FILLING THE VOID:

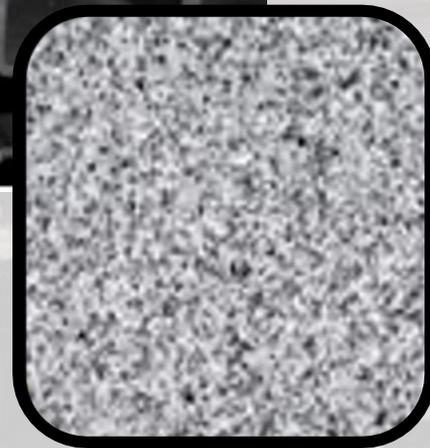## A Central Resource for Designing Concrete Filled HSS Columns

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Filling the Void:

A Central Resource for Designing Concrete Filled HSS Columns

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Concrete and steel are two of the most versatile building materials, but when they combine forces, even greater gains can materialize. HSS columns work efficiently to carry high loads without taking up much space. However, regardless of the size, inside is just wasted space, so why not fill it with concrete? Combining the materials creates an optimal blend through the synergistic effect of the steel, confining the concrete, while the concrete decreases the slenderness of the HSS, increasing the local buckling stability by bracing the sidewalls. However, understanding the behavior, knowing how to design, and understanding the logistics for installation in the field all require some research. This article will serve as a central information hub by providing a brief overview of concrete filled HSS columns.

Specifically, this article will touch upon the following aspects of HSS composite column design:
1. Design Example
2. Column Capacities with 4ksi and 6ksi NW Concrete
3. High Strength Steel and/or High Strength Concrete
4. Further Insights into Composite Member Design
5. Connecting to Composite HSS Columns
6. Fire Resistance
7. Logistical Considerations

Figure 1
Filling HSS With Concrete
Photo Credit: CIDECT Design Guide 5

1. Design Example

Given:
- ASTM A500 Gr. C (F_y = 50ksi)
- HSS 14x14x3/8
- Unreinforced Fill: f'_c = 6ksi
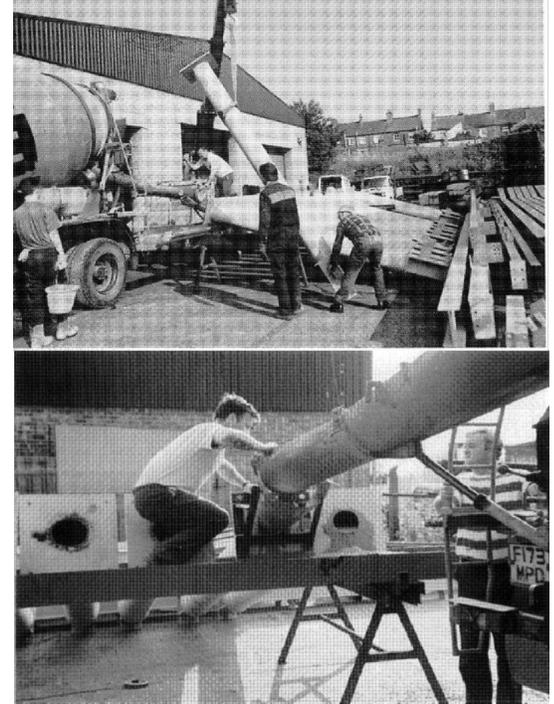- Normal Weight Concrete: w_c = 145pcf
- L_c = KL = 42'

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HSS Geometry   *[AISC 16th Manual Table 1-12]*

The following corner radius assumptions apply when calculating geometric properties for HSS (see Figure 2).

