

HSS

CONCRETE FILLED HSS

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WELCOME

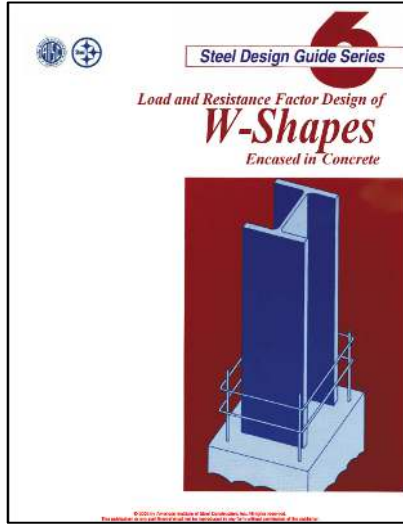
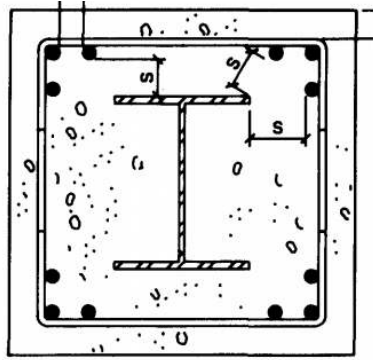
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Agenda

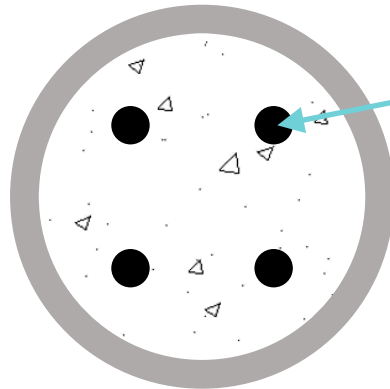
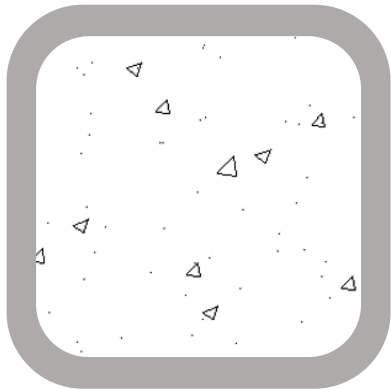


- Why CFT?
- Section Classifications
- Analysis Methods
- Design Requirements
- Recommendations
- Practical Considerations

Composite Members



- Two types
 - Encased composite members
 - Filled composite members



Optional
Reinforcement

Concrete Filled HSS

- Two components
 - Steel
 - Concrete
 - Unreinforced or reinforced
 - NWC or LWC
 - High-strength, steel fiber reinforced, self-consolidating mix
 - Members under static, impact, blast, seismic and fire loads
 - Gain benefits from the composite action of the two materials

Advantages of CFT

- Elimination of need for formwork
- Increased member capacity, stiffness, ductility
- Increased fire resistance
 - May negate need for external fire protection
- May increase connection strength
- Reduction of HSS size
- Protection for concrete

Disadvantages of CFT

- Need to account for concrete shrinkage in HSS
- Lack of knowledge of mechanical bond between concrete and steel
- Coordination between trades

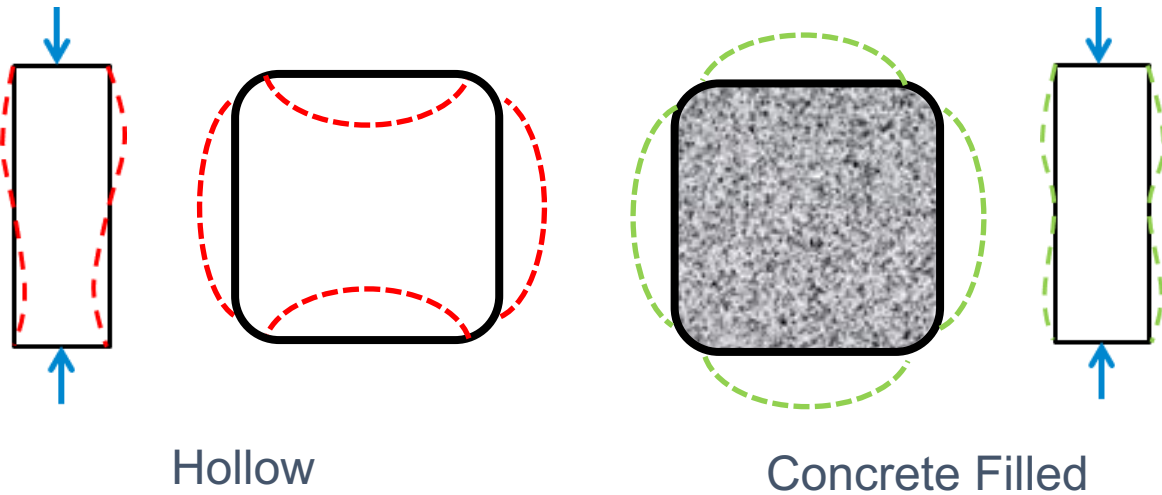
SECTION CLASSIFICATION



Materials

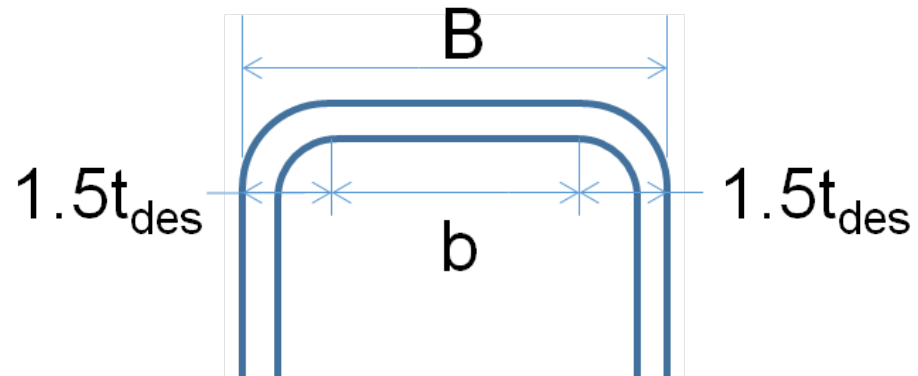
- Steel
 - A500, A1085
 - $F_y \leq 75$ ksi
- Concrete
 - NWC $3 \text{ ksi} \leq f'_c \leq 10 \text{ ksi}$
 - LWC $3 \text{ ksi} \leq f'_c \leq 6 \text{ ksi}$
- Reinforcing
 - A615 Gr. 40, 60, 75, 80
 - $F_y \leq 80$ ksi

