HSS Truss Connections With Three Branches

JEFFREY A. PACKER

ABSTRACT

Hollow structural section (HSS) three-branch (or KT) connections frequently occur in modified Warren trusses, but the design of these planar welded connections is beyond the scope of Chapter K of the 2010 AISC *Specification for Structural Steel Buildings*. Such connections are also not covered by other contemporary HSS design guides and standards. This paper reviews the many potential member and loading arrangements, for both gapped and overlapped KT connections, and offers some design guidance. A worked example for an overlapped square HSS KT connection is then given, in both LRFD and ASD formats, in accordance with the 2010 AISC *Specification for Structural Steel Buildings*.

Keywords: hollow structural sections, trusses, connections, KT, welded joints, overlapping branches.

INTRODUCTION

Hollow structural section (HSS) Warren trusses with K connections, which have two diagonal branch members, are frequently modified by the introduction of a third vertical branch to form a so-called KT connection, as shown in Figure 1. The vertical branch may be added to support an applied load between panel points or to reduce the effective length of a chord member, but in general, this vertical member is often lightly loaded. The design of statically loaded, planar, HSS KT connections is beyond the scope of the AISC 360 *Specification* (AISC, 2010), and AISC *Design Guide 24* (Packer et al., 2010), nor are they covered in the latest HSS design guidance from CIDECT (Packer et al., 2009; Wardenier et al., 2008; Wardenier et al., 2010), the International Institute of Welding (2012) or the International Organization for Standardization (2013). AWS D1.1 (2010) does not specifically address this type of connection either, although the American Welding Society method for handling overlapped tubular connections (Clause 2.25.1.6)—on a branch-by-branch basis—might be applied to overlapped KT connections between round HSS. The reason for this lack of contemporary coverage is the realization that there are a very large number of possible configurations for members in KT connections, combined with a large number of possible loading arrangements for the members. Very little research exists on HSS KT connections, so a synthesis of "best practice" guidance is offered in this paper, which serves to extend the scope of AISC *Specification* Chapter K (2010).

Jeffrey A. Packer, Bahen/Tanenbaum Professor of Civil Engineering, University of Toronto, Toronto, Ontario, Canada. E-mail: jeffrey.packer@utoronto.ca

METHODS OF ANALYSIS

Some of the possible load combinations on the three branch members of a KT connection are shown in Figure 2. Parts (a) through (d) of this figure illustrate combinations where the three branch member forces are in vertical equilibrium (i.e., normal to the chord direction), with the two diagonals either having the opposite or the same force sense. Parts (e) through (h) of this figure have the same branch member force sense as in parts (a) through (d), but some load is additionally transferred through the chord member. Parts (i) and (j) of Figure 2 have all of the load on one side of the connection transferred through the chord member to the other side; thus, these connections can be analyzed as cross (or X) connections.

Fig. 1. HSS KT connection.

Gapped KT Connections

When all three branches have gaps between them, at the junction with the chord connecting face, a suggested method of connection analysis is as follows:

1. In Figures 2(a) and 2(b), the force in branch 3 can be apportioned into two parts, each of which balances the vertical components of the forces in branches 1 and 2. Thus, the total connection can be subdivided into two K connections (bearing in mind that N connections are a special case of the general K connection), consisting of branches 1 and 3 and branches 2 and 3. The two K connections can then be checked using the procedures in Section K2 of the AISC 360 *Specification* (AISC, 2010). The total utilization of branch 3 in each sub-K connection would also need to be checked in the manner outlined in the *Commentary* to Section K2 of the *Specification*. A calculation example of a K connection, where a branch participates in two separate subconnections (or free-body diagrams), is given in Example 8.5 of AISC *Design Guide 24* (Packer et al., 2010).
2. In Figures 2(e) and 2(f), the procedure is similar to that in case 1, but the total-force, free-body diagram now needs to be split into separate free-body diagrams consisting of a cross connection plus two K connections, with the vertical branch 3 being checked for its utilization in three subconnections, as shown in Figure 3(a).
3. In Figures 2(c) and Figure 2(d), two neighboring branches have the same force sense, and these two branches could be possibly considered to have a "combined action." This is the one case of a KT connection covered in EN 1993-1-8 (CEN, 2005), where all the branches are illustrated with gaps between each other at the chord-connecting face. In Eurocode 3, Table 7.15, the checking method (using AISC LRFD terminology) is to confirm that [with reference to Figure 2(c)],