1. *corner radius = 1.5t$_{design}$* when determining b/t and h/t ratios
2. *corner radius = 2.25t$_{design}$* when determining workable flat width and depth
3. *corner radius = 2t$_{design}$* for A500 and A1085 when determining all other section properties including A_c, S_x, S_{xc}, I_x, and I_{xc}
4. *corner radius = 3t$_{design}$* for A1065 when determining all other section properties including A_c, S_x, S_{xc}, I_x, and I_{xc}
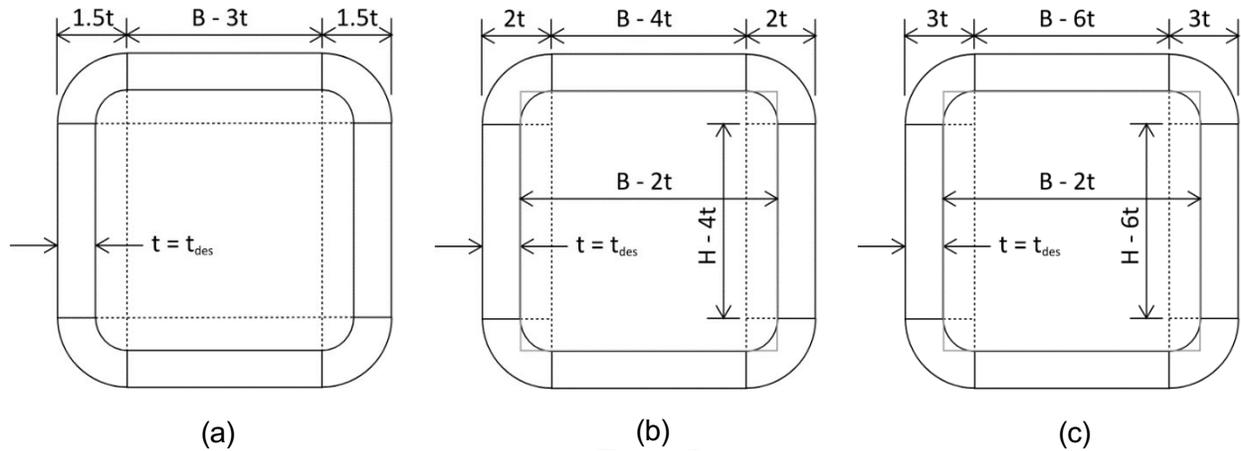

(a)   (b)   (c)

Figure 2

Dimensions Used in HSS Calculations
(a) Local Buckling b/t
(b) Section Properties A500/A1085
(c) Section Properties A1065

B = nominal HSS width

H = nominal HSS height

b = width of HSS flat (varies depending on the calculation being performed)

h = height of HSS flat (varies depending on the calculation being performed)

Workable flat = reasonable HSS flat distance for detailing connections

t_{nom} = nominal HSS thickness

t_{des} = HSS design thickness

     for ASTM A500 t_{des} = 0.93t_{nom}

     for ASTM A1085 and A1065 t_{des} = t_{nom}

λ = width-to-thickness slenderness ratio

$$B = H = 14 \, in$$

$$t_{nom} = 0.375 \, in$$

$$t_{des} = 0.349 \, in$$

$$b = h = B - 3t_{des} = 14 \, in - 3 \times 0.349 \, in = 12.953 \, in$$

$$\lambda = b/t_{des} = 12.953/0.349 = 37.1$$

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Area of Steel $A_s = 18.7in^2$

Area of Concrete $A_c = (B - 2t_{des})^2 - (t_{des})^2(4 - \pi) = 176.8in^2$

> Calculated by starting with a concrete square and subtracting the area outside each corner radius as shown in Figure 2b

Total Area $A_g = 18.7in^2 + 176.8in^2 = 195.5in^2$

Steel Moment of Inertia $I_s = 577in^4$

Concrete Moment of Inertia $I_c = 2605in^4$

> Calculated by breaking up the concrete area into one large rectangle, two small rectangles, and four quarter circles as shown in Figure 2b

$$I_c = \frac{(B - 4t_{des})(H - 2t_{des})^3}{12} + \frac{t_{des}(H - 4t_{des})^3}{6} + \frac{(9\pi^2 - 64)t_{des}^4}{36\pi} + \pi t_{des}^2\left(\frac{H - 4t_{des}}{2} + \frac{4t_{des}}{3\pi}\right)^2$$

$$I_c = \frac{[14 - 4(0.349)][14 - 2(0.349)]^3}{12} + \frac{0.349[14 - 4(0.349)]^3}{6} + \frac{(9\pi^2 - 64)0.349^4}{36\pi}$$
$$+ \pi t^2\left(\frac{[14 - 2(0.349)]}{2} + \frac{4(0.349)}{3\pi}\right)^2$$

Composite Section Limitations   *[AISC 360-22 I1.3 & I2.2a]*

Specified Yield Strength $F_y = 50ksi \le 75ksi$ OK

Specified Concrete Strength $3ksi \le f'_c = 6ksi \le 10ksi$ OK

Steel Cross-Sectional Area $A_s = 18.7in^2 \ge 0.01A_g = 1.96in^2$ OK

Rebar Reinforcement* $A_{sr} = 0in^2$ OK

 *(no required minimum)

Slenderness Check

Compression $\lambda = 37.1$ (see above)

