Technical Note

Design Aid for Selection of H-Piles

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Abstract: This paper presents design aids for the selection of HP sections for driven piles according to the American Institute of Steel Construction Specification 360-22 "Specification of Structural Steel Buildings." Graphical aids for the design selection of W-shapes have been provided by Keil (2000), Hosur and Augustine (2007), and Sa'Adat and Banan (2014). However, to date there are no aids available for the design of H-Piles. This work seeks to eliminate that gap by providing the data necessary to create interaction diagrams for combined stresses including compression, bending, and tension in both the strong and weak axes for 50 ksi grade steel HP sections.

Keywords: H-piles, driven pile design aid, AISC, AASHTO, ASD, LRFD, combined stress analysis

Introduction

Piles are structural members that transfer loads from a superstructure into the underlying ground. The design of piles consists of a geotechnical and structural component. The geotechnical design considers the capacity of the soil mass surrounding the pile; the structural design considers the capacity of the pile in compression, tension, and bending. The design of structural steel is governed by the American Institute of Steel Construction 360, "Specification for Structural Steel Buildings" (AISC, 2022, hereafter referred to as "Specification"). Structural steel design for highway projects is governed by the AASHTO LRFD Bridge Specifications (AASHTO, 2020).

Graphical aids for the design of W-shapes have been provided by Keil (2000), Hosur and Augustine (2007), and Sa'Adat and Banan (2014). However, to-date there are no similar aids for the design of H-piles. This work seeks to bridge that gap by providing the data necessary to construct both Allowable Stress Design (ASD) and Load Resistance Factor Design (LRFD) combined stress interaction diagrams. In this paper, the nominal strengths will be determined, and interaction diagrams may be constructed using either ASD or LRFD design methodology. The nominal strength is the calculated capacity of the section according to AISC 360 without reduction by the factor of safety in ASD or reduction factor for LRFD.

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For LRFD:

$$R_u \leq \phi R_n \tag{B3-1}$$

Where Ru is the required strength using LRFD load combinations, Rn is the nominal strength, ϕ is the resistance factor, and ϕR_n is the design strength. (Note: Equations beginning with a letter are from the corresponding section in the Specification; equations without a letter are internal to this paper.)

In ASD, the 'required strength' (i.e., allowable capacity) is:

$$R_a \leq \frac{R_n}{\Omega} \tag{B3-2}$$

Where R_a is the required strength using ASD load combinations, R_n is the nominal strength, Ω is the safety factor, and the ratio R_n/Ω is the allowable strength.

A typical interaction diagram for an HP shape is shown in Figure 1. The interaction diagram shows the relationship between nominal axial force and bending moment. The nominal bending strength of the member is plotted along the abscissa and the compressive/tensile strength along the ordinate; compressive strength is positive and tensile strength is negative.

There are five points that define the interaction diagram based on the nominal strength. Point 1 is the maximum compression strength with no bending ($M_1 = 0$). Point 3 is the maximum bending strength with no axial force ($P_3 = 0$). Point 5 is the maximum tension strength with no bending ($M_5 = 0$). Points 2 and 4 are inflection points. Point 1 is tabulated in Table 4-2 in AISC (2023). There are two commercially available HP shapes (HP12x102 and HP12x117) that are not tabulated in Table 4-2 but have been included here.

Section H1 of the Specification addresses the design of doubly and singly symmetric members (i.e., HP Sections) for combined loading. Four parameters are defined:

P_r = Required axial strength, kips
P_c = Available axial strength, kips (Chapter E)
M_r = Required flexural strength, kip-in
M_c = Available flexural strength, kip-in (Chapter F)