Section Classification



- Classify section as compact, non-compact or slender based on lowest element slenderness ratio for HSS
- Concrete infill changes the buckling mode within the cross-section and along the length of the member
- Influences strength, stiffness and ductility

Section Classification



- $b =$ clear distance between webs less than inside corner radius on each side
- $b = B - 3t_{des}$

Slenderness Limits – Axial Compression

Element	Width-Thickness Ratio	λ_p Compact/ Noncompact	λ_r Noncompact/ Slender	Max Permitted
Concrete Filled Rect. HSS	$\frac{b}{t}$	$2.26 \sqrt{\frac{E}{F_y}}$	$3.00 \sqrt{\frac{E}{F_y}}$	$5.00 \sqrt{\frac{E}{F_y}}$
Hollow Rect. HSS	$\frac{b}{t}$		$1.40 \sqrt{\frac{E}{F_y}}$	
Concrete Filled Round HSS	$\frac{D}{t}$	$\frac{0.15E}{F_y}$	$\frac{0.19E}{F_y}$	$\frac{0.31E}{F_y}$
Hollow Round HSS	$\frac{D}{t}$		$\frac{0.11E}{F_y}$	

ALL filled square HSS compact except:
 HSS7x7x1/8,
 HSS8x8x1/8,
 HSS10x10x3/16,
 HSS12x12x3/16

Filled HSS9x9x1/8 is slender

All filled round HSS are compact

Slenderness Limits – Flexure

Element	Width-Thickness Ratio	λ_p Compact/ Noncompact	λ_r Noncompact/ Slender	Max Permitted
Concrete Filled Rect. HSS Flange	$\frac{b}{t}$	$2.26 \sqrt{\frac{E}{F_y}}$	$3.00 \sqrt{\frac{E}{F_y}}$	$5.00 \sqrt{\frac{E}{F_y}}$
Hollow Rect. HSS Flange	$\frac{b}{t}$	$1.12 \sqrt{\frac{E}{F_y}}$	$1.40 \sqrt{\frac{E}{F_y}}$	
Concrete Filled Rect. HSS Web	$\frac{h}{t}$	$3.00 \sqrt{\frac{E}{F_y}}$	$5.70 \sqrt{\frac{E}{F_y}}$	$5.70 \sqrt{\frac{E}{F_y}}$
Hollow Rect. HSS Web	$\frac{h}{t}$	$2.42 \sqrt{\frac{E}{F_y}}$	$5.70 \sqrt{\frac{E}{F_y}}$	
Concrete Filled Round HSS	$\frac{D}{t}$	$\frac{0.09E}{F_y}$	$\frac{0.31E}{F_y}$	$\frac{0.31E}{F_y}$
Hollow Round HSS	$\frac{D}{t}$	$\frac{0.07E}{F_y}$	$\frac{0.31E}{F_y}$	

All filled square HSS compact except:
HSS7x7x1/8,
HSS8x8x1/8,
HSS10x10x3/16,
HSS12x12x3/16

All filled round HSS compact except:
HSS6.625x0.125,
~~HSS7.000x0.125,~~
HSS10.000x0.188,
HSS14.000x0.250,
HSS16.000x0.250,
HSS20.000x0.375

Filled HSS9x9x1/8 is slender

No filled round HSS is slender

ANALYSIS METHODS



Nominal Strength

ANSI/AISC 360-16
An American National Standard

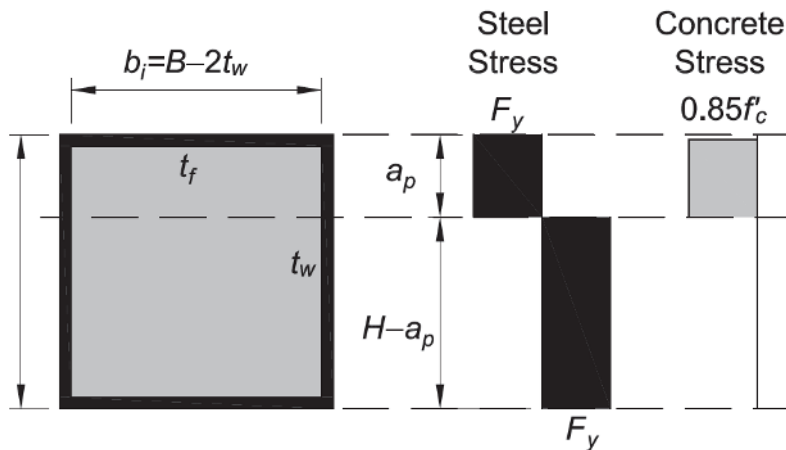
Specification for Structural Steel Buildings

July 7, 2016

Four Methods – AISC 360-16 I1.2

- 1 Plastic Stress Distribution
- 2 Strain Compatibility
- 3 Elastic Stress Distribution
- 4 Effective Stress-Strain

Plastic Stress Distribution Method



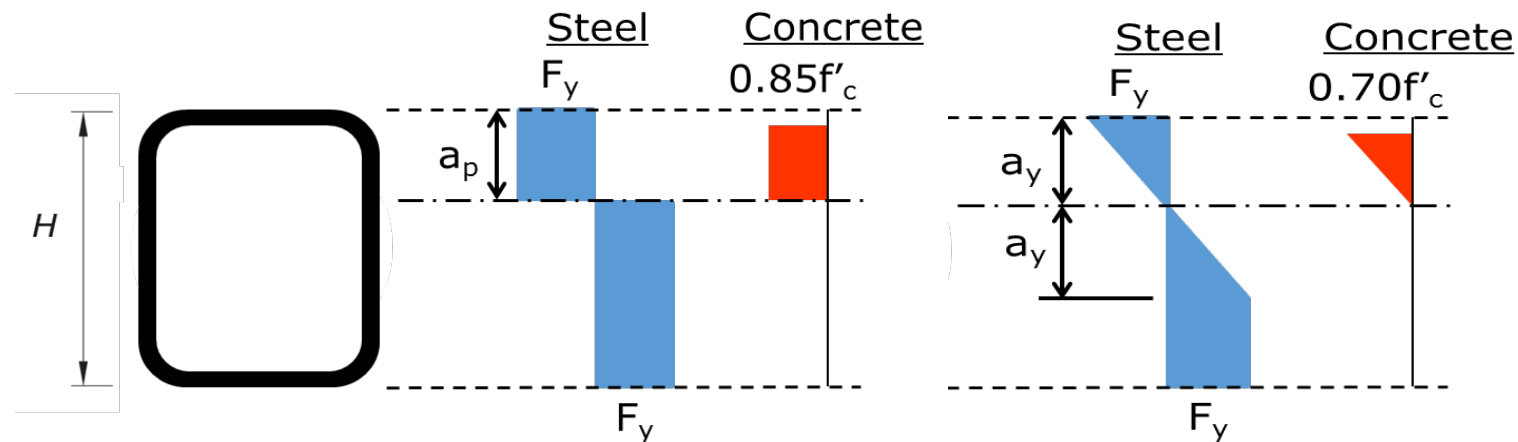
- Based on plastic limit analysis (form plastic hinge)
- Assume steel components have reached F_y (tension or compression)
- Compression in concrete due to axial or flexure reaches a stress of
 - $0.85f'_c$ (rectangular)
 - $0.95f'_c$ (round)
- Assumptions:
 - Sufficient strains to reach yield strength (concrete & steel)
 - Local buckling delayed until after yielding or concrete crushing