$\lambda_r = $ non-compact element width-to-thickness limit

$\lambda_p = $ compact element width-to-thickness limit

$\lambda_r = 1.40\sqrt{\frac{E}{F_y}} = 1.40\sqrt{\frac{29000ksi}{50ksi}} = 33.7$ *[AISC 360-22 Table B4.1a Case 6]*

$\lambda > \lambda_r$ → HSS steel section alone is slender

$\lambda_p = 2.26\sqrt{\frac{E}{F_y}} = 2.26\sqrt{\frac{29000ksi}{50ksi}} = 54.4$ *[AISC 360-22 Table I1.1a]*

$\lambda < \lambda_p$ → HSS composite section is compact

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Strength Determination

For calculating the strength of a composite column, AISC 360-22 Chapter I provides four different analysis options. The first method is called the plastic stress distribution method, which is the most general case and easiest to calculate, but it is limited to compact sections. Since nearly all filled HSS sections are compact, this method is most often used and has been selected for demonstration in this example.

Composite Axial Capacity   *[AISC 360-22 I2.1b & I2.2b]*

C_2 = geometric coefficient for the assumed concrete compressive stress in the plastic stress distribution method for composite members

C_3 = coefficient for the effective rigidity calculation of filled composite compression members

Rectangular section: $C_2 = 0.85$

Note: For round HSS, C_2 = 0.95 due to increased confinement

$$E_c = w_c^{1.5}\sqrt{f'_c} = (145pcf)^{1.5}\sqrt{6ksi} = 4{,}276.9ksi$$

$$C_3 = 0.45 + 3\left(\frac{A_s + A_{sr}}{A_g}\right) \leq 0.9 \qquad \text{[AISC 360-22 Eq. I2-13]}$$

$$C_3 = 0.45 + 3\left(\frac{18.7in^2 + 0in^2}{195.5in^2}\right) = 0.737 \leq 0.9$$

$$(EI)_{eff} = E_s I_s + E_s I_{sr} + C_3 E_c I_c \qquad \text{[AISC 360-22 Eq. I2-12]}$$

$$(EI)_{eff} = (29{,}000ksi)(577in^4) + (29{,}000ksi)(0in^4) + (0.737)(4{,}276.9ksi)(2605in^4)$$

$$(EI)_{eff} = 24{,}941{,}616 k \cdot in^2$$

P_{no} = nominal axial compressive strength without consideration of length effects
P_n = nominal compressive axial strength
P_e = elastic critical buckling load
P_p = plastic axial compressive strength

$$P_{no} = P_p = F_y A_s + C_2 f'_c \left(A_c + A_{sr}\frac{E_s}{E_c}\right) \qquad \text{[AISC 360-22 Eq. I2-9a \& I2-9b]}$$

$$P_{no} = (50ksi)(18.7in^2) + (0.85)(6ksi)\left\{176.8in^2 + \left[0in^2\left(\frac{29000ksi}{4{,}276.9ksi}\right)\right]\right\} = 1836.9k$$

$$P_e = \frac{\pi^2(EI)_{eff}}{L_c^2} = \frac{\pi^2(24{,}941{,}616 k \cdot in^2)}{(504in)^2} = 969k \qquad \text{[AISC 360-22 Eq. I2-4]}$$

$$P_{no}/P_e = 1837.2k/969k = 1.90 < 2.25$$

$$P_n = P_{no}\left(0.658^{\frac{P_{no}}{P_e}}\right) = 1836.9k(0.658^{1.90}) = 830.9k \qquad \text{[AISC 360-22 Eq. I2-2]}$$

$$\phi P_n = 0.75(830.9) = 623k$$

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2. Column Capacities with 4ksi and 6ksi NW Concrete