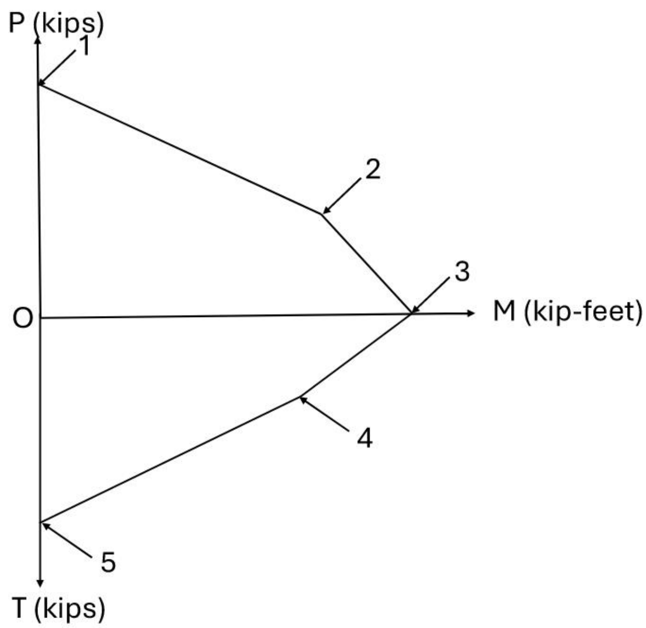

Figure 1. HP Interaction Diagram

The values of P_r and M_r are determined using Chapter C LRFD or ASD load combination; P_c and M_c are determined by calculating the nominal strengths in compression P_n and bending M_n, respectively, and then applying the LRFD strength reduction factor ($\phi_c P_n$ and ϕM_n) or ASD factor of safety (P_n/Ω_c) and M_n/Ω_b).

The Specification has two limiting equations that depend on the ratio of P_r/P_c. When P_r/P_c is ≥ 0.2, Eq. H1-1a governs. Otherwise, Eq. H1-1b governs:

$$\frac{P_r}{P_c} + \frac{8}{9}\left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}}\right) \leq 1.0 \qquad \text{(H1-1a)}$$

$$\frac{P_r}{2P_c} + \left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}}\right) \leq 1.0 \qquad \text{(H1-1b)}$$

In Eqs. H1-1a and H1-1b, x and y refer to bending about the strong and weak axis, respectively. The ASD or LRFD required strengths for compression, bending, and tension must be determined before the Chapter H equations can be applied.

In this paper, we will develop interaction equations using nominal values that can be easily modified for either LRFD or ASD design. First, we will recast Eqs. H1-1a and b using the neutral values of x and y for plotting of bending and compression, respectively, and change the available strengths to nominal strengths as follows:

$$\frac{y}{P_n} + \frac{8}{9}\left(\frac{x_x}{M_{nx}} + \frac{x_y}{M_{ny}}\right) \leq 1.0 \qquad \text{(H1-1a)}$$

$$\frac{y}{2P_n} + \left(\frac{x_x}{M_{nx}} + \frac{x_y}{M_{ny}}\right) \leq 1.0 \qquad \text{(H1-1b)}$$

where M_n is the bending strength in either the strong (x) or weak (y) axis. Following Sa'Adat and Banan (2014), major and minor axis bending equations H1-1a and H1-1b are simplified by setting the weak-axis ratio M_{ry}/M_{cy} to zero and removing the inequality by setting the equations equal to unity:

Set H1-1a equal to unity: $\frac{y}{P_n} + \frac{8}{9}\left(\frac{x_x}{M_{nx}} + \frac{x_y}{M_{ny}}\right) = 1.0$

Set x_y/M_{ny} to zero and solve for y:

$$y = P_n\left(1 - \frac{8}{9}\frac{x_x}{M_{nx}}\right) \qquad (1)$$

Similarly, set H1-1b equal to 1: $\frac{y}{2P_n} + \left(\frac{x_x}{M_{nx}} + \frac{x_y}{M_{ny}}\right) = 1.0$

Set x_y/M_{ny} to zero and solve for y:

$$y = 2P_n\left(1 - \frac{x_x}{M_{nx}}\right) \qquad (2)$$

On the tension side of the interaction diagram, we replace P_c with P_t which results in:

$$y = P_{nt}\left[1 - \frac{8}{9}\left(\frac{x_x}{M_{nx}}\right)\right] \qquad (3)$$

and

$$y = 2P_{nt}\left(1 - \frac{x_x}{M_{nx}}\right) \qquad (4)$$

We are now able to determine the points to plot an interaction diagram for an HP shape. In Figure 1, the coordinates of Point 1 are ($0, P_n$). The line from Point 1 to Point 2 is Eq. 1 and the line from Point 2 to Point 3 is Eq. 2.