Method used for AISC's Composite Design Tables

Strain Compatibility Method

- More general approach
 - Assume linear distribution of strain across section
 - Max concrete compressive strain = 0.003 in./in.
 - Stress-strain relationship from tests or published results

Works for noncompact and slender sections



Elastic Stress Distribution Method

- Retained from previous specifications to allow for composite beams with noncompact webs
- Determine nominal strength from superposition of elastic stresses
 - Limit state of yielding
 - Concrete crushing
- Useful when plastic stress distribution is not applicable
- In practical terms, does not apply to HSS

Elastic Stress - Strain Method

- Alternative approach for noncompact and slender sections
- Assume strain compatibility
- Applicable when using a fiber-based approach for axial force-moment strength interaction
- Sophisticated computer analysis – not intended for typical design practice

DESIGN REQUIREMENTS



Required Strengths

Account for stability

- Amplified first-order analysis (App 7)
- Second-order analysis (Ch C)
- Direct analysis
 - Use effective flexural stiffness of composite section
 - Nominal axial stiffness is sum of elastic axial stiffness of HSS and concrete
 - Apply stiffness reduction factor (0.64 for flexural stiffness and 0.8 for nominal axial stiffness)

Effective Stiffness

$$EI_{eff} = E_s I_s + E_s I_{sr} + C_3 E_c I_c$$

Effective rigidity of filled HSS

$$C_3 = 0.45 + 3 \left(\frac{A_s + A_{sr}}{A_g} \right) \leq 0.9$$

Rectangular HSS considering HSS corners

$$I_{cx} = \frac{(B - 4t)h_i^3}{12} + \frac{t(H - 4t)^3}{6} + \frac{(9\pi^2 - 64)t^4}{36\pi} + \pi t^2 \left(\frac{H - 4t}{2} + \frac{4t}{3\pi} \right)^2$$
$$I_{cy} = \frac{(H - 4t)b_i^3}{12} + \frac{t(B - 4t)^3}{6} + \frac{(9\pi^2 - 64)t^4}{36\pi} + \pi t^2 \left(\frac{B - 4t}{2} + \frac{4t}{3\pi} \right)^2$$

Nominal Strength – Tension

Limit State of Yielding

- Only steel components (HSS and reinforcing) contribute to the tensile strength

- $P_n = \underbrace{A_s F_y}_{\text{HSS}} + \underbrace{A_{sr} F_{ysr}}_{\text{reinforcing}}$

HSS reinforcing

- $\phi_t = 0.90$ (LRFD)

- $\Omega_t = 1.67$ (ASD)

Use AISC

Manual Table 5-4

Nominal Strength – Compression

- Based on a summation of the strengths of all components (HSS, concrete and reinforcing)
- Function of member slenderness (compact, noncompact, slender)
 - Reduce strength due to member slenderness
 - Reduce strength due to local buckling
 - Thinner HSS cannot adequately confine concrete infill at stresses above $0.7f'_c$.

Nominal Strength – Compression

- Limitations
 - Steel must comprise at least 1% of total cross-section
 - Minimum longitudinal reinforcing is not required
- General procedure
 - Calculate zero-length strength accounting for the influence of local slenderness
 - Consider length effects and end conditions (limit state of flexural buckling)

Compressive Strength – Compact Section

Develop yielding in HSS and compressive strength of the concrete fill

Zero length nominal axial strength $\rightarrow P_{no} = P_p \leftarrow$ Full plastic strength

$$P_p = A_s F_y + C_2 f'_c \left(A_c + A_{sr} \frac{E_s}{E_c} \right)$$

0.85 (RHS)
0.95 (CHS)

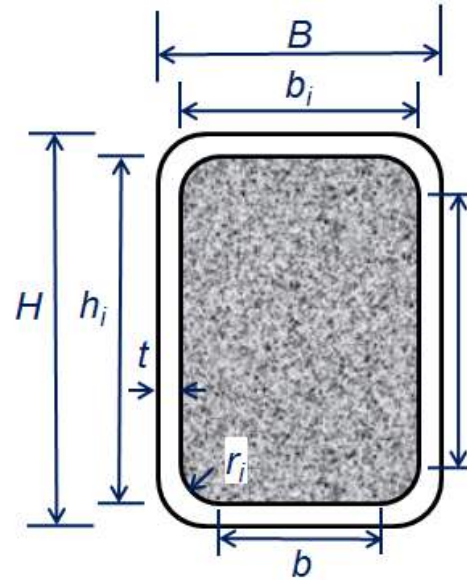
material transformation

$$E_c = w_c^{1.5} \sqrt{f'_c}$$

Area of Concrete - RHS

Simplified

$$A_c = (B - 2t)(H - 2t) = b_i h_i$$



Considering Corners

$$A_c = b_i h_i - t^2(4 - \pi)$$

$$A_c = 99 \text{ in}^2$$

HSS12x10x1/2

$$A_c = 98.79 \text{ in}^2$$

$$A_c = 28.89 \text{ in}^2$$

HSS6x6x5/8

$$A_c = 28.56 \text{ in}^2$$

Compressive Strength – Noncompact Section

Develop yielding in HSS but not confine the concrete fill after it reaches a compressive stress of $0.7f'_c$

$$P_{no} = P_p - \frac{P_p - P_y}{(\lambda_r - \lambda_p)^2} (\lambda - \lambda_p)^2$$

