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### Course Description

#### Session L4: Design of the Braced Frames

October 1, 2018

This live webinar presents the design of the buckling restrained braced frames including: sizing braces, beam and column design, gusset plate design and connection analysis. The session will also cover plastic mechanism analysis, base plate design and concludes with a course summary.



### Learning Objectives

- Describe the steps for the sizing of braces.
- Describe the steps of a plastic mechanism analysis.
- Describe the steps for the design of the beams and columns.
- Describe the steps for the design of the gusset plates.



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## Seismic Design in Steel: Concepts and Examples

**Session L4: Design of the Braced Frames**  
October 1, 2018



Rafael Sabelli, SE





## Course objectives

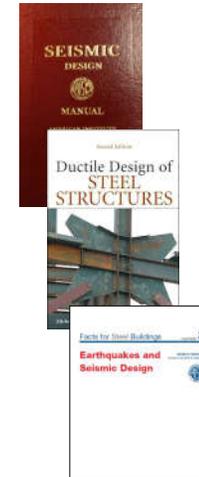
- Understand the principles of seismic design of steel structures.
- Understand the application of those principles to two common systems:
  - Special Moment Frames
  - Buckling-Restrained Braced Frames.
- Understand the application of design requirements for those systems.



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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 Webinars
  - Webinars@AISC.org



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## Course outline

### Part I: Concepts

- R1. Introduction to effective seismic design
- R2. Seismic design of moment frames
- R3. Seismic design of braced frames
- R4. Seismic design of buildings



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## Course outline

### Part II: Application

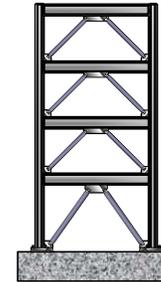
- L1. Planning the seismic design
- L2. Building analysis and diaphragm design
- L3. Design of the moment frames
- L4. Design of the braced frames



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## Session L4: Design of the braced frames



## Session topics

- Buckling-restrained brace sizing
- Plastic mechanism analysis
- Column and beam design
- Final analysis
- Gusset connections
- Base plate design
- Improved performance
- Course summary



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## BRBF design overview

- Compute demands using design base shear
- Size braces (fuses)
- Compute maximum brace forces
- Perform plastic mechanism analysis
- Size beams and columns for PMA forces
- Final analysis
  - Confirm period
  - Determine drift
- Design connections



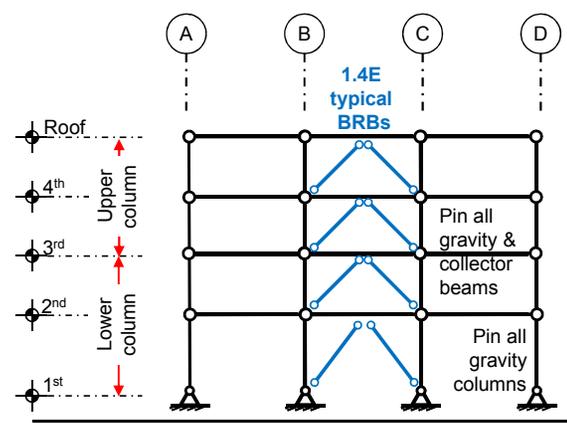
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## Brace sizing



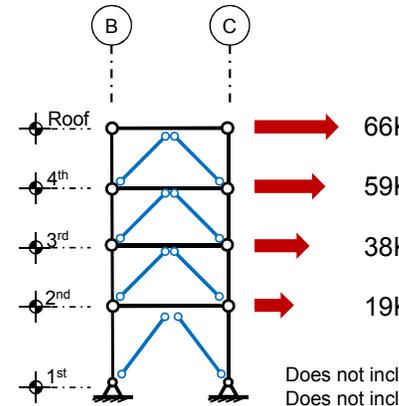
## Braced-frame model



Pin braces  
 Pin beams and columns  
 Pin all gravity & collector beams  
 Pin all gravity columns  
 Pin column bases

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## Braced-frame forces



66K  
 59K  
 38K  
 19K

Does not include  $\rho=1.3$   
 Does not include  $B_2$

Forces derived in sessions L1 & L2

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## Braced-frame forces

As an alternative to introducing pins in the model, the analysis results can be examined to confirm that the braces resist close to 100% of the required base shear. Brace forces can be adjusted upwards if necessary

Level	Frame $F_{xs}$ (kips)	$B_2$	$\rho$	Frame $\rho B_2 F_{xs}$ (kips)	Frame $\rho B_2 V_{xs}$ (kips)
Roof	66.0	1.02	1.30	87.6	88
4 <sup>th</sup>	59.2	1.03	1.30	79.3	167
3 <sup>rd</sup>	38.3	1.03	1.30	51.3	218
2 <sup>nd</sup>	18.7	1.04	1.30	25.3	243

Forces,  $\rho$ ,  $B_2$  derived in sessions L1 & L2

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## Force-based design

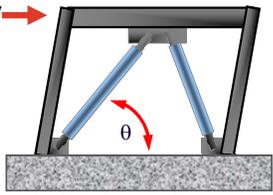
$$P_u = \frac{V}{2 \cos \theta}$$

• Assume braces resist 100% of story shear  $V$

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

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

Do not include gravity load





AISC 341 EQ F4-1

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## Brace design

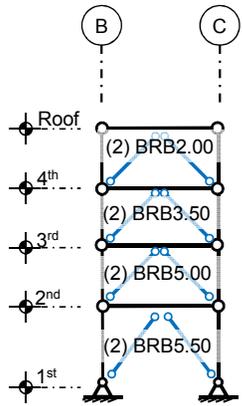
- Specifying area
  - “ $A_{sc} = 5.00 \text{ in}^2$ ”
  - Allow
    - $38 \text{ ksi} \leq F_y \leq 46 \text{ ksi}$
  - Determine area
    - Based on  $F_y \geq 38 \text{ ksi}$
  - Determine expected brace strength
    - Based on  $R_y F_y = 42 \text{ ksi}$

- Specifying strength
  - “ $\phi P_{sc} = 200 \text{ K}$ ”
  - Allow
    - $38 \text{ ksi} \leq F_y \leq 46 \text{ ksi}$
  - Determine area for model
    - Based on  $R_y F_y = 42 \text{ ksi}$
  - Determine expected brace strength
    - Based on  $R_y F_y A_{sc} = P_{sc}$
    - i.e.,  $R_y = 1.0$
    - Use  $R_y = 1.05$  for tolerance



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## Brace sizes



From brace manufacturer:  
 $38 \text{ ksi} \leq F_y \leq 46 \text{ ksi}$   
 Use  $F_y = 38 \text{ ksi}$

Level	Brace Force $\rho B_2 P_x$ , (kips)	Required core area $A_{sc}$ , ( $\text{in}^2$ )	Design core area $A_{sc}$ , ( $\text{in}^2$ )
4 <sup>th</sup>	62	1.81	2.00
3 <sup>rd</sup>	118	3.45	3.50
2 <sup>nd</sup>	154	4.51	5.00
1 <sup>st</sup>	183	5.34	5.50

Typically rounded up  $\leq 10\%$   
 For example,  $\frac{1}{4} \text{ in}^2$  typically used up to  $5 \text{ in}^2$ ,  $\frac{1}{2} \text{ in}^2$  up to  $10 \text{ in}^2$ , etc.



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## Plastic mechanism analysis



## Plastic mechanism analysis

- Determine maximum brace forces
- Determine vertical and horizontal components
- Apply components to frame
  - Use spreadsheet, or
  - Use temperature (or stress) based analysis



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## Maximum brace forces

- Based on testing

$$\omega = T_{max} / A_g F_y$$

Typical  $1.3 \leq \omega \leq 1.5$

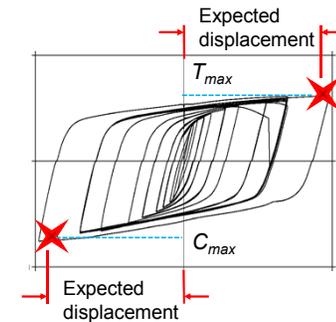
$$\beta \omega = C_{max} / A_g F_y$$

Typical  $1.1 \leq \beta \leq 1.2$

- For design

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

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



AISC 341 F4.2a

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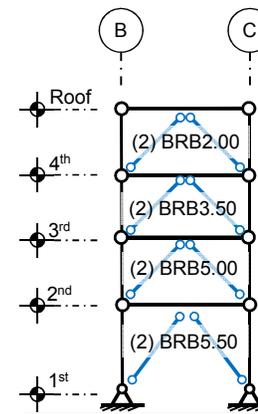
## Maximum brace forces

- Based on testing
  - May vary with manufacturer
- Based on deformation demands
  - Drift not known at this stage
  - Drift subject to change during design
    - Don't be overly precise
- Use reasonably liberal values for frame design
  - $\beta = 1.15$ 
    - Tends to be more than this for longer & larger braces
  - $\omega = 1.4$
  - $R_y F_y = 42 \text{ ksi}$
  - $\beta \omega R_y F_y = 67.6 \text{ ksi}$
  - $\omega R_y F_y = 58.8 \text{ ksi}$