$$P_1\sin\theta_1 + P_3\sin\theta_3 \le \phi P_{n1}\sin\theta_1 \quad (1a)$$

$$P_2\sin\theta_2 \le \phi P_{n1}\sin\theta_1 \quad (1b)$$

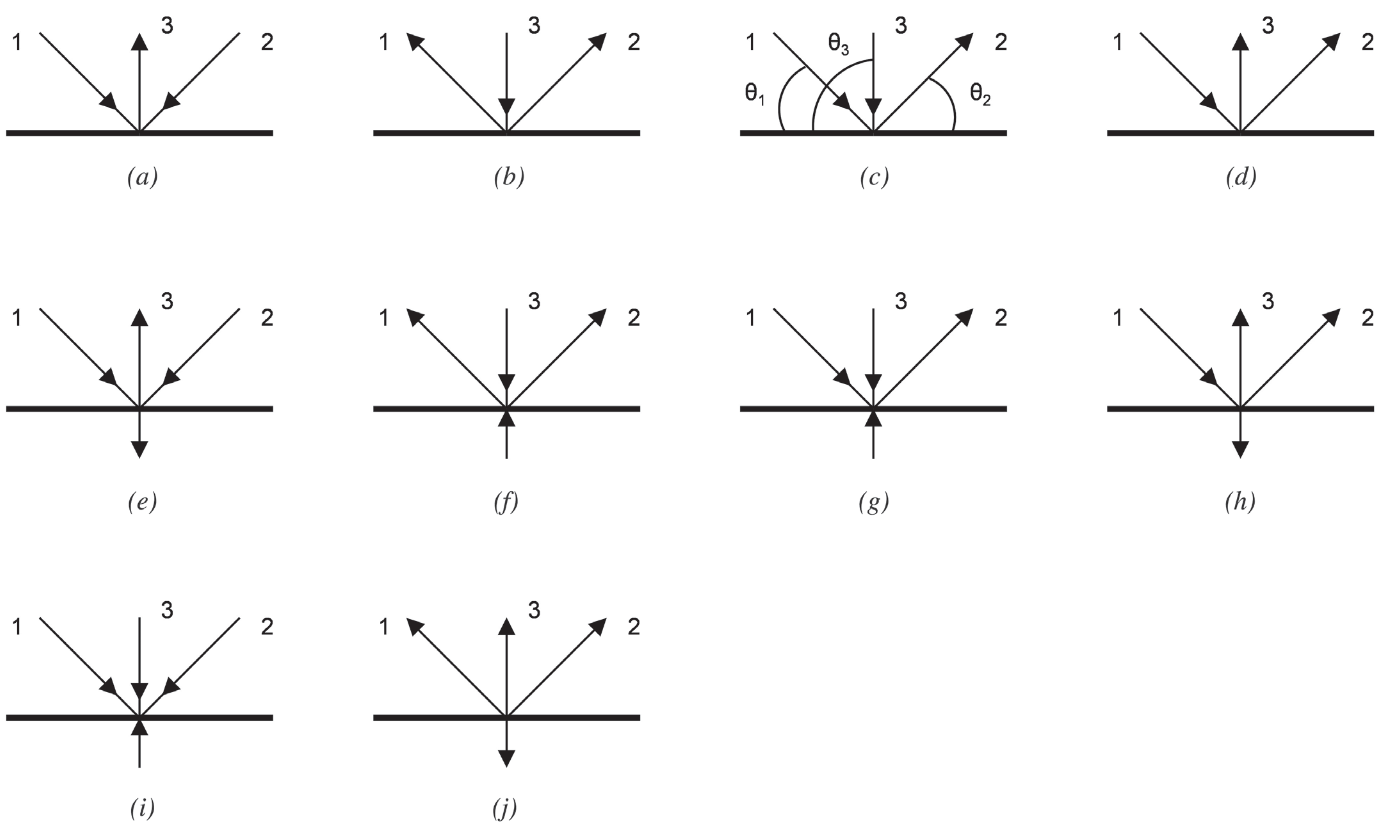

Fig. 2. Examples of load combinations on KT connections (after Tata Steel, 2011).