$$P_y = A_s F_y + 0.7 f'_c \left(A_c + A_{sr} \frac{E_s}{E_c} \right)$$

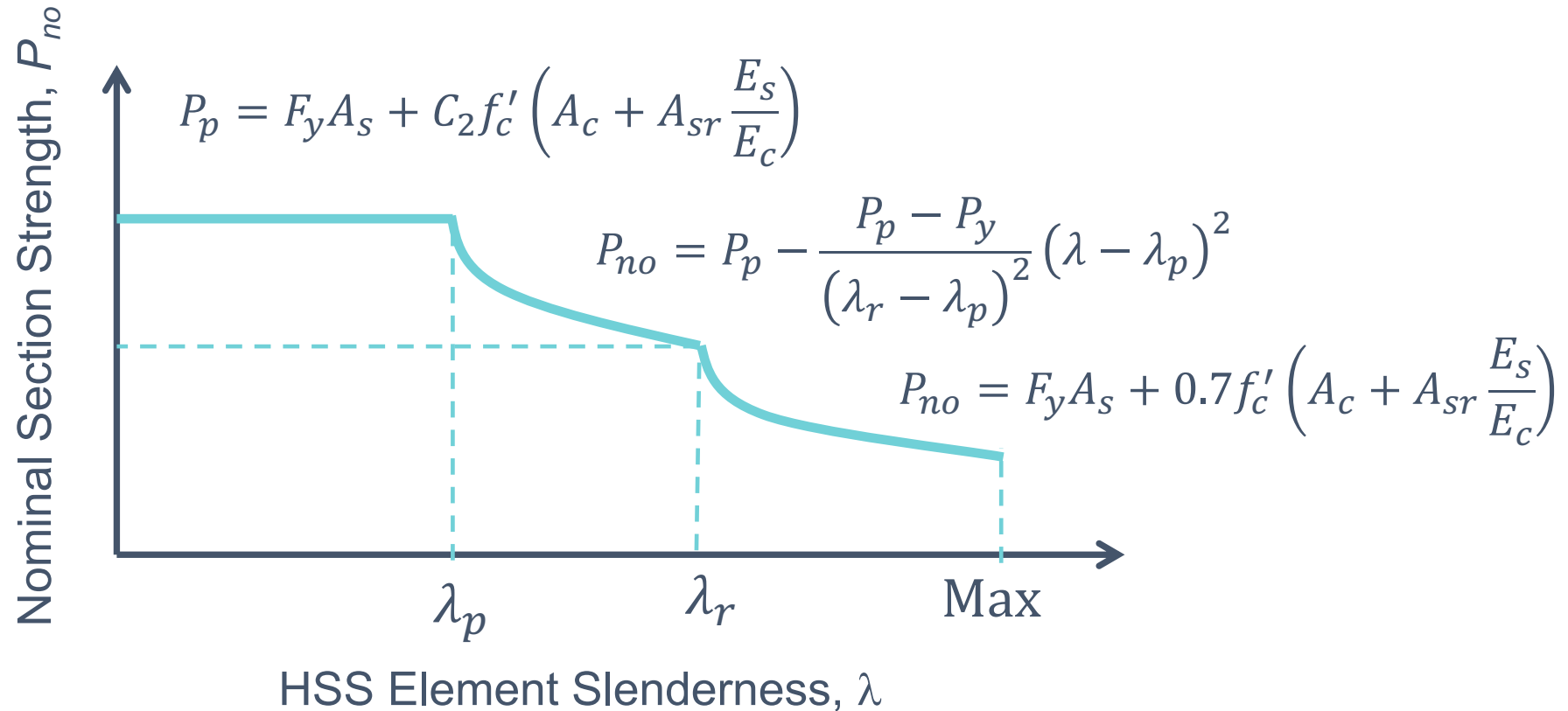
Compressive Strength – Slender Section

Cannot reach yielding in HSS (limited to critical buckling stress, F_{cr}) and cannot confine the concrete fill after it reaches a compressive stress of $0.7f'_c$

$$P_{no} = A_s F_{cr} + 0.7f'_c \left(A_c + A_{sr} \frac{E_s}{E_c} \right)$$

$$F_{cr} = \frac{9E_s}{\left(\frac{b}{t}\right)^2} \text{ (RHS)} \quad F_{cr} = \frac{0.72F_y}{\left[\left(\frac{D}{t}\right)\frac{F_y}{E_s}\right]^2} \text{ (CHS)}$$

Zero Length Nominal Compressive Strength



Design Compressive Strength

$$\frac{P_{no}}{P_e} \leq 2.25$$

$$P_n = P_{no} \left(0.658 \frac{P_{no}}{P_e} \right)$$

$$\frac{P_{no}}{P_e} < 2.25$$

$$P_n = 0.877 P_e$$

$$P_{no} = F_y A_s + F_{ysr} A_{sr} + 0.85 f'_c A_c$$

$$P_e = \frac{\pi^2 (E I_{eff})}{L_c^2}$$

Compression of Bare Steel

- Composite and Non-Composite HSS have different SF
 - Composite ($\phi_c = 0.75$, $\Omega_c = 2.00$)
 - Non-Composite ($\phi_c = 0.9$, $\Omega_c = 1.67$)
- Difference can result in the non-composite section having a higher strength
- Take the larger of the two values

Nominal Flexural Strength

- Function of member slenderness
- HSS section reduces lateral-torsional instability
- Concrete infill changes local buckling mode
- General procedure:
 - Classify the section
 - Calculate nominal strength
 - Neglect variation of stress through the thickness of the flange
 - Equations provided based on plastic stress distribution method for compact sections
 - Use strain compatibility for noncompact and slender concrete filled HSS

Nominal Shear Strength

- Three options
 - Shear strength based on HSS alone (Chapter G)
 - Shear strength based on reinforced concrete alone (ACI 318)
 - Sum of shear strength of HSS and the reinforcing steel



POLL QUESTION

Load Transfer

- How much of applied load is resisted by HSS? How much resisted by concrete?
 - External force applied to HSS only
 - External force applied to the concrete only
 - External force applied to both
- Assumes load transfer occurs between materials to achieve equilibrium across the cross-section

Load Transfer

HSS to Concrete (external force applied to HSS)

$$V_r' = P_r \left(1 - \frac{F_y A_s}{P_{no}} \right) \quad (I6-1)$$

Concrete to HSS (external force applied to concrete only)

$$V_r' = P_r \left(\frac{F_y A_s}{P_{no}} \right) \text{ (compact \& non-compact)} \quad (I6-2a)$$

$$V_r' = P_r \left(\frac{F_{cr} A_s}{P_{no}} \right) \text{ (slender)} \quad (I6-2b)$$