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## Maximum brace forces



From brace manufacturer:  
 $\beta \omega R_y F_y = 67.6 \text{ ksi}$   
 $\omega R_y F_y = 58.8 \text{ ksi}$

Level	Design core <sup>2</sup> area $A_{sc}$ , (in <sup>2</sup> )	Tension Brace Force $\omega R_y F_y A_{sc}$ , (kips)	Compression Brace Force $\beta \omega R_y F_y A_{sc}$ , (kips)
4 <sup>th</sup>	2.00	118	135
3 <sup>rd</sup>	3.50	206	237
2 <sup>nd</sup>	5.00	294	338
1 <sup>st</sup>	5.50	323	372



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### Maximum brace forces

From brace manufacturer:  
 $\beta \omega R_y F_y A_{sc} = 67.6 \text{ ksi}$   
 $\omega R_y F_y = 58.8 \text{ ksi}$

Level	Required Brace Strength $P_u$ (kips)	Tension overstrength $\omega R_y F_y A_{sc} / P_u$	Compression overstrength $\beta \omega R_y F_y A_{sc} / P_u$
4 <sup>th</sup>	62	1.90	2.18
3 <sup>rd</sup>	118	1.74	2.01
2 <sup>nd</sup>	154	1.91	<b>2.19</b>
1 <sup>st</sup>	183	1.77	2.03

Use of 2.19E OK for seismic axial forces, but will not capture beam flexure due to  $\beta$ .

### A little trigonometry

### Maximum brace forces

Level	Tension Brace Force $\omega R_y F_y A_{sc}$ (kips)	Tension Brace x component (kips)	Tension Brace y component (kips)
4 <sup>th</sup>	118	83	83
3 <sup>rd</sup>	206	146	146
2 <sup>nd</sup>	294	208	208
1 <sup>st</sup>	323	215	241

Level	Compression Brace Force $\beta \omega R_y F_y A_{sc}$ (kips)	Compression Brace x component (kips)	Compression Brace y component (kips)
4 <sup>th</sup>	135	96	96
3 <sup>rd</sup>	237	167	167
2 <sup>nd</sup>	338	239	239
1 <sup>st</sup>	372	248	277

### Plastic mechanism analysis

Level	Tension Brace x component (kips)	Tension Brace y component (kips)
4 <sup>th</sup>	83	83
3 <sup>rd</sup>	146	146
2 <sup>nd</sup>	208	208
1 <sup>st</sup>	215	241

Level	Compression Brace x component (kips)	Compression Brace y component (kips)
4 <sup>th</sup>	96	96
3 <sup>rd</sup>	167	167
2 <sup>nd</sup>	239	239
1 <sup>st</sup>	248	277

Level	Tension Brace x component (kips)	Tension Brace y component (kips)
4 <sup>th</sup>	83	83
3 <sup>rd</sup>	146	146
2 <sup>nd</sup>	208	208
1 <sup>st</sup>	215	241

Level	Compression Brace x component (kips)	Compression Brace y component (kips)
4 <sup>th</sup>	96	96
3 <sup>rd</sup>	167	167
2 <sup>nd</sup>	239	239
1 <sup>st</sup>	248	277



### Plastic mechanism analysis

Column detail

$\frac{1}{2} \sin(\theta)(\beta-1) \omega R_y F_y A_{sc}$   
 $\sin(\theta) \omega R_y F_y A_{sc}$   
 $\frac{1}{2} \sin(\theta)(\beta-1) \omega R_y F_y A_{sc}$   
 $\sin(\theta) \omega R_y F_y A_{sc}$   
 $\frac{1}{2} \sin(\theta)(\beta-1) \omega R_y F_y A_{sc}$   
 $\sin(\theta) \omega R_y F_y A_{sc}$   
 $\sum_{i=2}^n \frac{1}{2} [(\beta+1) \omega R_y F_y A_{sc} \sin \theta] + [\frac{1}{2} \sin(\theta)(\beta-1) \omega R_y F_y A_{sc}]_1$   
 $\sum \frac{1}{2} (\beta+1) \omega R_y F_y A_{sc} \sin \theta$

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### Column design

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### Plastic mechanism analysis

Level	Tension Brace y component (kips)	Compression Brace y component (kips)
4 <sup>th</sup>	83	96
3 <sup>rd</sup>	146	167
2 <sup>nd</sup>	208	239
1 <sup>st</sup>	241	277

Level	Column tension force $E_{cl}$ (kips)	Column compression force $E_{cl}$ (kips)
4 <sup>th</sup>	6	-6
3 <sup>rd</sup>	100	78
2 <sup>nd</sup>	261	230
1 <sup>st</sup>	487	451
Base	729	729

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### Column design

- Axial loads
  - $P_D = 147K$
  - $P_L = 60.0K$
  - $P_{Ecl} = 451K$  (compression)
  - $P_{Ecl} = 487K$  (tension)
- Compression
  - $R_u = 1.4D + 0.5L + E_{cl}$
  - $R_u = 687K$
- Tension
  - $R_u = 0.7D + E_{cl}$
  - $R_u = 384K$

Use W10x77  
 $\phi P_n = 753K$  (Manual Table 4-1)  
 Seismically compact (SDM Table 1-3)

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### Member Selection

- Compactness
  - Use SDM table
  - AISC 341-16 permits moderately ductile members for BRBF beams and columns
    - Use IMF column

Table 1-3 (continued)  
 Sections That Satisfy Seismic Width-to-Thickness Requirements  
 $F_y = 50$  ksi

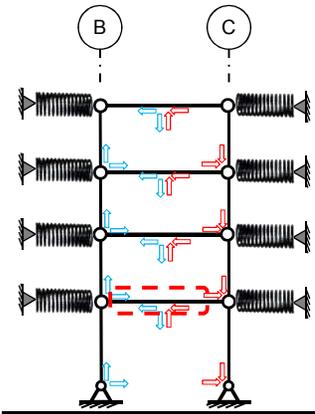
Shape	EBF		BRBF	SPSW	Prest. Nbr ASD		Prest. Nbr LRFD		Web Access Rules
	Diagonal Braces	Columns	Links and Columns	HBE and VBE	$\lambda_{max}$	$\lambda_{min}$	$\lambda_{max}$	$\lambda_{min}$	
W10x112	•	•	•	•	•	•	•	•	D D C C B A or B
>100	•	•	•	•	•	•	•	•	
>88	•	•	•	•	•	•	•	•	
>77	•	•	•	•	•	•	•	•	
>68	•	•	•	•	•	•	•	•	
>60	•	•	•	•	•	•	•	•	
>54	•	•	•	•	•	•	•	•	
>49	•	•	•	•	•	•	•	•	



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## Beam design

### Plastic mechanism analysis



Level	Beam axial force $E_{cl}$ (kips)	Beam shear force $E_{cl}$ (kips)	Beam moment $E_{cl}$ (ft-kips)
Roof	96	6.2	78
4 <sup>th</sup>	167	10.9	136
3 <sup>rd</sup>	239	15.6	195
2 <sup>nd</sup>	248	18.1	226

$$P_{Ecl} = \cos(\theta) \beta \omega R_y F_y A_{sc}$$

$$V_{Ecl} = \frac{1}{2} \sin(\theta) (\beta - 1) \omega R_y F_y A_{sc}$$

$$M_{Ecl} = \frac{1}{2} V_{Ecl} L$$



## Beam design

- Shear
  - $V_D = 11.2K$
  - $V_L = 8.5K$
  - $V_E = -18.1K$
  - $V_u = 0.7D + E_{cl} = -10.3K$
- Moment
  - $M_D = 120'K$
  - $M_L = 100'K$
  - $M_E = -226'K$
  - $M_u = 0.7D + E_{cl} = -142'K$

- Axial
  - $P_D = 0K$
  - $P_L = 0K$
  - $P_E = 248K$
  - $P_u = 248K$

Bottom-flange lateral brace

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## Beam design

- W18x55
  - Shear
    - $\phi V_n = 212K > V_u$  OK
    - Check chevron connection
  - Moment
    - $\phi M_n = 417K$ 
      - Table 3-10
        - $L_b = 6'$
        - $C_b = 1$
      - $C_b = 1.25$  (for  $M_2 = 2M_1$ )
        - $(1.25) 417K = 521K$
    - $\phi M_p = 420K$
    - $\phi M_n = \phi M_p = 420K$

$$L_g \geq \frac{2(P_1 + P_2) \cos \theta e_b}{\phi V_n}$$

•  $L_g \geq 40" < L/6 = 48"$  OK (rule of thumb)

$V_u = \frac{2(P_1 + P_2) \cos \theta e_b}{L_g}$

Chevron check illustrated in connection design. However, it should be considered in member selection.