where P_1, P_2 and P_3 are the axial forces in branches 1, 2 and 3, respectively, and P_{n1} is the connection's available strength expressed as an axial force in branch 1, per *Specification* Equation K2-14. Also, it is stipulated that the value of β_{eff} in *Specification* Equation K2-24 be calculated by averaging over the three branches, as follows:

$$\beta_{eff} = \left[(B_b + H_b)_{branch\ 1} + (B_b + H_b)_{branch\ 2} + (B_b + H_b)_{branch\ 3}\right]/6B \tag{1c}$$

This method has the following drawbacks: (1) it is tailored to the limit state of chord-wall plastification, (2) it applies only to gapped KT connections with this unique pattern of branch loads, and (3) it presumes that the diagonal branches and their forces dominate. The EN 1993 (CEN, 2005) procedure has also been applied to round-to-round, gapped, HSS KT connections, pointing out that $(D_{b\ comp}/D)$ in *Specification* Equation K2-4 should be replaced by $(D_{b1} + D_{b2} + D_{b3})/3D$, where D_{b1}, D_{b2} and D_{b3} are the outside diameters of branches 1, 2 and 3, respectively. Very similar methods to this EN 1993 technique were cited earlier by Wardenier et al. (1991), Packer et al. (1992) and Packer and Henderson (1992, 1997), where the gap is recommended to be taken as "the largest gap between two [branches] having significant forces acting in the opposite sense" (Packer et al., 1992). Packer et al. (1992, 1997) also used a variant of Equation 1b, still with reference to Figure 2(c), as given in Equation 1d:

$$P_2 \sin\theta_2 \le \phi P_{n2} \sin\theta_2 \tag{1d}$$

where P_{n2} is the connection's available strength measured as a force in branch 2, per *Specification* Equation K2-14.

Despite all of the foregoing in case 3, it is much more logical, however, if the free-body diagram of KT connection forces is again broken into its constituent subconnections, as illustrated in Figure 3(b), and analyzed in this preferred manner.

4. In Figures 2(g) and 2(h), the procedure is similar to Figure 3(b), except an additional cross connection component will be introduced, thus making three separate subconnections (or free-body diagrams).