Point 2 is determined by simultaneously solving Eq. 5 and Eq. 6 for the unknown value, M_{nx}:

$$\frac{y}{P_n} = 0.2 \Rightarrow y = 0.2P_n \qquad (5)$$

$$y = P_n\left[1 - \frac{8}{9}\left(\frac{x_x}{M_{nx}}\right)\right] \qquad (6)$$

Equating 5 and 6:

$$P_n\left[1 - \frac{8}{9}\left(\frac{x_x}{M_{nx}}\right)\right] = 0.2P_n \qquad (7)$$

Dividing by P_n and rearranging:

$$1 - \frac{8}{9}\left(\frac{x_x}{M_{nx}}\right) = 0.2 \Rightarrow 0.8 = \frac{8}{9}\left(\frac{x_x}{M_{nx}}\right) \Rightarrow \frac{8}{10} = \frac{8}{9}\left(\frac{x_x}{M_{nx}}\right) \qquad (8)$$

$$\frac{9}{8} \times \frac{8}{10} = \frac{x_x}{M_{nx}} \Rightarrow \frac{9}{10} = \frac{x_x}{M_{nx}} \Rightarrow x_x = 0.9M_{nx} \qquad (9)$$

Using Eqs. 5 and 8, the coordinates of Point 2 are ($0.9M_n$,$0.2P_n$) and the coordinates of Point 3 are (M_n, 0) where M_n is the nominal flexural strength. Point 4 is located at a distance from the horizontal axis calculated in a similar manner to Point 2 but using the tension strength P_{nt} instead of P_n. Point 5 has

Table 1. Nominal Compression, Tension, and Bending

HP Shape	P_n (kips)	P_{nt} (kips)	M_{nx} (kip-ft)	M_{ny} (kip-ft)
HP8x36	530	-530	140	106
HP10x42	620	-620	187	124
HP10x57	835	-835	277	167
HP12x53	770	-775	273	154
HP12x63	920	-920	344	184
HP12x74	1090	-1090	428	218
HP12x84	1230	-1230	500	246
HP12x89	1295	-1295	529	259
HP12x102	1495	-1495	615	299
HP12x117	1720	-1720	712	344
HP14x73	1046	-1070	429	209
HP14x89	1305	-1305	567	261
HP14x102	1505	-1505	680	301
HP14x117	1720	-1720	806	344
HP16x88	1259	-1290	582	252
HP16x101	1495	-1495	712	299
HP16x121	1790	-1790	907	358
HP16x141	2085	-2085	1100	417
HP16x162	2385	-2385	1275	477
HP16x183	2705	-2705	1454	541
HP18x135	1995	-1995	1090	399
HP18x157	2310	-2310	1323	462
HP18x181	2660	-2660	1579	532
HP18x204	3010	-3010	1804	602

the coordinates (0, P_{nt}). For a weak-axis interaction diagram, the above procedure can be followed to create the necessary equations to plot weak-axis interaction.

As seen by equations 1-9, only four nominal values are required to plot both strong-axis and weak-axis interaction diagrams: P_n, P_{nt}, M_{nx}, and M_{ny}, where P_n is the nominal compressive strength, P_{nt} is the nominal tensile strength, M_{nx} is the nominal strong-axis bending strength, and M_{ny} is the nominal weak-axis bending strength. These points have been tabulated in Table 1:

A guide to performing the calculations in the Table above is provided in the Appendix along with an example. A Mathcad Prime 9.0 template to calculate the nominal strength values in the Table is available at https://github.com/dwdotson/Hpile-Interaction.

Appendix

Example Problem: An analysis of a pile cap has been performed and the maximum service compression load on a single pile in the cap consists of a 100 kip dead load and a live load of 50 kips along with a service bending moment of 40 kip-ft. Determine whether an HP8x36 pile is suitable for the applied loads using both ASD and LRFD criteria. Assume the bending moment is in the strong axis of the pile and is a live load.

Solution:

(a) ASD: The required strength in compression from ASCE 7-22 is D+L = 150 kips and the required bending strength is 40 kip-ft. From Table 1, the allowable compression strength is 530 kips/1.67 = 317.4 kips. The allowable bending strength is 140 kip-ft/1.67 = 83.8 kip-ft.