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## Member Selection

- Compactness
  - Use SDM Table
  - AISC 341-16 permits moderately ductile members for BRBF beams and columns
    - Use IMF column

Table 1-3 (continued)  
 Sections That Satisfy Seismic Width-to-Thickness Requirements  
 $F_y = 50$  ksi

**W-Shapes**

Shape	EBF		BRBF		SPSW		ASD		IMF		Web Access Holes
	Diagonal Braces	Columns	Beams and Columns	Links	Beams and Columns	Links	$P_u$	$M_u$	$P_u$	$M_u$	
W21-57	*	*	*	*	*	*	217	307	326	461	B
>50	*	*	*	*	*	*	117	219	176	330	A or B
>44	*	*	*	*	*	*	98.3	133	107	201	A or B
W18-311	*	*	*	*	*	*	—	—	—	—	F
>293	*	*	*	*	*	*	—	—	—	—	H
>258	*	*	*	*	*	*	—	—	—	—	G
>234	*	*	*	*	*	*	—	—	—	—	F
>211	*	*	*	*	*	*	—	—	—	—	F
>182	*	*	*	*	*	*	—	—	—	—	E
>175	*	*	*	*	*	*	—	—	—	—	D
>158	*	*	*	*	*	*	—	—	—	—	D
>143	*	*	*	*	*	*	—	—	—	—	C
>130	*	*	*	*	*	*	—	—	—	—	C
>119	*	*	*	*	*	*	—	—	—	—	C
>108	*	*	*	*	*	*	—	—	—	—	C
>97	*	*	*	*	*	*	—	—	—	—	C
>86	*	*	*	*	*	*	—	—	—	—	C
>76	*	*	*	*	*	*	595	820	995	932	C
W18-71	*	*	*	*	*	*	—	—	—	—	C
>65	*	*	*	*	*	*	—	—	—	—	C
>60	*	*	*	*	*	*	444	672	669	706	B
>55	*	*	*	*	*	*	246	391	329	389	B
>50	*	*	*	*	*	*	217	288	326	433	A or B
W18-45	*	*	*	*	*	*	212	273	319	—	B
>40	*	*	*	*	*	*	65.4	158	98.3	46	A or B
>35	*	*	*	*	*	*	30.9	107	48.3	191	A or B

## Beam design

- $B_1 = \frac{C_m}{1 - P_u/P_{E1}} \geq 1$ 
  - Assume  $C_m = 0.8$  ( $M_1/M_2 = -2$ )
    - $C_m < 0.6$
    - $C_m = 0.6$
    - $C_m > 0.6$
    - $C_m = 1.0$

- $P_{E1} = \frac{\pi^2 EI}{L^2} = 45,300K$  If  $C_m = 0.8$
- $B_1 = 1$  If  $C_m = 0.8$   $B_1 = 1$  for  $P_u \leq 0.2P_{E1}$

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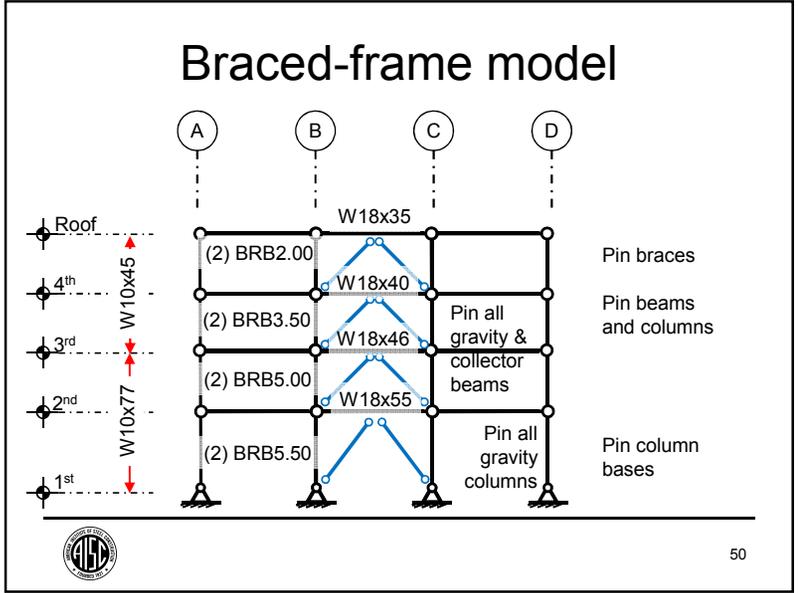
## Beam design

- Axial
  - $KL/r_y = 75"/1.67" = 44.9$
  - $\phi F_{cr} = 38.8$ ksi
    - Table 4-22
  - $\phi F_{cr} A = 629K$
- Chapter H Interaction
  - $P_u / \phi F_{cr} A = 0.39$
  - $P_u / \phi F_{cr} A + 8/9 M_u / \phi M_n = 0.39 + 8/9(142K/420K) = 0.69$  OK

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## Final analysis

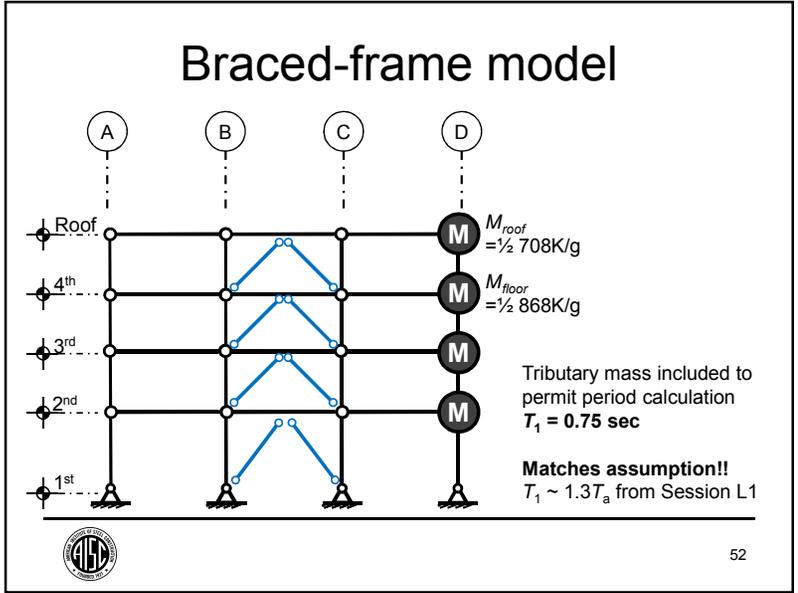



### Brace stiffness

- Consult manufacturer
  - Direct communication
  - Brochure

Level	Design core area $A_{sc}$ (in <sup>2</sup> )	Workpoint length (ft)	Stiffening factor
4 <sup>th</sup>	2.00	17.7	1.39
3 <sup>rd</sup>	3.50	17.7	1.39
2 <sup>nd</sup>	5.00	17.7	1.43
1 <sup>st</sup>	5.50	18.8	1.46

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## Drift

- Obtain from model
- Recalculate  $B_2$
- Amplify drift for second-order effects
  - Only necessary per ASCE 7 if  $\theta > 0.1$  ( $B_2 > 1.1$ )
  - Preferable not to modify process for  $B_2 < 1.1$

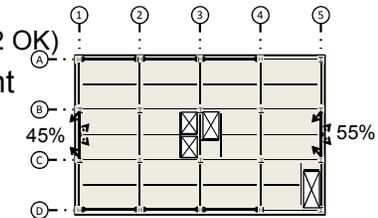
Level	Model drift (%)	$B_2$	Drift* $B_2$
4 <sup>th</sup>	1.76%	1.02	1.80%
3 <sup>rd</sup>	1.68%	1.02	1.71%
2 <sup>nd</sup>	1.60%	1.03	1.65%
1 <sup>st</sup>	1.36%	1.03	1.40%



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## Check irregularities

- Horizontal torsional irregularity
  - Same check as initial
    - Lines A & D identical
    - Lines 1 & 5 identical
    - $\Delta_5 \leq 1.1\Delta_{ave}$  (up to 1.2 OK)
  - Irregularity not present



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## Check irregularities

- Vertical soft story
    - Results from model
- | Level           | Displacement (in.) | Shear (kips) | Stiffness (kips/in) |
|-----------------|--------------------|--------------|---------------------|
| 4 <sup>th</sup> | 0.528              | 66.0         | 125                 |
| 3 <sup>rd</sup> | 0.504              | 125.2        | 248                 |
| 2 <sup>nd</sup> | 0.480              | 163.6        | 341                 |
| 1 <sup>st</sup> | 0.457              | 182.3        | 399                 |
- Story stiffness increases with story shear
  - Irregularity not present



(at least 70% of the stiffness above)

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## Check irregularities

- Vertical weak story
  - Brace strength

Level	Design core area $A_{sc}$ (in <sup>2</sup> )	Tension Brace Force $\omega R_y F_y A_{sc}$ (kips)	Compression Brace Force $\beta \omega R_y F_y A_{sc}$ (kips)	Story shear strength (kips)
4 <sup>th</sup>	2.00	118	135	358
3 <sup>rd</sup>	3.50	206	237	626
2 <sup>nd</sup>	5.00	294	338	894
1 <sup>st</sup>	5.50	323	372	926

- Story strength increases with story shear
- Irregularity not present



(at least 80% of the stiffness above)

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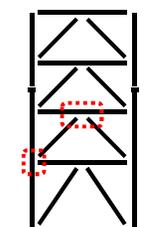
There's always a solution in steel.