Concurrent application

$$V_r' = P_{r,concrete} - P_r \left(1 - \frac{F_y A_s}{P_{no}} \right)$$

$$V_r' = P_{r,HSS} - P_r \left(\frac{F_y A_s}{P_{no}} \right)$$

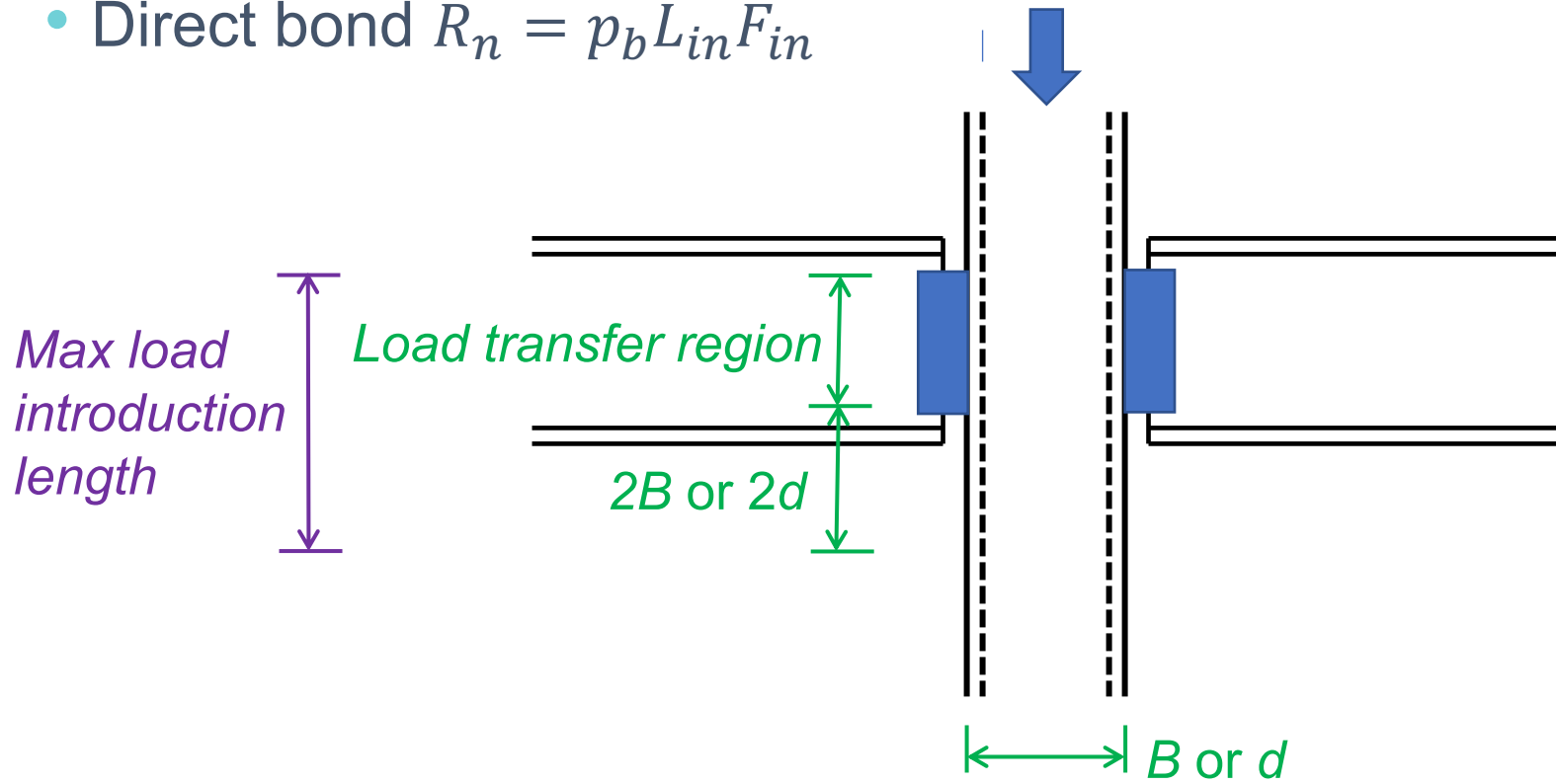
Load Transfer

$$= 12t/H^2 \text{ for rectangular HSS}$$

$$= 30t/D^2 \text{ for rectangular HSS}$$

Cannot superimpose mechanisms – use largest

- Direct bearing (bearing pl) $R_n = 1.7f'_c A_1$ (I6-3)
- Shear connection (hdas, channel anchors) $R_n = \sum Q_{cv}$ (I6-4)
- Direct bond $R_n = p_b L_{in} F_{in}$ (I6-5)