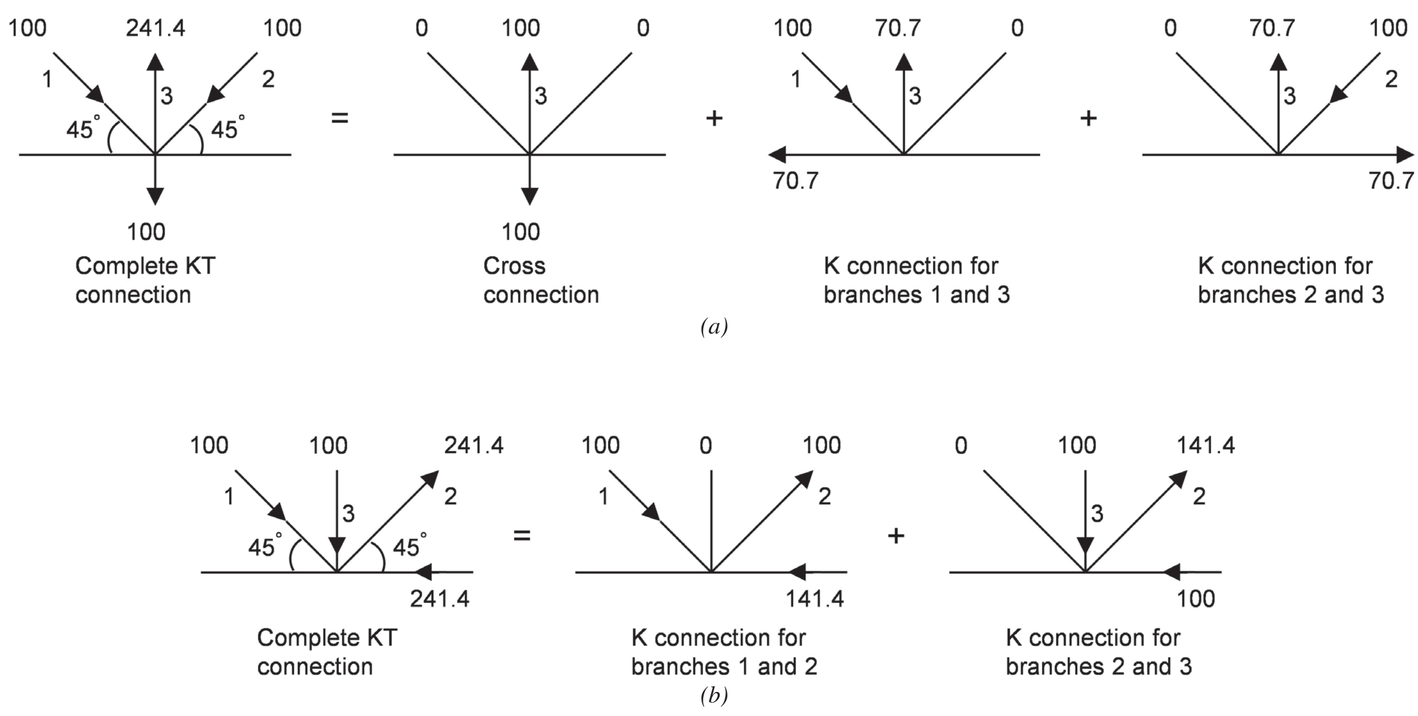

Fig. 3. Recommended analysis methods for gapped KT connections: (a) example of Fig. 2(e) broken into its constituent subconnections; (b) example of Fig. 2(c) broken into its constituent subconnections.

5. In Figures 2(i) and 2(j), the connection is a single cross connection—in both cases—because all branch-force components normal to the chord member are transferred through the chord. A calculation example of a very similar cross connection is given in Example 8.3 of AISC *Design Guide 24* (Packer et al., 2010).

If the vertical branch in a gapped KT connection has zero (or near-zero) force in it, then it can be ignored and the connection treated as a K connection, with the gap taken as the distance between the toes of branches 1 and 2 in Figure 2. This will be very conservative because the mere presence of additional steel (branch 3) welded to the gap region will stiffen the connection.

Overlapped KT Connections

Overlapped KT connections are much more probable than gapped KT connections because the latter produces a large positive noding eccentricity, which is likely to violate the limit of applicability for joint eccentricity in the AISC 360 *Specification* (AISC, 2010), Tables K2.1A or K2.2A. The common types of overlapped KT connections are shown in Figure 4. The sequence of overlapping should follow the basic premise that narrower branch members "sit on" (or frame into) wider members. If two overlapping branch members have the same width, then the thinner should sit on the thicker branch (i.e., the thicker branch should be the through member). As with overlapped K connections, overlapped KT connections should have (at least) one branch welded directly to the chord.

The resistance of round HSS overlapped KT connections can be handled in a similar way to cases 1 through 5, described for gapped KT connections, which involves splitting the free-body diagram of connection axial loads into subconnections involving K and cross connection types. Branch members participating in multiple subconnection types need to have their total utilization checked to ensure that it is less than unity by linear addition of their respective utilizations in each subconnection. As noted previously, refer to Example 8.5 of AISC *Design Guide 24* (Packer et al., 2010). The resistance of overlapped K connections between round HSS is based only on the limit state of chord plastification (Equations K2-4 and K2-5 of Table K2.1 of the *Specification*). The amount of overlap (O_v), or negative gap (g), to be used in Equation K2-6 pertains to the two branches under consideration in a particular subconnection. Again, if the vertical branch in an overlapped KT connection has zero (or near-zero) force in it, then it can be ignored and the connection treated as a K connection.