## Gusset connections



## Gusset connection

- Beam-column-brace connection
  - Rotation approach
  - Configuration
  - Gusset design
  - Beam-to-gusset connection
- Chevron connection
  - Minimum length
  - Local forces
  - Gusset design




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## Gusset connection

- Manufactured braces
  - Manufacturer-designed brace to gusset connection
  - Gusset thickness relates to BRB core plate thickness
  - Manufacturer can assist with gusset connection to beam & column
- EOR
  - Remains responsible for structure
  - Must communicate
    - Non-brace forces at connection
      - Beam shear
      - Column shear?
    - Load path restrictions
      - Especially at base plates



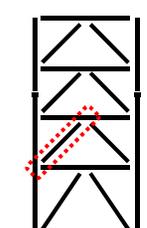
59

## Gusset connection

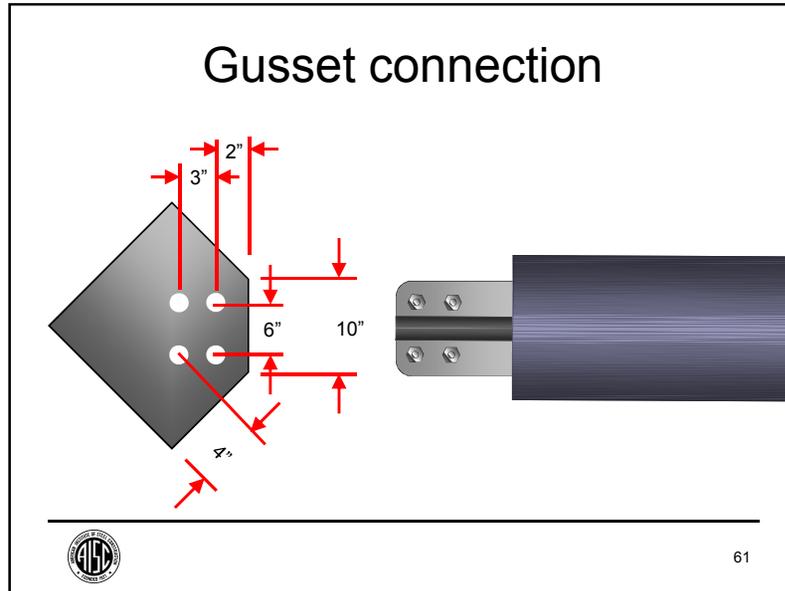
- Brace-to-gusset connections
  - Check manufacturer's design
    - (4)1"Ø A490X bolts
    - Double shear
    - 3/4" A572 Gr. 50 gusset



$P_u = 338K$  (compression)  
 $P_u = 294K$  (tension)




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### Gusset connection

- Compression
  - $R_u = 338K$
  - Bolt shear
    - (Table 7-1)
    - $\phi R_n = 4 * 98.9K = 396K$
  - Bearing (spacing)
    - (Table 7-4)
    - $\phi R_n = 4 * 3/4 * 113K = 339K$
- Tension
  - $R_u = 294K$
  - Bearing (edge distance)
    - (Tables 7-4 & 7-5)
    - $\phi R_n = 2 * 3/4 * 113K$
    - $+ 2 * 3/4 * 85.9K = 298K$



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### Gusset connection

- Block shear
  - $R_n = 0.6F_u A_{nv} + U_{bs} F_u A_{nt} \leq 0.6F_y A_{gv} + U_{bs} F_u A_{nt}$
  - $0.6(65\text{ksi})(5.53\text{in}^2) + (1.0)(65\text{ksi})(3.84\text{in}^2) = 466K$
  - $0.6(50\text{ksi})(7.5\text{in}^2) + (1.0)(65\text{ksi})(3.94\text{in}^2) = 475K$
  - $\phi R_n = 0.75(466K) = 349K$



AISC 360 §J.4

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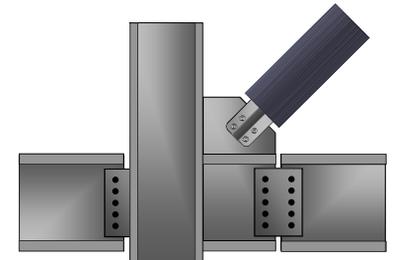
## Beam-column-brace connection

There's always a solution in steel.



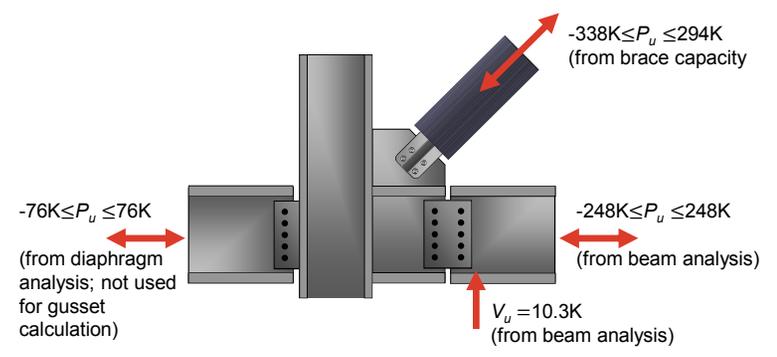
### Beam-column-brace connection

- Mega-gusset
  - Beam connection outside gusset
    - Follow "simple connection" limits to allow for rotation
  - Flange plates
    - Stability
    - Deck support
  - Eccentric moment on column



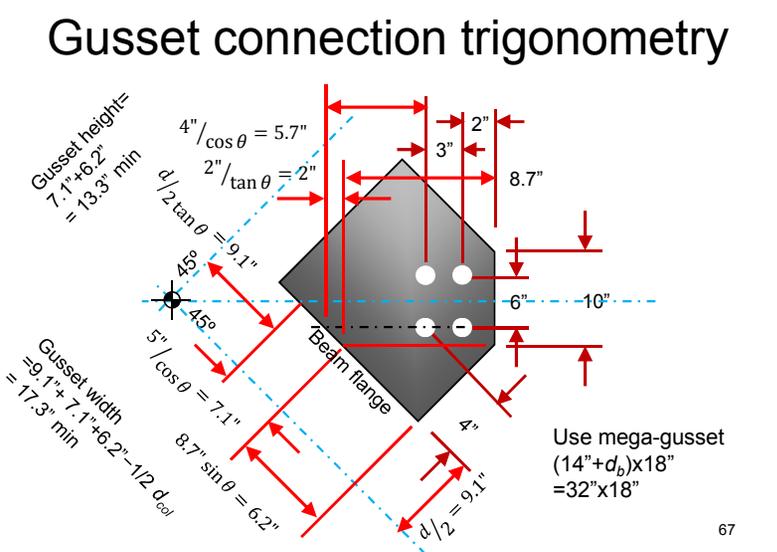

65

### Beam-column-brace connection



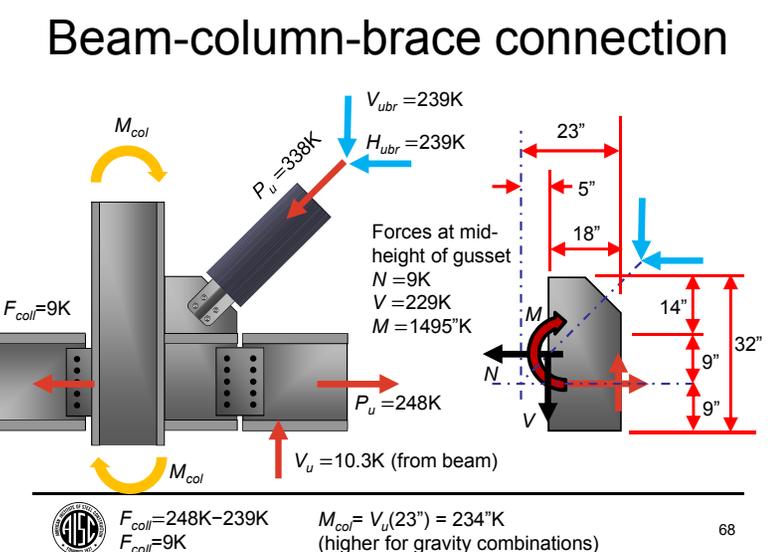

66

### Gusset connection trigonometry




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### Beam-column-brace connection