Design Recommendations



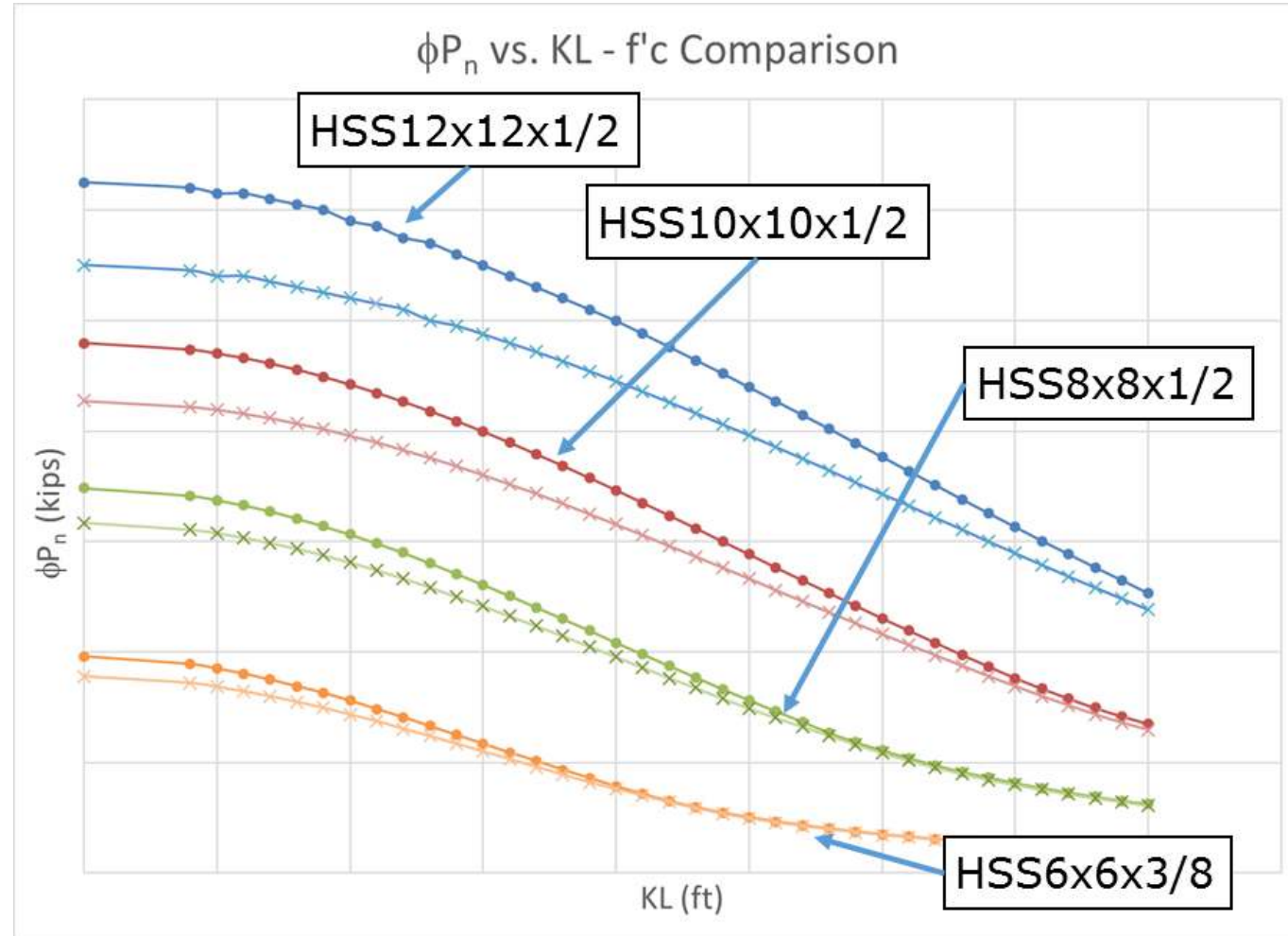
Design Recommendations

- Limit to compact HSS member
- Use C-13.7 equations for noncompact and slender RHS
- Use plastic stress distribution method for beam-columns
 - Use P-M equations from EJ Discussion (Geschwinder, 2010)
- Choose $f'_c = 4$ ksi to 5 ksi – benefits above 5 ksi are limited

Design Recommendations

Concrete Strength Effect: Member Size

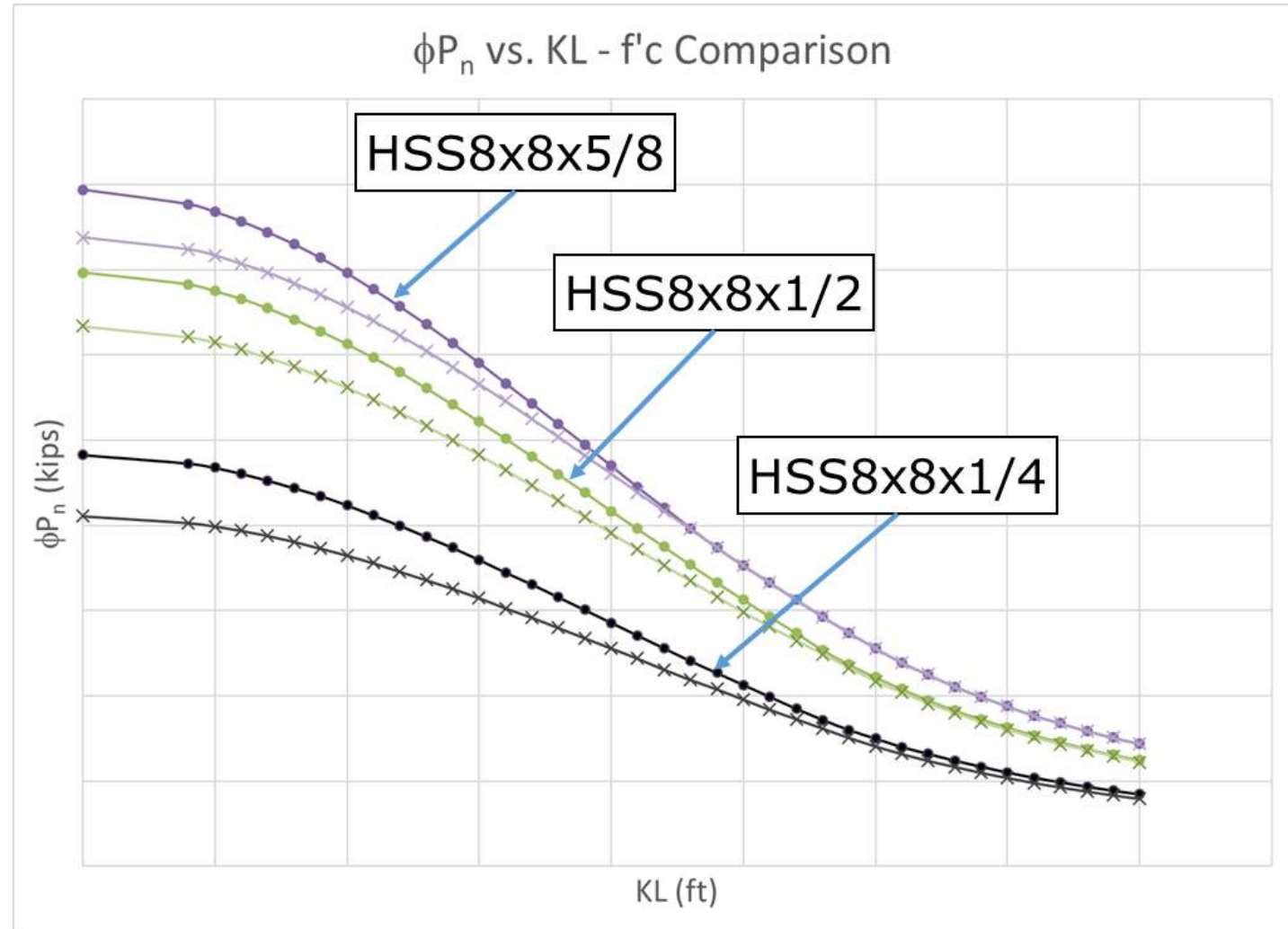
$f'_c = 4$ ksi versus 6 ksi



Design Recommendations

Concrete Strength Effect: Member Thickness

$f'_c = 4 \text{ ksi}$ versus 6 ksi



Practical Considerations



Practical Considerations



Practical Considerations



- Concrete mix
 - High strength grout can also be used to fill HSS in lieu of concrete
- Care must be taken when filling the HSS from top
 - Segregation of concrete
 - Damage to HSS walls
- Consider constructability of the column if rebar is used
 - Interference with the connection
 - Adequate rebar spacing to place the concrete

