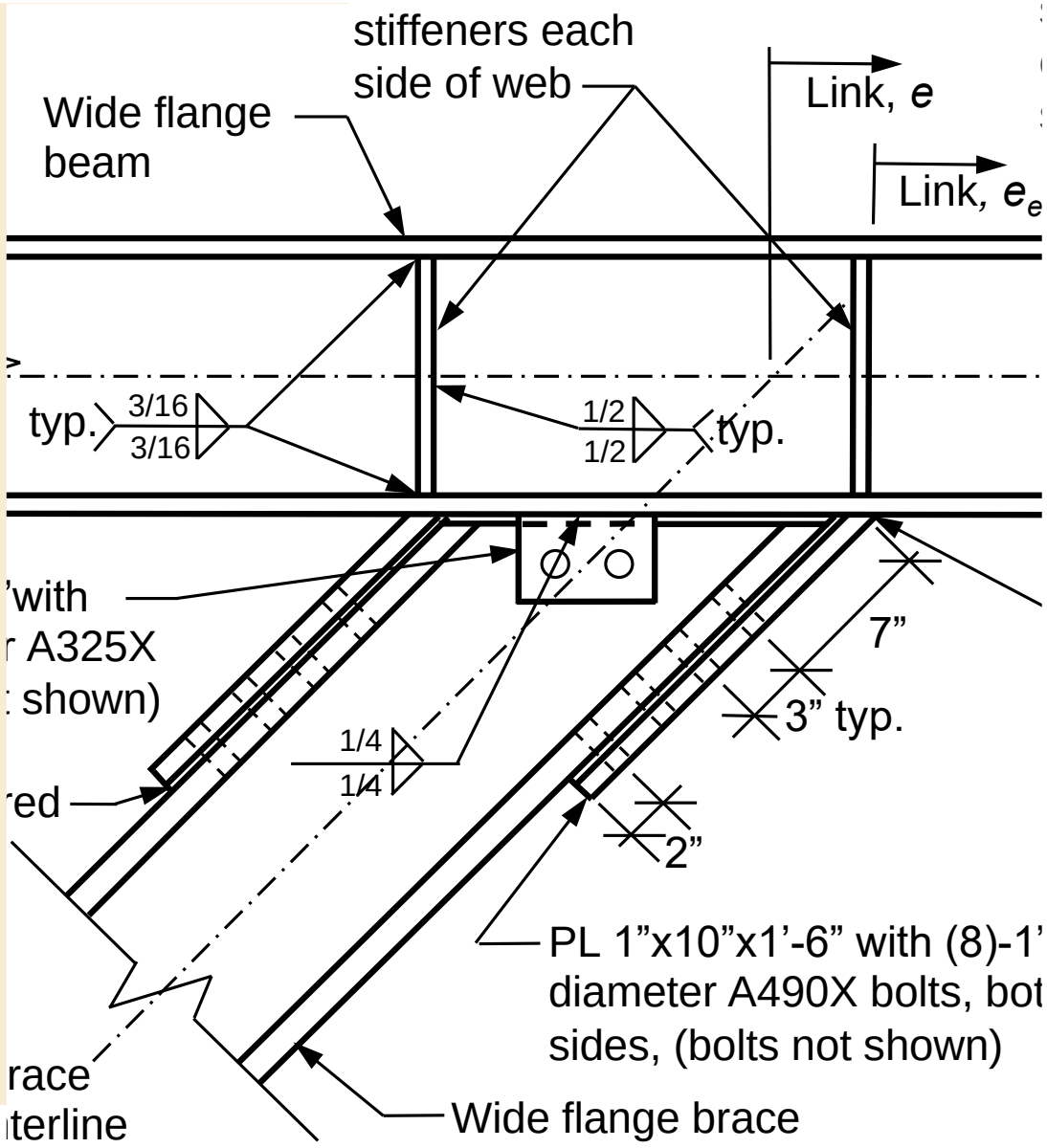
$s = 17.2$ in



Connection Design

Possible Alternatives:

- Welded Flange Plate (WFP) not prequalified
- Welded Unreinforced Flange (WUF) geometric compatibility, overhead groove welding, preheat and HAZ
- Pin Connection stiffness reductions, brace options



Alternative Connection Designs

Connection Design

Beam-to-Column AISC F3.6b.(a) and (b)

- Beam Segment Is Elastic (Outside the Link) AISC 341.F3.5a – user note.
- Shall Accommodate Inelastic Drift
- WUF-W Example 2, Figure 2-11

Connection Design

Beam-to-Gusset AISC F3.6b.(a) and (b)

- Beam Segment Is Elastic (Outside the Link) AISC 341.F3.5a – user note.
- Shall Accommodate Inelastic Drift
- WUF-W Example 2, Figure 2-11

Connection Design

Link Stability AISC 341.F3.4b.

- Brace Both Flanges
- End of the Link
- Strength and Stiffness AISC 341.D1.2c
- Similar to SMF Design Example 1 Section 5.3

Connection Design

Inelastic Strain AISC 341.F3.5c., I2.1

- Protected Zones (Link, Column Base, Column Splice, WUF-W)
  AISC 341.F3.6a

Quality Requirements AISC 341.J, AISC 360.N

- Quality Assurance Plan (QAP)

Design Procedure

Four Step Process:

1. Preliminary Member Design (Link, Column and Brace)
2. Analytical Analysis and Evaluation
3. Final Member Design
4. Connection Design

Items Not Addressed

Not Addressed

- Comparison of Wind and Seismic Forces
- Collector Elements
- Column Splice
- Column Base Connection
- Foundations
- Diaphragm System

Questions?

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