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### Beam-column-brace connection

$$V = 229K$$

$$f_v = \frac{229k}{(0.75in)(32in)} = 9.5ksi$$

$$N = 9K$$

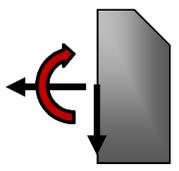
$$f_a = \frac{9k}{(0.75in)(32in)} = 0.4ksi$$

$$M = 1495''K$$

$$f_b = \frac{4 * 1495''K}{(0.75in)(32in)^2} = 7.8ksi$$

Plate:

$$f_e = \sqrt{(f_a + f_b)^2 + 3f_v^2} = 22.7ksi < \phi F_y$$



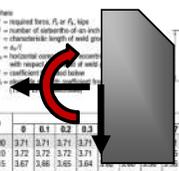
### Beam-column-brace connection

- Weld:
  - $e=M/V = 6.5''$ 
    - (ignore small  $N$ )
  - $a=e/L = 6.5''/32'' = 0.20$
  - Table 8-4
    - Angle = 0°
    - $k=0$  for out-of-plane
    - $C=3.51K/in/(1/16in)$
    - $D \geq 229/(0.75 * 3.51 * 32)$
    - $D \geq 2.7, x1.25=3.4$
    - Use (2)  $5/16''$  fillet welds

**Table 8-4**  
**Coefficients, C,**  
**for Eccentrically Loaded Weld Groups**  
**Angle = 0°**

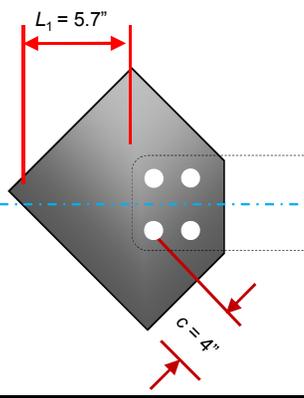
Analyze strength of a weld group,  $\phi R_n$  or  $\phi R_w$ , is determined with  
 $R_n = C \phi D^2$  ( $\phi = 0.75, \Omega = 2.00$ )

LWFD	ASD			
	$C_{min} = \frac{P_u}{\phi C D^2}$	$D_{min} = \frac{P_u}{\phi C D^2}$	$C_{max} = \frac{P_u}{\phi C D^2}$	$D_{max} = \frac{P_u}{\phi C D^2}$
0.00	3.71	3.71	3.71	3.71
0.10	3.72	3.72	3.72	3.72
0.15	3.87	3.86	3.85	3.84
0.20	3.91	3.91	3.90	3.89
0.25	3.91	3.91	3.91	3.90
0.30	3.91	3.91	3.91	3.90
0.40	3.91	3.91	3.91	3.90
0.50	3.91	3.91	3.91	3.90
0.60	3.91	3.91	3.91	3.90
0.70	3.91	3.91	3.91	3.90
0.80	3.91	3.91	3.91	3.90
0.90	3.91	3.91	3.91	3.90
1.00	3.91	3.91	3.91	3.90
1.10	3.91	3.91	3.91	3.90
1.20	3.91	3.91	3.91	3.90
1.30	3.91	3.91	3.91	3.90
1.40	3.91	3.91	3.91	3.90
1.50	3.91	3.91	3.91	3.90
1.60	3.91	3.91	3.91	3.90
1.70	3.91	3.91	3.91	3.90
1.80	3.91	3.91	3.91	3.90
1.90	3.91	3.91	3.91	3.90
2.00	3.91	3.91	3.91	3.90



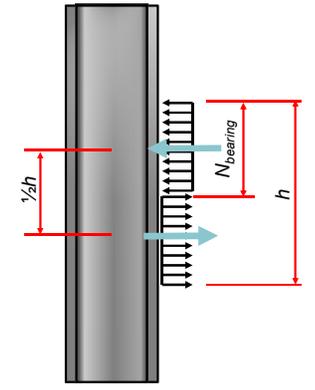
### Beam-column-brace connection

- Check gusset compactness
    - Per Dowswell (2006 AISC Engineering Journal)
- $$t_B = 1.5 \sqrt{\frac{F_y c^3}{EL_1}} = 1.5 \sqrt{\frac{(50 \text{ ksi})(4 \text{ in})^3}{(29,000 \text{ ksi})(5.7 \text{ in})}}$$
- $$= 0.14 \text{ in} \leq 0.75 \text{ in}$$
- Gusset is compact
  - No further stability evaluation required



### Beam-column-brace connection

- Check column
  - WLY, WC
  - Forces
    - $R_u = M/(1/2h) + 1/2N$   
 $= 98K$
    - $N_{bearing} = 1/2h = 16''$
    - (evaluation not presented)



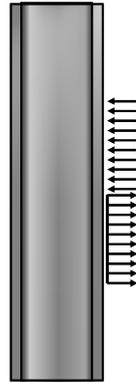
## Beam-column-brace connection

- Panel Zone

- $R_u = M/(1/2h)$   
 $= 93K$

- $\frac{P_u}{P_y} = \frac{687K}{(50ksi)(22.7in^2)} = 0.6$

- $\phi R_n = 0.9 * 0.6F_y t_w d \left( 1.4 - \frac{P_u}{P_y} \right)$   
 $= 121K \text{ OK}$



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## Beam-column-brace connection

- Double plate connection

- (5)  $\frac{7}{8}$ "  $\text{\O}$  A325X bolts

- At beam
  - At gusset

- Double shear

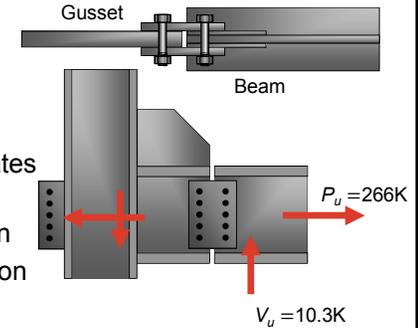
- (2)  $\frac{3}{8}$ " A572 Gr. 50 plates

- 15"x12"

- Tack welds for erection

- See collector connection calculations

- Reinforce beam web



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## Beam-column-brace connection

- Double plate connection

- Meets limits for single plate connection

- #bolts = 5  $\leq$  12

- Bolt-to-weld distances  $\leq 3\frac{1}{2}$ "
    - Bolt-line-to-bolt-line distances  $\leq 7$ "

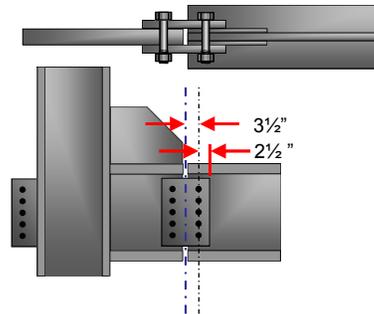
- STD holes

- Horizontal edge distance

- $L_{eh} \geq 2d$

- Maximum plate thickness

- $d/2 + \frac{1}{16}$ " =  $\frac{1}{2}$ "