The resistance of rectangular and square HSS overlapped KT connections can be determined on a branch-by-branch basis, in a similar manner to overlapped K connections, using Equations K2-17 to K2-22 in Table K2.2 of the *Specification*. This is demonstrated in the following design example. This method of checking overlapped KT and K connections is different for square/rectangular HSS connections compared to round HSS connections (described previously) in the AISC *Specification*, but it is worth noting here that the most recent international design guidance for round HSS overlapped K connections (Wardenier et al., 2008; Wardenier et al., 2010; IIW, 2012; ISO, 2013) translates the round HSS branches into equivalent square HSS and then proceeds to use the square/rectangular HSS checking method.

(a) (b) (c)

Fig. 4. Common types of overlapped KT connections.

DESIGN EXAMPLE FOR HSS OVERLAPPED KT CONNECTION

Figure 5 illustrates a KT connection using the new ASTM A1085 HSS (ASTM, 2013), with the branch member force arrangement being similar to Figure 3(b). The loads shown consist of live load (P_L) and dead load (P_D) in the ratio 3:1. Of the two diagonal HSS members, which are the largest branches and which are also of the same size, the branch with the largest force is welded directly to the chord member. The branches labeled 1 and 2 in Figure 5 have an overlap (O_v) of 50% at the chord connecting face. Thus, $l_{ov} = 0.50l_p = 0.50(5.774) = 2.89$ in. The aim is to determine the adequacy of this given connection.

Material Properties:

HSS chord member	ASTM A1085 Grade A steel	$F_y = 50$ ksi	$F_u = 65$ ksi
HSS branch members	ASTM A1085 Grade A steel	$F_{yb} = 50$ ksi	$F_{ub} = 65$ ksi

Geometric Properties:

HSS 10×10×3⁄8	$H = B = 10$ in.	$t = 0.375$ in.	$A = 14.1$ in.^{2}
HSS 5×5×5⁄16	$H_b = B_b = 5$ in.	$t_b = 0.313$ in.	$A_b = 5.61$ in.^{2}
HSS 4×4×1⁄4	$H_b = B_b = 4$ in.	$t_b = 0.250$ in.	$A_b = 3.60$ in.^{2}

Note that the full nominal thickness is used as the design thickness for ASTM A1085 material.

Solution:

Check the limits of applicability of Specification Section K2, Table K2.2A.

The overlap length, l_{ov}, measured along the connecting face of the chord beneath branches 1 and 2, is 2.89 in., which implies a noding eccentricity, e, of −2.5 in. (negative because the branch centerlines intersect toward the branches, relative to the chord