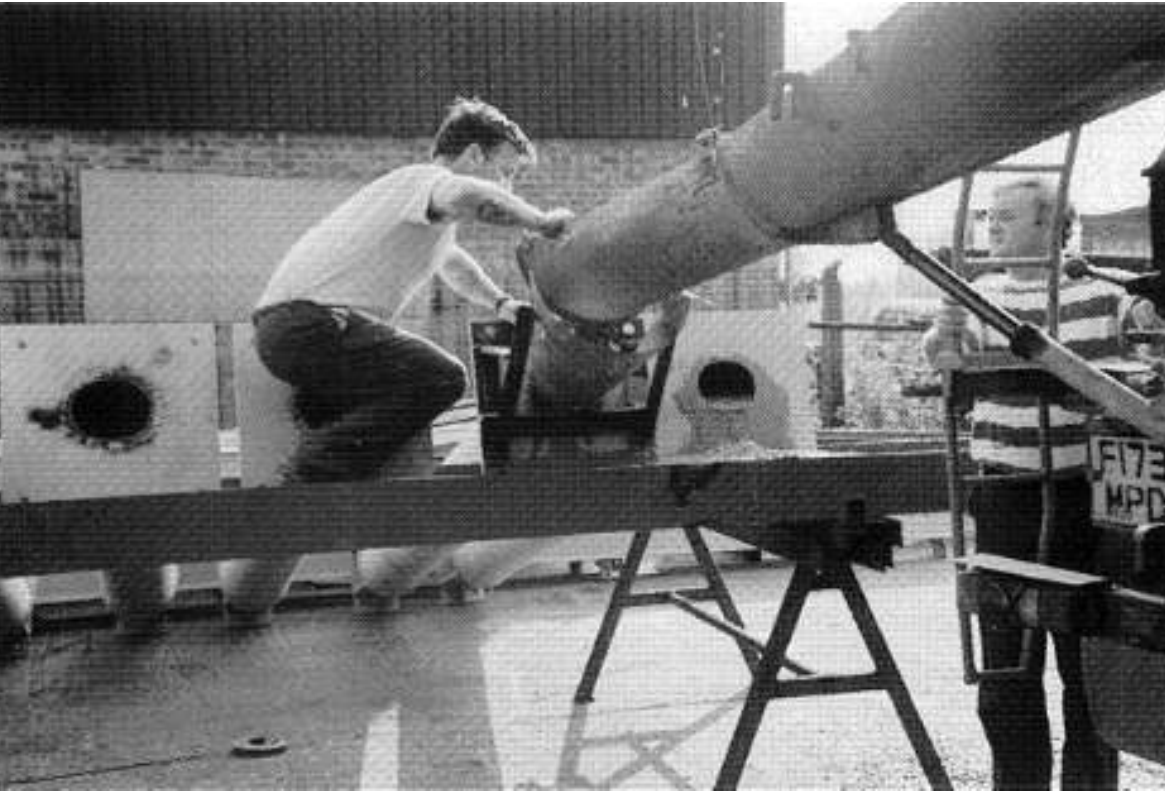
Concrete Placement



Jeffrey A. Packer

- Concrete placement
 - Typically done after erection
 - Pumped through an opening in the top or bottom of the column using the same types of equipment that would be required for filling tall concrete wall forms

Concrete Placement



CIDECT Design Guide #5

- Alternate concrete placement
 - Using a staging area where the columns are filled in a vertical or inclined position
 - All columns could be filled at one time

Concrete Placement

- Ensure concrete doesn't segregate during placement per ACI 318
 - Avoid any situation where concrete could free fall and hit the HSS walls, reinforcing, etc. within the HSS cavity
 - Rule of thumb – concrete should not free fall more than 3 to 5 feet
 - See also ACI 304R, Chapter 5

Concrete Placement

- Concrete placed at top
 - Use a tremie chute
 - Concrete may need to be vibrated to achieve adequate consolidation
 - Some contractors prefer a self-consolidating concrete mix to avoid the concrete vibration
 - Detail access at the top of the column

Concrete Placement

- Concrete placed at top - access
 - Simple where no cap plate is required
 - Cap plate required
 - Specify field welding after concrete placement or
 - Detail a hole to allow for concrete placement

Recommendation

- Specify holes in the column
 - Approximately 1” in diameter
 - Venting and concrete fill verification
 - Vent steam during an active fire scenario
 - Pressure due to buildup of steam within the HSS can deform or rupture the HSS

Concrete Placement – Tall Column

- Pump concrete in lifts through openings spaced along the length of a column
 - Similar to procedure for a tall wall form
 - See ACI 304R
 - Holes required are fairly large – their impact on the column capacity must be evaluated

Practical Considerations

- Connection Geometry
 - Through plate and diaphragm plate connections are problematic