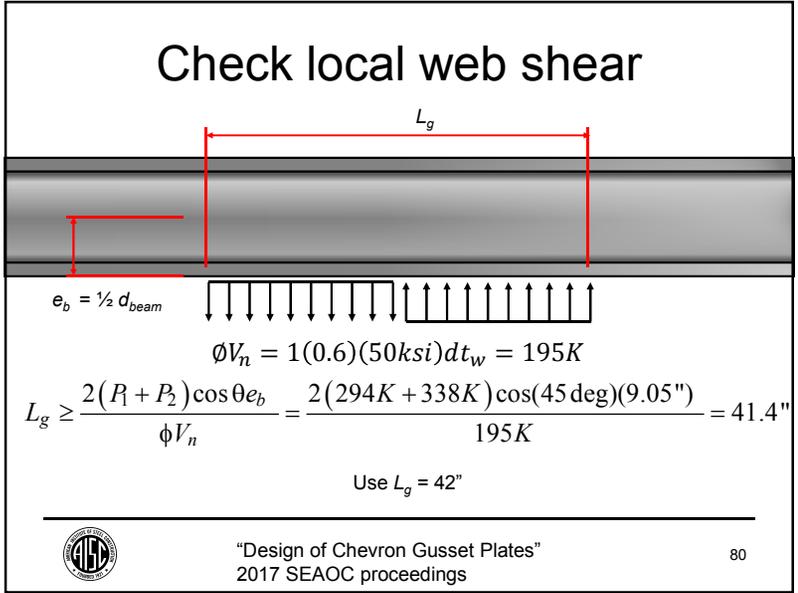
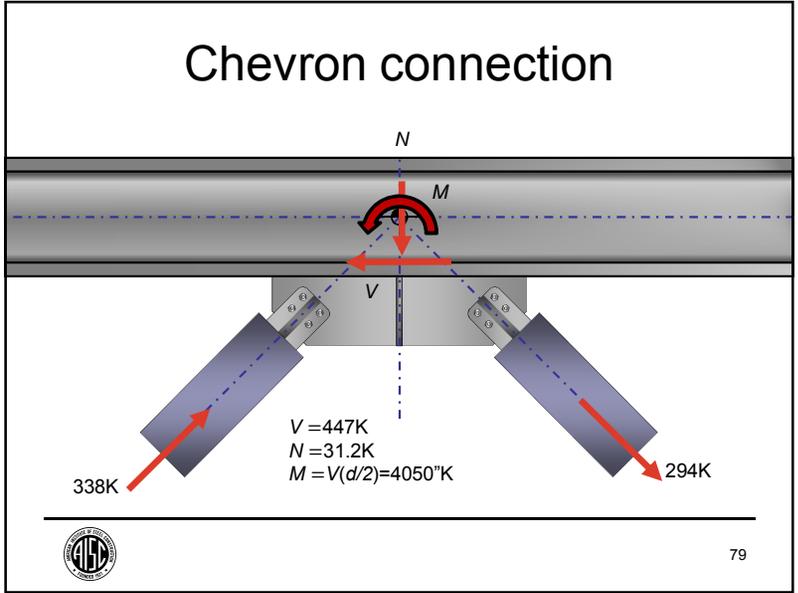
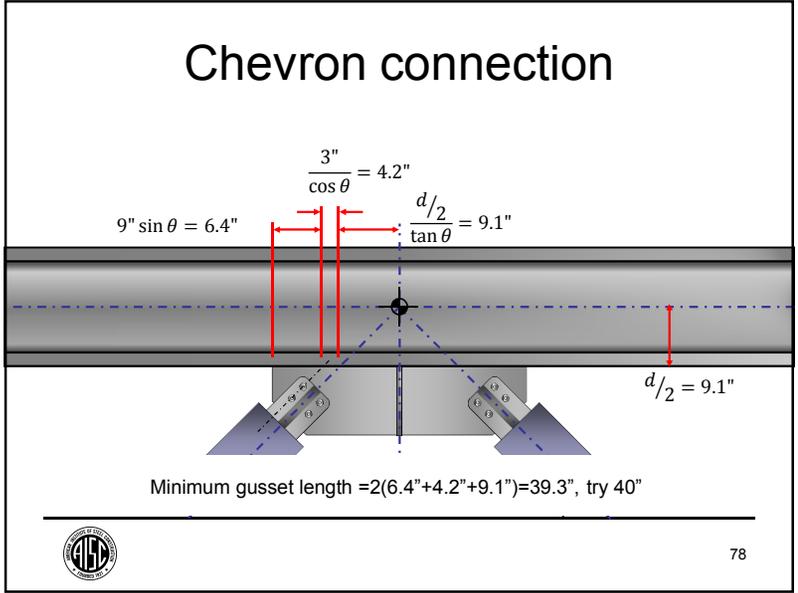
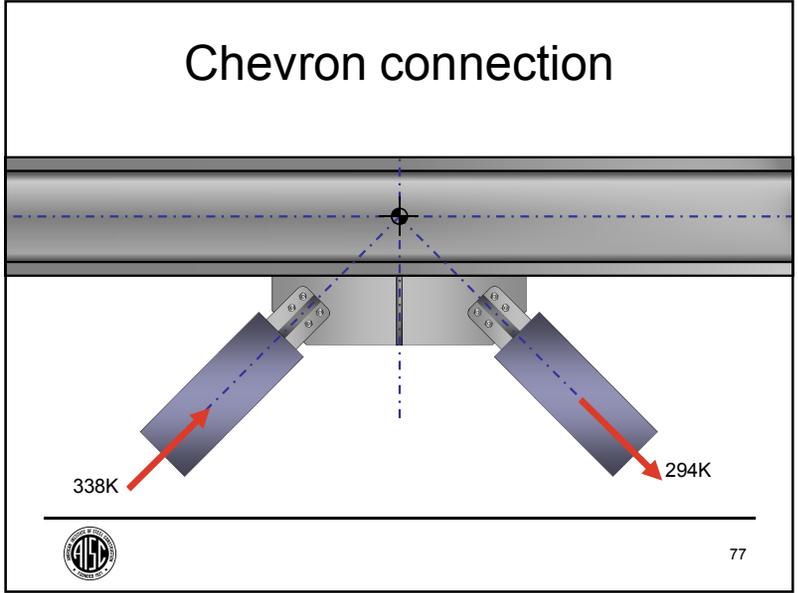
Extended configuration procedure  
 available beyond these limits

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## Chevron connection

There's always a solution in steel.





## Chevron connection

$$V = 447K$$

$$f_v = \frac{447k}{(0.75in)(42in)} = 14.2ksi$$

$$N = 31K$$

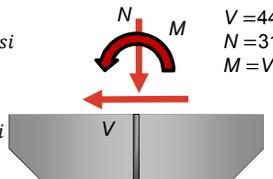
$$f_a = \frac{31k}{(0.75in)(42in)} = 1.0ksi$$

$$M = 4050^{\circ}K$$

$$f_b = \frac{4 * 4050^{\circ}K}{(0.75in)(42in)^2} = 12.2ksi$$

$$f_e = \sqrt{(f_a + f_b)^2 + 3f_v^2} = 28ksi < \phi F_y$$

von Mises effective stress





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## Chevron connection

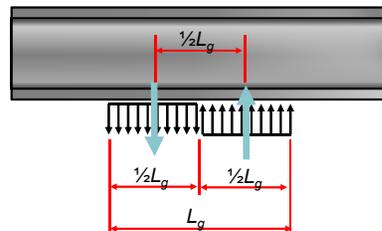
- Weld:
  - $e = M/V = 9.1''$ 
    - (ignore small N)
  - $e/L = 9.1''/42'' = 0.23$  Table 8-4
    - Angle =  $0^{\circ}$
    - $k=0$
    - $C=3.31K/in/(1/16in)$
    - $D \geq 447/(0.75*3.51*42)$
    - $D \geq 4.3, x1.25=5.4$
    - Use (2)  $3/8''$  fillet welds



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## Chevron connection

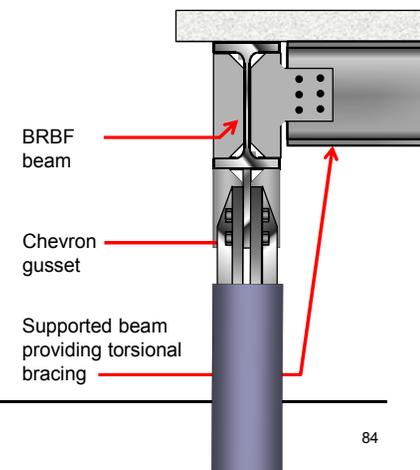
- Check beam
  - WLY
  - WC
  - Forces
    - $R_u = M/(\frac{1}{2}L_g) + \frac{1}{2}N$   
 $= 208K$
    - $N_{bearing} = \frac{1}{2}L_g = 21''$
  - (evaluation not presented)



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## Chevron connection

- Provide torsional bracing at chevron connection
  - AISC 341 F4.4a(2)



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There's always a solution in steel.

## Base plate

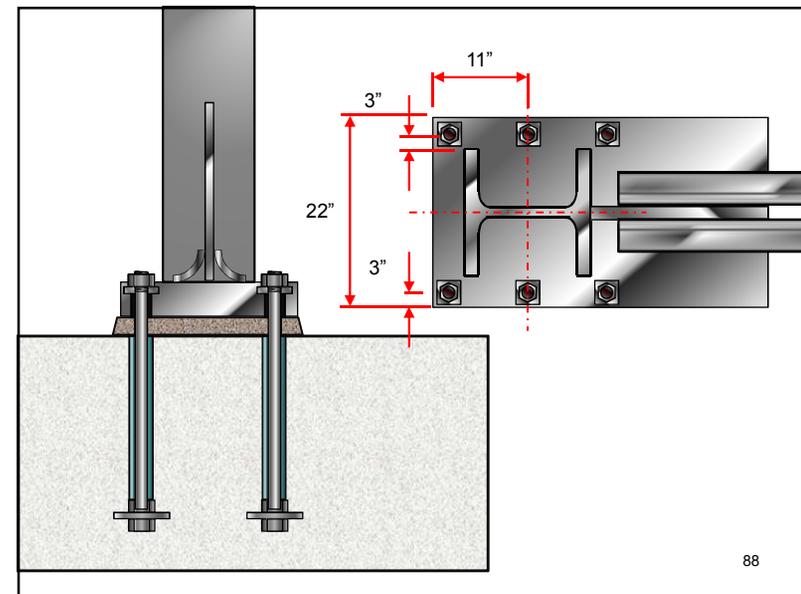
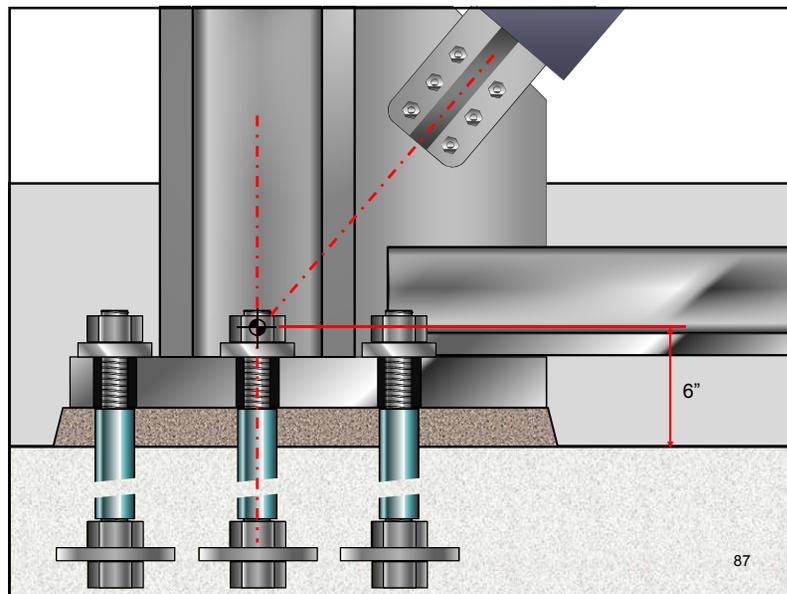