(b) LRFD: The factored compression load using ASCE 7-22 is 1.2(100 kips) + 1.6(50 kips) = 184 kips; the factored bending moment is 1.6(40 kip-ft) = 64 kip-ft. From Table 1,

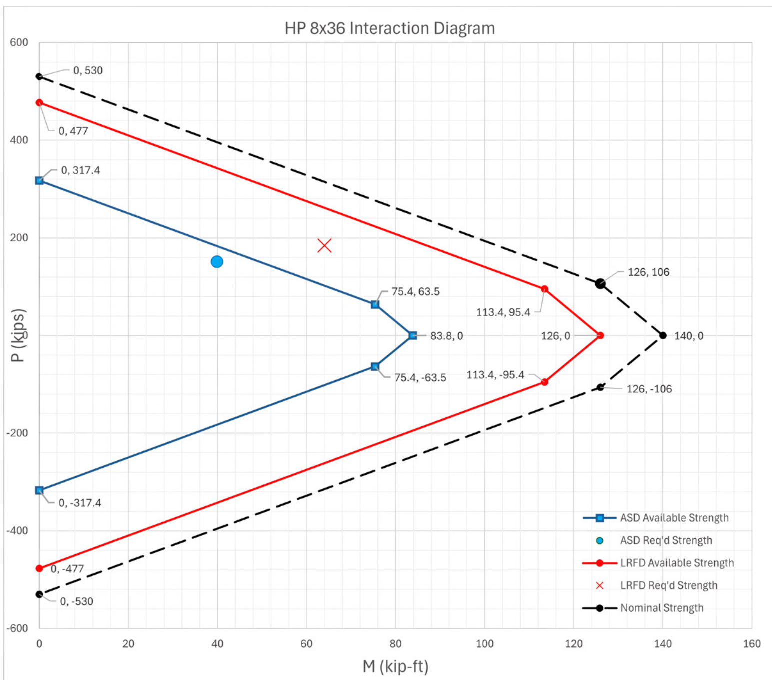

Figure 2. Solution Interaction Diagram

the available compression strength is 0.9(530 kips) = 477 kips and the available bending strength is 0.9(140 kip-ft.) = 126 kip-ft.

Plotting the Nominal, ASD, and LRFD interaction curves along with the ASD and LRFD required strengths shows that the required strengths plot inside the interaction curves and therefore the HP8x36 is suitable for the applied loads.

The values in Table 1 are determined from Chapters D, E, and F in AISC (2022).

TENSION, CHAPTER D

Chapter D is used to design members subject to tension and Sections D2 and D3 apply to HP Shapes. There are no maximum slenderness limits for members in tension, however the Specification suggests that L/r should not exceed 300, but this does not apply to HP shapes.

Section D2 states that the design tensile strength, $\phi_t P_n$, and the allowable tensile strength, P_n/Ω_t, of tension members is the lower value of (a) tensile yielding in the gross section and (b) tensile rupture in the net section.
(a) For tensile yielding in the gross section:

$$P_n = F_y A_g \qquad \text{(D2-1)}$$

with $\phi_t = 0.90$ (LRFD) and $\Omega_t = 1.67$ (ASD)
(b) for tensile rupture in the net section:

$$P_n = F_u A_e \qquad \text{(D2-2)}$$

with $\phi_t = 0.75$ (LRFD) and $\Omega_t = 2.00$ (ASD)
where:
A_e = effective net area
A_g = gross area of member
F_y = specified minimum yield stress
F_u = specified minimum tensile strength

Section D3 states that A_e and A_g are to be determined in accordance with Section B4.3. The effective net area is determined as:

$$A_e = A_n U \qquad \text{(D3-1)}$$

Where A_n is the net area of the tension member and U is the shear lag factor determined in Table D3.1. According to Section B4.3b, for members without holes, A_n is equal to A_g. Here, A_n is set equal to A_g and U is taken as unity.

AXIAL COMPRESSION, CHAPTER E

Chapter E of the Specification addresses axial compression of members. For HP shapes, Sections E1 - E3 and E7 apply. In determining the nominal compressive strength, P_n, values for the effective length, L_c, are required. It has been recognized by the foundation industry since at least the 1930s, that piles embedded in soil (regardless of how weak or loose) may be considered fully supported (Cummings, 1938, Glick, 1948). Because embedded H-Piles are considered fully supported, L_c is essentially zero and lateral-torsional buckling does not apply (Murat, 2022).