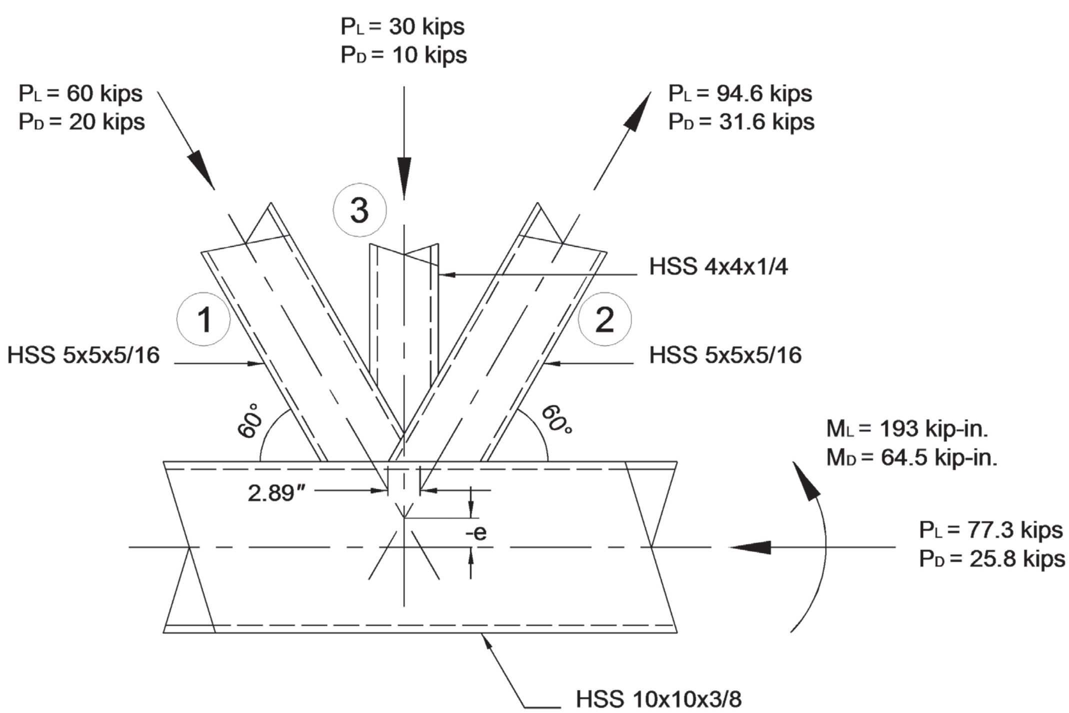

Fig. 5. Overlapped KT connection for design example.

centerline). A similar calculation example relating O_v, l_{ov} and e can be found in AISC *Design Guide 24* (Packer et al., 2010), page 111.

$-0.55 \le e/H = -0.25 \le 0.25$ **o.k.**

Branch angles, θ, are 60° and 90°, both of which are greater than 30° **o.k.**

$B/t = (10.00 \text{ in.}/0.375 \text{ in.}) = 26.7 \le 30$ **o.k.**

$H/t = (10.00 \text{ in.}/0.375 \text{ in.}) = 26.7 \le 35$ **o.k.**

For tension branch 2, $B_b/t_b = H_b/t_b = (5.00 \text{ in.}/0.313\text{in.}) = 16.0 \le 35$ **o.k.**

For compression branch 1, $B_b/t_b = H_b/t_b = (5.00 \text{ in.}/0.313\text{in.}) = 16.0 \le 1.1\ (E/F_{yb})^{0.5} = 26.5$ **o.k.**

For compression branch 3, $B_b/t_b = H_b/t_b = (4.00 \text{ in.}/0.250\text{in.}) = 16.0 \le 1.1\ (E/F_{yb})^{0.5} = 26.5$ **o.k.**

For branches 1 and 2, $B_b/B = H_b/B = (5.00 \text{ in.}/10.00 \text{ in.}) = 0.50 \ge 0.25$ **o.k.**

For branch 3, $B_b/B = H_b/B = (4.00 \text{ in.}/10.00 \text{ in.}) = 0.40 \ge 0.25$ **o.k.**

$0.5 \le H_b/B_b = (5.00 \text{ in.}/5.00 \text{ in.})$ or $(4.00 \text{ in.}/4.00 \text{ in.}) = 1.00 \le 2.0$ **o.k.**

$0.5 \le H/B = (10.00 \text{ in.}/10.00 \text{ in.}) = 1.00 \le 2.0$ **o.k.**

Between branches 1 and 2 only, $25\% \le O_v = 50\% \le 100\%$ **o.k.**

Between branch 3 and the two diagonal branches, $25\% \le O_v = 100\% \le 100\%$ **o.k.**

Between branches 1 and 2, $B_{bi}/B_{bj} = (5.00 \text{ in.}/5.00 \text{ in.}) = 1.00 \ge 0.75$ **o.k.**

Between branches 3 and 1, or branches 3 and 2, $B_{bi}/B_{bj} = (4.00 \text{ in.}/5.00 \text{ in.}) = 0.80 \ge 0.75$ **o.k.**

Between branches 1 and 2, $t_{bi}/t_{bj} = (0.313 \text{ in.}/0.313 \text{ in.}) = 1.00 \le 1.00$ **o.k.**

Between branches 3 and 1, or branches 3 and 2, $t_{bi}/t_{bj} = (0.250 \text{ in.}/0.313 \text{ in.}) = 0.80 \le 1.00$ **o.k.**

$F_y = F_{yb} = 50 \text{ ksi} \le 52 \text{ ksi}$ **o.k.**

$F_y/F_u = F_{yb}/F_{ub} = (50 \text{ ksi}/65 \text{ ksi}) = 0.77 \le 0.8$ **o.k.**

Calculate the required strength.