## Base-plate design

- Maximum forces from plastic mechanism analysis
- Use anchor rods for tension
- Do not use anchor rods for shear
- Provide rotational ductility
- Is the manufacturer assisting with gusset design?
  - Specify if base plate is designed to resist vertical gusset force



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## Base-plate design

- Tension
  - Size rods
  - Check plate bending
  - Rotational ductility
    - Anchor rods
    - Base plates
    - Column rotation
    - Foundation rotation
- Compression
  - Check bearing
  - Check plate bending
  - Rotational ductility
    - Column rotation
    - Foundation rotation
    - Base plates and anchor rods will not provide rotation



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## Base-plate design

- Axial loads
  - $P_D = 147K$
  - $P_L = 60.0K$
  - $P_{Ecl} = 729K$
- Compression
  - $R_u = 1.4D + 0.5L + E_{cl}$
  - $R_u = 965K$
- Tension
  - $R_u = 0.7D + E_{cl}$
  - $R_u = 626K$

Level	Column tension force $E_{cl}$ (kips)	Column compression force $E_{cl}$ (kips)
4 <sup>th</sup>	6	-6
3 <sup>rd</sup>	100	78
2 <sup>nd</sup>	261	230
1 <sup>st</sup>	487	451
Base	729	729



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## Base-plate design

- Shear loads
  - Brace in tension
    - $V_{Ecl} = 215K$
  - Brace in compression
    - $V_{Ecl} = 248K$

Level	Tension Brace Force $\omega R_y F_y A_{sc}$ (kips)	Tension Brace x component (kips)	Tension Brace y component (kips)
4 <sup>th</sup>	118	83	83
3 <sup>rd</sup>	206	146	146
2 <sup>nd</sup>	294	208	208
1 <sup>st</sup>	323	215	241

Level	Compression Brace Force $\beta \omega R_y F_y A_{sc}$ (kips)	Compression Brace x component (kips)	Compression Brace y component (kips)
4 <sup>th</sup>	135	96	96
3 <sup>rd</sup>	237	167	167
2 <sup>nd</sup>	338	239	239
1 <sup>st</sup>	372	248	277



## Anchor-rod design

- $F_{nt} = \phi 0.75 F_u = 44.7 \text{ksi}$
- $A_{required} = 626K / 44.7 \text{ksi} = 14.0 \text{in}^2$
- Use (6) 1 $\frac{3}{4}$ "  $\phi$  F1554 Gr 55 anchor rods
  - $A_{net} = 1.90 \text{in}^2$
  - $\phi F_u A_{net} = 0.75(75 \text{ksi})1.90 \text{in}^2 = 107K/\text{rod}$
  - 6 rods:  $6 * 107K = 641K$  OK



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## Anchor-rod design

**Table 14-2**  
**Recommended Maximum Sizes for**  
**Anchor-Rod Holes in Base Plates**

Increase  
for grade  
55

- Use (6) 1 3/4" Grade 55 anchor rod F1554, S1

Anchor Rod Diameter, in.	Hole Diameter, in.	Min. Washer Size, in.	Min. Washer Thickness
1 1/2	2 5/16	3 1/2	1/2
1 3/4	2 3/4	4	3/4
2	3 1/4	5	3/4
2 1/2	3 3/4	5 1/2	7/8

Notes: 1. Circular or square washers meeting the washer size are acceptable.  
 2. Clearance must be considered when choosing an appropriate anchor rod hole location, noting effects such as the position of the rod in the hole with respect to the column, weld size and other interferences.  
 3. When base plates are less than 1/4 in. thick, punching of holes may be an economical option. In this case, 3/4-in. anchor rods and 1 1/16-in.-diameter punched holes may be used with ASTM F844 (USS Standard) washers in place of fabricated plate washers.

## Base-plate design

- Flexure under tension
  - $x = 3" + 0.1b_f = 3.10"$
  - Use  $B=22"$
  - $T=626K/2=313K$ 
    - $M=313K(3.10")=970"K$
  - $t_p \geq 2.11 \sqrt{\frac{Tx}{BF_y}} = 1.98"$  Use 2" plate



AISC Design Guide 1 §3.2

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## Base-plate design

- Compression: assume 18"x18" bearing area
  - $965K/(18in \times 18in) = 2.98ksi$
  - $L = \frac{1}{2} [18" - 0.8b_f] = \frac{1}{2} [18" - 0.8(10.2")] = 4.92"$
  - $\lambda n' = \lambda \cdot \frac{\sqrt{db_f}}{4} = 1 \cdot \frac{\sqrt{(10.6)(10.2)}}{4} = 2.6"$
  - $M = WL^2/2 = 2.98ksi(18in)(4.92in)^2/2 = 649"K$
  - $t_p \geq 2.11 \sqrt{\frac{M}{BF_y}} = 1.79in$ . Use 2" plate



AISC Design Guide 1 §3.1

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## Shear design

- $V_u = 248K$
- Provide direct transfer to concrete slab
  - Embedded structural steel angles (or other shapes)
  - A706 bar
  - etc.
  - Provide load path into foundation
- Combined tension shear and bending:
  - 3"Ø anchor rods



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### Gusset design coordination

- Communicate load path to gusset designer:
  - Tension
    - $H_2 = H_3 = 50\% H_u$
    - $V_1 = 100\% V_u$
    - $M_1 = 100\% eV_u$
  - Compression
    - $H_2 = H_3 = 50\% H_u$
    - No tension on gusset bottom edge
  - EOR must check column

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### Base Plate

Gr. 50 Plate 2"x22"x30"  
 (6) 1½" Gr. 55 Anchor rods with ¾"x3½"x3½" plate washers at base plate and at bottom.  
 De-bond rods from concrete.

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There's always a solution in steel.

## Improved performance

structural STEEL

### Improved performance

- BRBF provide very good reliability against collapse
- Residual drift is not addressed in AISC 341
  - Residual drift can be reduced through the introduction of a modest restoring force
  - Add moment frames adjacent to braced frames
    - Act as robust collectors
    - Reduce overturning on braced-frame columns

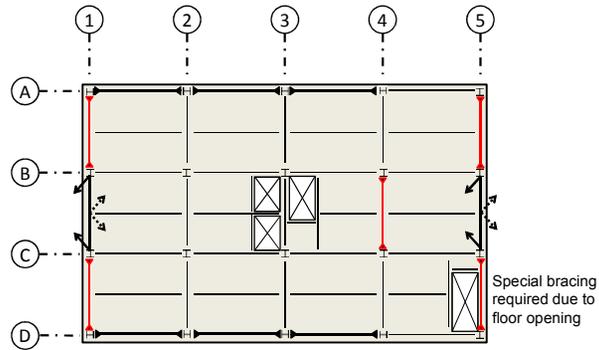
100

# Improved performance

- Supplemental moment frames
  - Design as OMF
    - Follow OMF connection detailing requirements
  - Do not utilize OMF in the analysis
    - Design BRBF for 100% of the force



# Improved performance



# Completion of design

There's always a solution in steel.



# Completion of design

- Braces
  - Indicate protected zone
  - Review manufacturer's design
  - Review testing information
- Connections
  - Indicate DCW
- Beam
  - Design lateral bracing
- Column
  - Design column splice



## Completion of design

- Base plate
  - Provide load path for shear
  - Design concrete anchorage/force transfer to foundation
  - Design grade beam for ductile rotation
- Specifications
  - Specify weld toughness requirements
  - Specify Quality Assurance Plan



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## Summary

There's always a solution in steel.



## Summary

- BRBF have a rigorous capacity design procedure
  - Design braces first
  - Compute maximum brace forces
    - Requires data from manufacturers
  - Design
    - Beams
    - Columns
    - Connections



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## Summary

- BRBF require coordination and partnership with manufacturers
  - Review assumptions
    - Load path
    - Design responsibilities
  - Review factors
    - $\beta$ ,  $\omega$
  - Review testing
    - Factors
    - Cover all project braces



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There's always a solution in steel.

## Course wrap-up



AMERICAN INSTITUTE OF STEEL CONSTRUCTION  
structural STEEL

## Course wrap-up

- Mild structural steel provides excellent ductility
- Proper proportioning and detailing of steel systems provides controlled inelastic behavior
- Ductile design permits economical buildings
  - Required strength is reduced
  - Large inelastic drifts can be accommodated

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## Course wrap-up

- Design example
  - Efficient design can result from
    - Early identification of governing design loads
    - Simplifying as appropriate so that analysis supports design decisions
  - Economical design can result from
    - Selecting the appropriate systems
    - Reducing the need for member reinforcement

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There's always a solution in steel.