Hollow HSS versus filled HSS can have a substantial difference in axial strength capacity. The concrete greatly affects the stiffness, strength, and ductility of the steel in the composite section. As shown in equations I2-2, I2-4, and I2-12 on page 5, the effective stiffness of the composite section increases and thus the global P_e and P_n values get larger as well. At the local level, Figure 3 demonstrates a comparison of the compressive buckling behavior of HSS both with and without concrete fill.
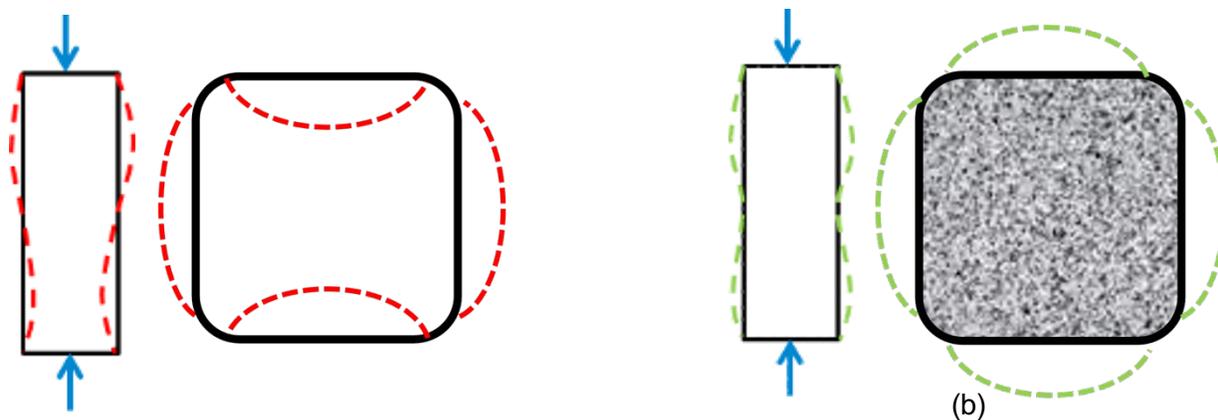

(b)

Figure 3
Buckling Patterns for (a) Square HSS Steel Only and (b) Filled Square HSS

To punctuate the difference, the allowable b/t ratio limits drastically change when comparing AISC 360-22 Tables B4.1a (unfilled HSS = 1.40 rectangular slenderness coefficient) and I1.1a (filled HSS = 2.26 rectangular compactness coefficient), meaning that many slender HSS columns become compact when filled with concrete. The reality is that almost all ASTM A500 Grade C HSS sizes are considered compact for composite members. AISC 360-22 Section I1.4 has a user note that provides guidance on which member sizes fit into the composite compact designation and lists the handful that do not.

Below is a table that highlights the composite capacity of various HSS sizes, with both 4ksi and 6ksi normal weight concrete fill, with the 42-foot unbraced length from the example above. The percentages listed demonstrate the increase in axial capacity compared to bare steel HSS as a baseline. Note that the effects of the concrete fill increase as the area of steel decreases.

	Bare Steel	Composite (4ksi)	Composite (6ksi)
	Non-Slender	Compact	Compact
HSS14x14x3/4	850k	883k (+3.9%)	937k (+10.2%)
HSS14x14x5/8	728k	792k (+8.8%)	850k (+16.8%)
HSS14x14x1/2	598k	686k (+14.7%)	743k (+24.2%)
HSS20x20x3/4	1750k	2050k (+17.1%)	2290k (+30.9%)
HSS20x20x5/8	1480k	1830k (+23.6%)	2070k (+39.9%)
	Slender	Compact	Compact
HSS14x14x3/8	460k	569k (+23.7%)	623k (+35.4%)
HSS14x14x5/16	389k	507k (+30.3%)	559k (+43.7%)
HSS20x20x1/2	1190k	1600k (+34.5%)	1840k (+54.6%)
HSS20x20x3/8	821k	1360k (+65.7%)	1600k (+94.9%)

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Fortunately, the axial capacity calculation steps have already been tabulated by both STI and AISC covering various conditions. STI HSS Design Manual Volume 2A (link) has capacity tables 2.2-3 through 2.2-8 for HSS round, square, and rectangular HSS including A500, A1085, and A1065 filled with $f'_c = 4\,ksi$ concrete up to a maximum unbraced length $L_c = 65\,ft$. Additionally, STI Professional Members have access to a spreadsheet at this link that performs calculations for any HSS size, unbraced length, and concrete strength within the limits listed in the next section. AISC 360-22 has filled HSS composite design tables in volume 2 of the companion to the 16th Edition Steel Manual. Tables 4-A through 4-F cover filled round, square, and rectangular HSS for A500 Gr. C $F_y = 50ksi$ filled with concrete strengths of $f'_c = 4\,ksi$ and $5\,ksi$ up to a maximum unbraced length $L_c = 40\,ft$. The manual companion can be found on AISC's website at this [link.](link)

3. High-Strength Steel and/or High Strength Concrete

In the AISC 360-22 Specification, Appendix 2 has been revised to cover the design of rectangular filled composite members with higher-strength materials than what is covered by Chapter I of the Specification. This appendix accommodates increased strength for the HSS steel, the concrete fill, or both. Following is a chart showing the limits of applicability for each specification section.