From Chapter 2 of ASCE 7, the required connection strength, expressed as a force in each branch is:

LRFD	ASD
$P_{r1} = 1.2(20 \text{ kips}) + 1.6(60\text{kips}) = 120 \text{ kips}$	$P_{r1} = 20 \text{ kips} + 60 \text{ kips} = 80 \text{ kips}$
$P_{r2} = 1.2(31.6 \text{ kips}) + 1.6(94.6\text{kips}) = 189 \text{ kips}$	$P_{r2} = 31.6 \text{ kips} + 94.6 \text{ kips} = 126 \text{ kips}$
$P_{r3} = 1.2(10 \text{ kips}) + 1.6(30\text{kips}) = 60 \text{ kips}$	$P_{r3} = 10 \text{ kips} + 30 \text{ kips} = 40 \text{ kips}$

Check the limit state of branch local yielding due to uneven load distribution (per Specification *Section K2, Table K2.2, with appropriate modifications where necessary to account for the actual overlapping of branch member walls).*

For branch 3 (which overlaps onto both branches 1 and 2), both transverse faces are represented by b_{eov} terms because both are welded to overlapped branches and not to the chord. Hence, Equation K2-19 of the *Specification* for overlapped K connections needs to be modified to:

$$P_{n,i} = F_{ybi}\, t_{bi}\, (2H_{bi} - 4t_{bi} + 2b_{eov}) \tag{2}$$

where

$$b_{eov} = [10/(B_{bj}/t_{bj})][F_{ybj}t_{bj}/(F_{ybi}t_{bi})]B_{bi} \le B_{bi} \qquad (Spec.\ \text{Eq. K2-21})$$

and the subscript i refers to the overlapping branch 3 and the subscript j refers to the overlapped branch 1 or 2.

Thus,

$$b_{eov} = [10/(5.00 \text{ in.}/0.313 \text{ in.})][(50 \text{ ksi})(0.313. \text{ in.})/(50 \text{ ksi})(0.250 \text{ in.})](4.00 \text{ in.}) \le 4.00 \text{ in.}$$
$$= 3.14 \text{ in.} \le 4.00 \text{ in.}$$

and

$$P_{n3} = (50 \text{ ksi})(0.250 \text{ in.})[2(4.00 \text{ in.}) - 4(0.250 \text{ in.}) + 2(3.14 \text{ in.})]$$
$$= 166 \text{ kips} < \text{yield strength of branch} = (A_{b3}F_{yb3}) = (3.60 \text{ in.}^2)(50 \text{ ksi}) = 180 \text{ kips}$$

LRFD	ASD
$\phi = 0.95$	$\Omega = 1.58$
$\phi P_{n3} = 0.95(166 \text{ kips}) = 158 \text{ kips}$	$P_{n3}/\Omega = 166 \text{ kips}/1.58 = 105 \text{ kips}$
$P_{r3} = 60 \text{ kips} < \phi P_{n3}$ **o.k.**	$P_{r3} = 40 \text{ kips} < P_{n3}/\Omega$ **o.k.**

For branch 1, checking can be performed as an overlapped K connection with branch 1 overlapping branch 2.