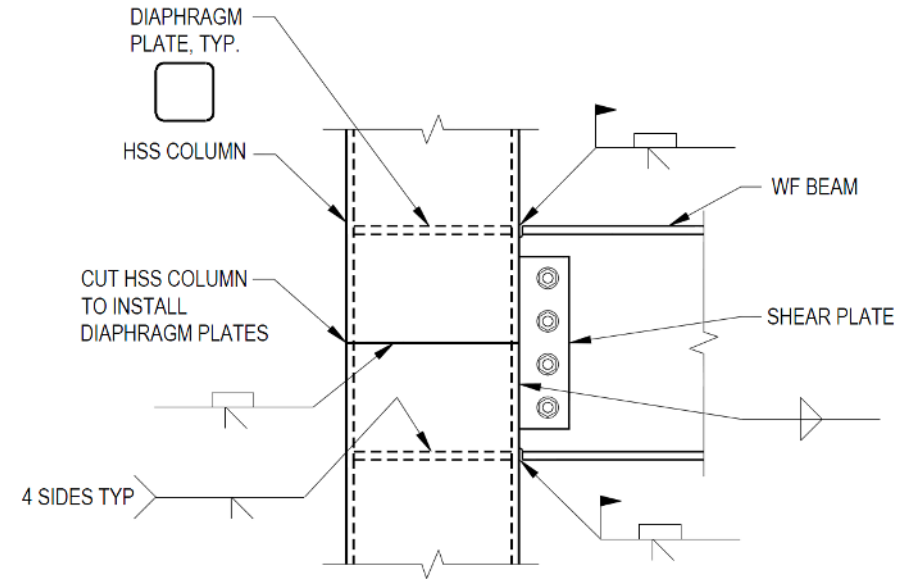
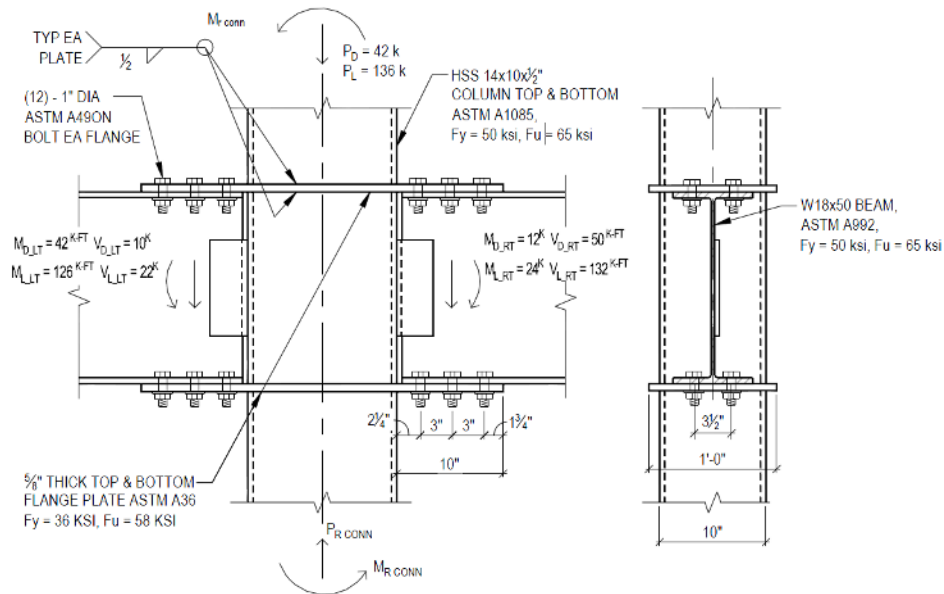
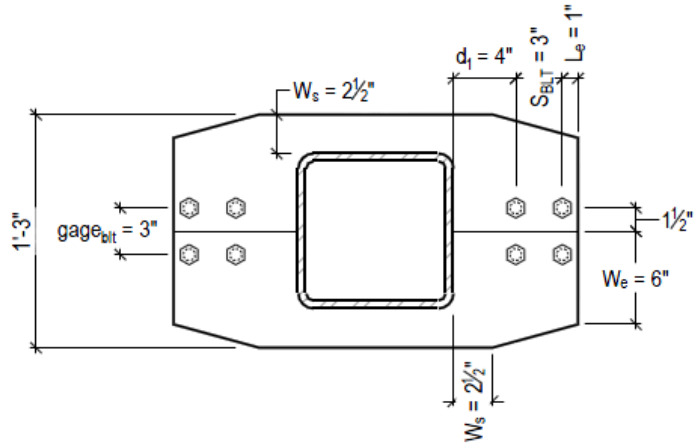


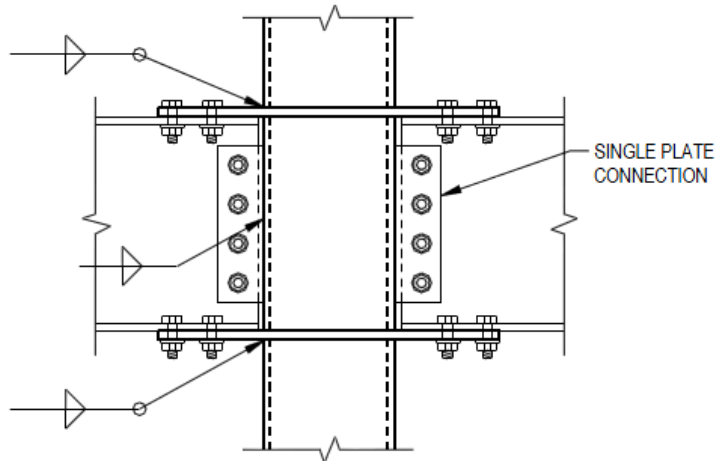
FIG. 3-20 DIAPHRAGM PLATE MOMENT CONNECTION

Practical Considerations

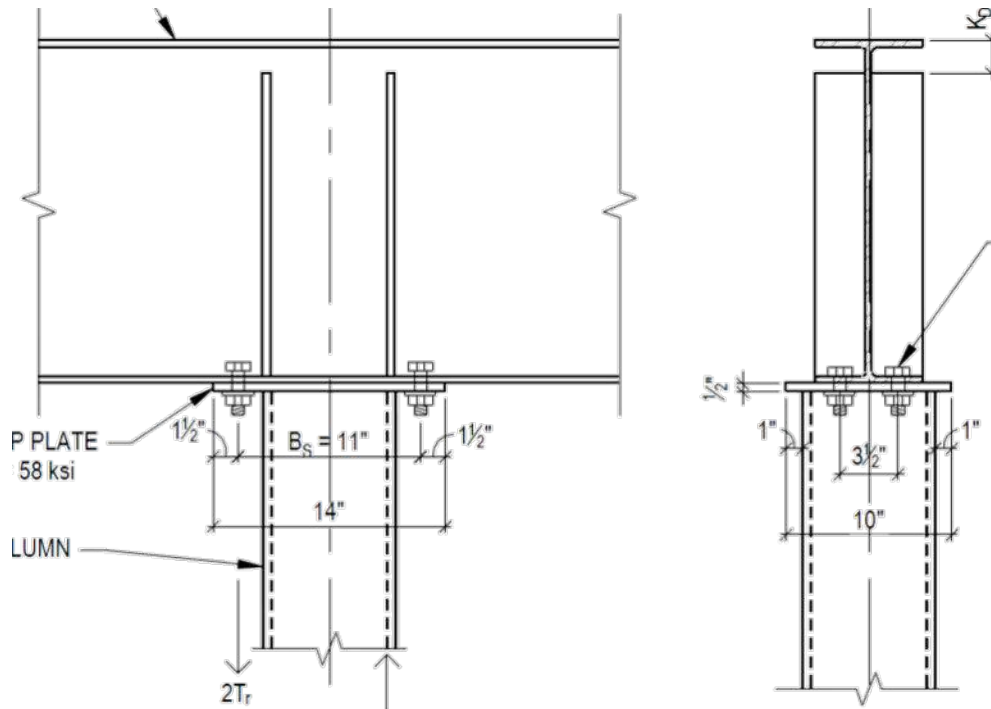


■ Connection Geometry

- Cut out plate or direct connections remove interior plates



Practical Considerations



- Bearing at the top of the column
 - Detail the top of column condition to ensure load is transferred to the column in a manner that is consistent with the design assumptions
 - Concrete shrinkage results in a void between the top of column and underside of column cap pl
 - Provide 2-4" of NS grout at the top
 - Provide embedded anchorage at the underside of the cap pl

Concrete used as Fire Protection

- During a fire event, the full axial load is carried by the concrete alone
 - Design of the column and connecting members must consider the load path
 - More information on Fire Protection of HSS on STI website

POLL QUESTION



THANK YOU

HSSINFO@STEELTUBEINSTITUTE.ORG