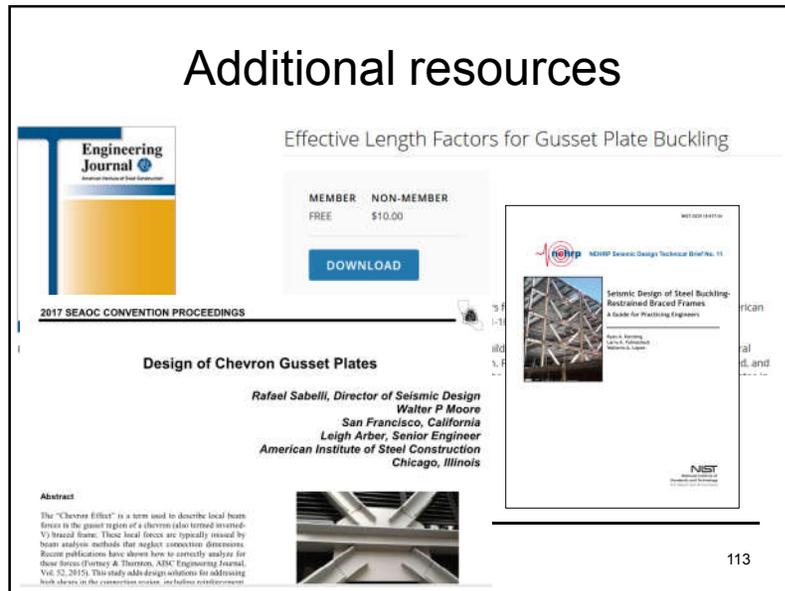
## End of session L4

*And the end of the webinar series*



AMERICAN INSTITUTE OF STEEL CONSTRUCTION  
structural STEEL

## Additional resources



Effective Length Factors for Gusset Plate Buckling

MEMBER: FREE | NON-MEMBER: \$10.00

DOWNLOAD

2017 SEAC CONVENTION PROCEEDINGS

### Design of Chevron Gusset Plates

Rafael Sabelli, Director of Seismic Design  
Walter P Moore  
San Francisco, California  
Leigh Arber, Senior Engineer  
American Institute of Steel Construction  
Chicago, Illinois

Abstract

The "Chevron Effect" is a term used to describe local beam forces in the gusset region of a chevron (also termed inverted-V) braced frame. These local forces are typically ignored by design analysis methods that neglect connection dimensions. Recent publications have shown how to correctly analyze for these forces (Parney & Thornton, AISC Engineering Journal, Vol. 32, 2015). This study adds design solutions for addressing both shear in the connection and local web crippling.



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## Question time

There's always a solution in steel.



## Individual Webinar Registrants

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### CEU/PDH Certificates

Within 2 business days...

- You will receive an email on how to report attendance from: [registration@aisc.org](mailto:registration@aisc.org).
- Be on the lookout: Check your spam filter! Check your junk folder!
- Completely fill out online form. Don't forget to check the boxes next to each attendee's name!



## Individual Webinar Registrants

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### CEU/PDH Certificates

Within 2 business days...

- New reporting site (URL will be provided in the forthcoming email).
- Username: Same as AISC website username.
- Password: Same as AISC website password.



## 8-Session Package Registrants CEU/PDH Certificates

One certificate will be issued at the conclusion of all 8 sessions.



## 8-Session Package Registrants CEU/PDH Certificates

### Videos and Quizzes

- For Sessions R1 – R4, access has been available since July 16.
- For Sessions L1 – L4, find access within two days after the live air date. (An email will be sent from [webinars@aisc.org](mailto:webinars@aisc.org).)
- All video recordings are available through October 22.
- All quizzes are due October 22.
- A final exam will also be given. It will be available October 5 and due October 22.
- Quiz scores are displayed in the Course Resources table.



## 8-Session Package Registrants CEU/PDH Certificates

### 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 course is completed (the week of October 22). Only the registrant will receive certificates for the course.



## 8-Session Package Registrants Course Resources

Find all your handouts, quizzes and quiz scores, recording access, and attendance information all in one place!



## 8-Session Package Registrants Course Resources

Go to [www.aisc.org](http://www.aisc.org) and sign in.

The screenshot shows the AISC website's login page. At the top, there is a navigation menu with links for EDUCATION, PUBLICATIONS, STEEL SOLUTIONS CENTER, AWARDS AND COMPETITIONS, and TECHNICAL RESOURCES. Below the menu is a large banner image of a modern building with a glass facade. The AISC logo is prominently displayed in the center of the banner. Below the banner, there is a login form with fields for USERNAME and PASSWORD, a Remember Me checkbox, and a LOGIN button. To the right of the login form, there is a section titled "DON'T HAVE AN ACCOUNT?" with a REGISTER NOW button. At the bottom of the login form, there are links for "Forgot Username?" and "Forgot Password?".

## 8-Session Package Registrants Course Resources

Go to [www.aisc.org](http://www.aisc.org) and sign in.

The screenshot shows the MyAISC user profile page. On the left side, there is a sidebar menu with links for Edit Profile, My Downloads, My Pending Quizzes, My Events, Order History, and Course History. The 'Course Resources' link is circled in red. On the right side, there is a main content area with sections for My PROFILE, MY PURCHASED DOWNLOADS, and MY COURSE RESOURCES. The 'MY COURSE RESOURCES' section is also circled in red and contains a VIEW RESOURCES button. The text below this button reads: "View online resources for Night School and Live Webinar package registrations."

## 8-Session Package Registrants Course Resources

The screenshot shows the AISC website's course resources page. At the top, there is a navigation menu with links for EDUCATION, PUBLICATIONS, STEEL SOLUTIONS CENTER, AWARDS AND COMPETITIONS, and TECHNICAL RESOURCES. Below the menu is a large banner image of a modern building with a glass facade. The AISC logo is prominently displayed in the center of the banner. Below the banner, there is a breadcrumb trail: AISC > MY ACCOUNT > COURSE RESOURCES. Below the breadcrumb trail, there is a section titled "Course Resources" with a table listing various courses.

Event	Start Date
Steel Course	1/1/1901 12:00:00 AM
8-Session Package Registrants Session L1 - Fundamentals of Construction Design	10/01/2018 10:00:00 PM
8-Session Package Registrants Session L2 - Seismic Design in Steel	10/02/2018 10:00:00 PM
8-Session Package Registrants Session L3 - Design of Tension Members	10/03/2018 10:00:00 PM
8-Session Package Registrants Session L4 - Design of Compression Members	10/04/2018 10:00:00 PM

## 8-Session Package Registrants Course Resources

The screenshot shows the AISC website's course resources page. At the top, there is a navigation menu with links for EDUCATION, PUBLICATIONS, STEEL SOLUTIONS CENTER, AWARDS AND COMPETITIONS, and TECHNICAL RESOURCES. Below the menu is a large banner image of a modern building with a glass facade. The AISC logo is prominently displayed in the center of the banner. Below the banner, there is a breadcrumb trail: AISC > MY ACCOUNT > COURSE RESOURCES > SEISMIC DESIGN IN STEEL. Below the breadcrumb trail, there is a section titled "Seismic Design in Steel" with a sub-section titled "8-SESSION PACKAGE RESOURCES". Below this sub-section, there is a table listing various courses.

Event	Date	Members	Video	Quiz	Attendance
R1 Introduction to Effective Seismic Design	N/A	Completed	Video	Pass	N/A
R2 Seismic Design Concepts - Moment Frames	N/A	Completed	Video	Pass	N/A
R3 Seismic Design Concepts - Braced Frames	N/A	Completed	Video	Pass	N/A
R4 Seismic Design Concepts - Design	N/A	Completed	Video	Pass	N/A
L1 Application - Planning the Seismic Design	See 10/2018 1:00PM EDT	Completed	Available 10/22/2018 5:00PM EDT	Available 10/12/2018 5:00PM EDT	Pending
L2 Application - Building Analytical Diagrams	See 17/2018 1:00PM EDT	Completed	Available 10/20/2018 5:00PM EDT	Available 10/13/2018 5:00PM EDT	Pending
L3 Application - Moment Frames	See 04/2018 1:00PM EDT	Completed	Available 10/20/2018 5:00PM EDT	Available 10/13/2018 5:00PM EDT	Pending
L4 Design of the Braced Frames	See 11/2018 1:00PM EDT	Completed	Available 10/20/2018 5:00PM EDT	Available 10/13/2018 5:00PM EDT	Pending
Seismic Design in Steel - Final Exam	Oct 3, 2018 12:00AM EDT	Completed	Available 10/03/2018 5:00PM EDT	Available 10/03/2018 5:00PM EDT	Pending



There's always a solution in steel.

# Thank You

Please give us your feedback!  
*Survey at conclusion of webinar.*