Although lateral torsional buckling is not a potential failure mode for embedded piles, local buckling must be checked. For compression, H-pile sections are classified either with or without slender elements. To determine whether slender elements are present in a section, the width-to-thickness ratio of the flanges b/t are checked against the limiting width-to-thickness ratio, λ_r in Chapter B of the Specification:

$$\lambda = \frac{b_f}{2t_f} \le 0.56\sqrt{\frac{E}{F_y}}, \qquad \text{Table B4.1a Case 1}$$

Where bf is the flange width, t_f is the flange thickness, E and F_y are the modulus of elasticity and yield strength of the steel, respectively.

If the inequality is true, the flange element of the section is nonslender; otherwise, it is slender. A slender section is one that cannot develop the yield stress prior to web or flange local buckling (Williams, 2011).

The width-to-thickness ratio of the web h/t_w is checked against the limiting width-to-thickness ratio, λ_r:

$$\lambda = \frac{h}{t_w} \le 1.49\sqrt{\frac{E}{F_y}} \qquad \text{Table B4.1a Case 5}$$

If this inequality is true, then the web element of the H-pile is nonslender; otherwise, slender.

Where there are no slender elements in the section, the nominal axial compressive strength of the H-pile is determined based on the limit state of flexural buckling as:

$$P_n = F_n A_g \qquad \text{(E3-1)}$$

Where F_n, the nominal stress, is determined as follows:

when $\frac{L_c}{r} \le 4.71\sqrt{\frac{E}{F_y}}$ $\left(\text{or } \frac{F_y}{F_e} \le 2.25\right)$, then

$$F_n = \left[0.658^{\frac{F_y}{F_e}}\right] F_y \qquad \text{(E3-2)}$$

when $\frac{L_c}{r} \le 4.71\sqrt{\frac{E}{F_y}}$ $\left(\text{or } \frac{F_y}{F_e} \le 2.25\right)$, then

$$F_n = 0.877 F_e \qquad \text{(E3-3)}$$

where

$$F_e = \frac{\pi^2 E}{\left(\frac{L_c}{r}\right)^2} \qquad \text{(E3-4)}$$

L_c is the effective length, and r is the radius of gyration.

When slender elements are present, the nominal axial compressive strength of the H-pile is determined from Specification section E7, “Members with Slender Elements” using Eq. E7-1:

$$P_n = F_n A_e \qquad \text{(E7-1)}$$

Where A_e is the summation of the effective areas of the cross section based on reduced effective widths, b_e, d_e, or h_e. The width b_e is for flanges, d_e is for tees, and h_e is for webs. For members with slender elements, the width/depth of the slender flange/web, respectively, is reduced by equations E7-2 or E7-3 and a revised area, A_e, is calculated.

(a) When $\lambda \le \lambda_r \sqrt{\frac{F_y}{F_n}}$,

$$b_e = b \tag{E7-2}$$

(b) When $\lambda \le \lambda_r \sqrt{\frac{F_y}{F_n}}$,

$$b_e = b\left(1 - c_1\sqrt{\frac{F_{el}}{F_n}}\right)\sqrt{\frac{F_{el}}{F_n}} \tag{E7-3}$$

where:
b = width of the element (b for flanges, h for webs)
c_1 = effective width imperfection adjustment

$$c_2 = \frac{1 - \sqrt{1 - 4c_1}}{2c_1} \tag{E7-4}$$

λ = width-to-thickness ratio for the element defined in Section B4.1, λ_r = limiting width-to-thickness ratio defined in Table B4.1a, and F_{el} is the elastic local buckling stress:

$$F_{el} = \left(c_2 \frac{\lambda_r}{\lambda}\right)^2 F_y \tag{E7-5}$$

Then the nominal compressive strength is determined according to E7-1. For design, ϕ_c = 0.90(LRFD) and Ω_c = 1.67(ASD)

These calculations have been performed and are tabulated in the AISC (2023) in Table 4-3 for both ASD and LRFD available axial compressive strengths. The nominal compressive strengths can be obtained by dividing the tabulated ASD value by Ω_c or multiplying the tabulated LRFD value by ϕ_c. There are three HP shapes that are slender for compression, HP12x53, HP14x73, and HP16x88.