	Chapter I	**Appendix 2**
HSS Steel Strength	$f_y \le 75ksi$	$75ksi \le f_y \le 100ksi$
Normal Weight Concrete	$3ksi \le f'_c \le 10ksi$	$f'_c \le 15ks$
Light Weight Concrete	$3ksi \le f'_c \le 6ksi$	N/A

Longitudinal reinforcement (rebar) is not required but can be used. However, the effect of the reinforcement is ignored in the available strength calculation. For axial compression, the capacity calculation is almost entirely the same as the regular-strength counterpart with one main exception. The axial nominal compressive strength without consideration of length effects, P_{no}, has a revised equation in the appendix based on the critical buckling stress of the composite section. The Appendix 2 commentary references the two main research papers listed below that the Appendix 2 provisions are based on, which provide additional discussion on the revised procedure. For more information on high strength steel, AISC has a report available from the ad hoc task group on its website (link).

Alghossoon, A.M. and Varma, A.H. (2020), "Interaction of Section and and Member Slenderness on Behavior and Design of Rectangular High Strength Concrete Filled Tube Members," Bowen Laboratory Research Report, Purdue University, West Lafayette, Ind. (Link)

Lai, Z. and Varma, A.H. (2018), "High-Strength Rectangular CFT Members: Database, Modeling, and Design of Short Columns," *Journal of Structural Engineering*, ASCE, Vol. 144, No. 5, pp. 04018036-1-04018036-18. (Link)

4. Further Insights into Composite Member Design

The example in Part 1 above highlights the main design procedure for calculating the capacity of compact filled HSS members for axial loads with the plastic stress distribution design method. But what about non-compact or slender composite columns, or flexural design?

Slender or Non-compact Shapes

When composite members are slender or non-compact, AISC 360-22 Section I1.2 and commentary provides three design options: Strain Compatibility Method, Elastic Stress Distribution Method, and Effective Stress-Strain Method. Each section describes the procedure and applicability of each method.

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Flexural Design and Force Interaction

Flexural members are covered in section I3.4 and have the same four analysis methods as for columns. Finally, force interaction is covered by section I5. Note that when using high-strength materials, the interaction of axial and flexural forces in section I5 must be modified per appendix section 2.4.

For more in-depth information on these topics, please refer to the following resource available on the STI website. "Composite Concrete Filled HSS: Design Considerations" ([link](#)).

5. Connecting to Composite HSS Columns

Another important topic is connections to composite HSS members. Due to the synergistic effect of the steel and concrete working together, it is not enough to simply connect to the HSS steel member as is normally done. A portion of the load must transfer from the steel to the concrete to properly take advantage of the composite strength. Be aware that steel thickness is a factor in the connection capacity. Thus, it is recommended to consider the connections when selecting the HSS section to prevent issues with connection capacities down the line. A balance must be reached between column efficiency and connection requirements. Thus, the next referral is "Composite Column Connections" ([link](#)), which steps through the design concepts for ensuring the connection forces are properly transferred to the entire composite section.

6. Fire Resistance

Composite columns offer a significant advantage with their inherent fire-resistant properties. Based on research, ratings up to three hours can be achieved without the need for any external fire resistance. When using the concrete fill to achieve fire ratings, internal concrete reinforcement should be used since the HSS will shed load into the concrete core as the temperature rises. Thus, in a fire event, the concrete core must eventually support the load by itself. For additional information and a list of resources, see the STI article called "Keeping Your Cool: How To Get Started With HSS Fire Ratings" ([link](#)).

7. Logistical Considerations

Finally, this article has been focusing entirely on engineering design up to this point. However, there are many logistical considerations for making a successful project. Some of these items include type of concrete to use, concrete installation methods, detailing requirements, constructability and more. For further discussion on this, refer to the STI article "Practical Guidance for Concrete Filled HSS Columns" ([link](#)).

Conclusion

HSS columns are efficient members with many benefits. One unique benefit is the convenient hole in the middle that is perfect for filling with concrete to reap additional rewards such as increased strength and fire ratings without the need for additional materials for installation. Whether the intent is to reduce the column footprint or maximize height limits, composite HSS columns offer a significant boost to the positive impact of HSS. A wealth of information is available to grasp the full scope of capabilities and nuances of composite design. Recognizing that this topic could fill volumes, STI offers a companion resource that compiles all these resources into one convenient Reference Guide, which can be found on the STI website at this [link](#).

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