FLEXURE, CHAPTER F

Chapter F of the Specification applies to flexure of members; Sections F1 – F3 and F6 apply to HP shapes. For flexure, the ASD safety factor Ω_b is 1.67 and the LRFD strength reduction factor ϕ_b is 0.90.

In Section F2, the nominal flexural strength, M_n of members bent about their major axis with compact webs and flanges is the lower value obtained by either the limit states of yielding (using the plastic moment) or lateral-torsional buckling. Since lateral-torsional buckling does not apply to H-piles because they are fully supported, the lateral-torsional buckling modification factor, C_b, from F1 is not used and the lateral-torsional buckling limit state is not checked. A User Note in Section F2 states that all current HP shapes have compact webs for $F_y \le 70$ ksi. Therefore, only the flanges are subject to being (1) compact, (2) non-compact, or (3) slender.

The nominal moment based on yielding is determined by Eq. F2-1:

$$M_n = M_p = F_y Z_x \tag{F2-1}$$

Section F3 applies to H-Piles since all HP sections have compact webs, but some have noncompact flanges. According to Table B4.1b, Case 10, the limiting width-to-thickness ratio for compact flanges is:

$$\lambda = b_f / 2t_f < \lambda_{pf} = 0.38\sqrt{E / F_y}$$

Once it has been determined that the flange is not compact, then the flange should be checked to see whether:

$$\lambda = \frac{b_f}{2t_f} < \lambda_{rf} \text{ where } \lambda_{rf} = 1.0\sqrt{E / F_y}$$

where:
b_f = width of flange
t_f = thickness of flange
λ_{pf} = the limiting slenderness for a compact flange
λ_{rf} = the limiting slenderness for a noncompact flange
If the inequality is true,
(a) then the nominal moment strength is:

$$M_n = M_p - \left(M_p - 0.7F_y S_x\right)\left(\frac{\lambda - \lambda_{pf}}{\lambda_{rf} - \lambda_{pf}}\right) \tag{F3-1}$$

(b) otherwise, the flange is slender, and the nominal moment strength is:

$$M_n = \frac{0.9Ek_c S_x}{\lambda^2} \tag{F3-2}$$

where:

$$k_c = 4 / \sqrt{\frac{h}{t_w}} \quad \text{with limits of } 0.35 \le k_c \le 0.76$$

where h is defined in Table B4.1b. Since h/t_w is tabulated in Table 1-4 of AISC (2023), h can be determined by multiplying h/t_w by t_w.

The nominal weak axis flexural strength is determined from Section F6. Some engineers prefer to orient H-Piles in a pile cap so that only the major axis is subject to bending. In these arrangements, for example, some piles are oriented with their major axes aligned in the north-south direction orthogonal to other piles oriented with their major axes in the east-west direction. For conditions where minor-axis bending is employed, the nominal bending strength of members with compact flanges is the lower value obtained according to the limit states of plastic moment yielding and flange local buckling.

For sections with compact flanges, the limit state of flange local buckling does not apply. For sections with noncompact flanges:

$$M_n = M_p - \left(M_p - 0.7F_y S_y\right)\left(\frac{\lambda - \lambda_{pf}}{\lambda_{rf} - \lambda_{pf}}\right) \tag{F6-2}$$

For sections with slender flanges:

$$M_n = F_{cr} S_y \tag{F6-3}$$

where:

$$F_{cr} = \frac{0.70E}{\left(\frac{b}{t_f}\right)^2}, \tag{F6-4}$$

b = half the full flange width, i.e., $b_f/2$, and the remaining variables are as previously defined.

The flanges for HP Shapes with 50 ksi yield strength have been checked for compactness. There are ten HP shapes with compact flanges for flexure: HP10x57, HP12x84, HP12x89, HP12x102, HP12x117, HP16x141, HP16x162, HP16x183, HP18x181, HP18x204. The remaining HP shapes have non-compact flanges; no HP shapes have flanges that are slender.

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