Thus, because $O_v = 50\%$, and one transverse face of the overlapping branch is welded to the chord,

$$P_{n,i} = F_{ybi}\, t_{bi}\, (2H_{bi} - 4t_{bi} + b_{eoi} + b_{eov}) \qquad (\textit{Spec}. \text{ Eq. K2-18})$$

where

$$b_{eoi} = [10/(B/t)][F_y t/(F_{ybi}t_{bi})]B_{bi} \le B_{bi} \qquad (\textit{Spec}. \text{ Eq. K2-20})$$
$$= [10/(10 \text{ in.}/0.375 \text{ in.})][(50 \text{ ksi})(0.375 \text{ in.})/(50 \text{ ksi})(0.313 \text{ in.})](5.00 \text{ in.}) \le 5.00 \text{ in.}$$
$$= 2.25 \text{ in.} \le 5.00 \text{ in.}$$

and

$$b_{eov} = [10/(B_{bj}/t_{bj})][F_{ybj}t_{bj}/(F_{ybi}t_{bi})]B_{bi} \le B_{bi} \qquad (\textit{Spec}. \text{ Eq. K2-21})$$
$$= [10/(5.00 \text{ in.}/0.313 \text{ in.})][(50 \text{ ksi})(0.313 \text{ in.})/(50 \text{ ksi})(0.313 \text{ in.})](5.00 \text{ in.}) \le 5.00 \text{ in.}$$
$$= 3.13 \text{ in.} \le 5.00 \text{ in.}$$

Hence,

$$P_{n1} = (50 \text{ ksi})(0.313 \text{ in.})[2(5.00 \text{ in.}) - 4(0.313 \text{ in.}) + 2.25 \text{ in.} + 3.13 \text{ in.}] = 221 \text{ kips}$$
$$< \text{yield strength of branch} = (A_{b1}\, F_{yb1}) = (5.61 \text{ in.}^2)(50 \text{ ksi}) = 281 \text{ kips}$$

LRFD	ASD
$\phi = 0.95$	$\Omega = 1.58$
$\phi P_{n1} = 0.95(221 \text{ kips}) = 210 \text{ kips}$	$P_{n1}/\Omega = 221 \text{ kips}/1.58 = 140 \text{ kips}$
$P_{r1} = 120 \text{ kips} < \phi P_{n1}$ **o.k.**	$P_{r1} = 80 \text{ kips} < P_{n1}/\Omega$ **o.k.**

For branch 2, which is an overlapped member, the nominal available axial strength of this branch—as a proportion of its yield strength—is not to exceed the nominal available axial strength of the overlapping branch, as a proportion of its yield strength, which is the basis of the *Specification* Equation K2-22.

Thus, for two overlapping branches, $P_{n2}/(A_{b2}\,F_{y2}) \le P_{n1}/(A_{b1}\,F_{y1})$ and $P_{n3}/(A_{b3}\,F_{y3})$, i.e.,

$P_{n2}/(5.61\text{ in.}^2)(50\text{ ksi}) \le (221\text{ kips})/(281\text{ kips})$ and $(166\text{ kips})/(180\text{ kips})$

Hence,

$P_{n2} = 220$ kips

LRFD	ASD
$\phi = 0.95$	$\Omega = 1.58$
$\phi P_{n2} = 0.95(220\text{ kips}) = 209$ kips	$P_{n2}/\Omega = 220\text{ kips}/1.58 = 139$ kips
$P_{r2} = 189\text{ kips} < \phi P_{n2}$ **o.k.**	$P_{r2} = 126\text{ kips} < P_{n2}/\Omega$ **o.k.**

SYMBOLS

A Gross cross-sectional area of chord member, in.

A_b Gross cross-sectional area of branch member, in.

B Overall width of rectangular HSS chord member, measured 90 degrees to the plane of the connection, in.

B_b Overall width of rectangular HSS branch member, measured 90 degrees to the plane of the connection, in.

B_{bi} Overall width of the rectangular HSS overlapping branch member, in.

B_{bj} Overall width of the rectangular HSS overlapped branch member, in.

D Outside diameter of round HSS chord member, in.

D_b Outside diameter of round HSS branch member, in.

$D_{b\,comp}$ Outside diameter of round HSS compression branch member, in.

E Modulus of elasticity of steel, 29,000 ksi

F_u Tensile strength of the HSS chord member material, ksi

F_{ub} Tensile strength of the HSS branch member material, ksi

F_y Yield strength of the HSS chord member material, ksi

F_{yb} Yield strength of the HSS branch member material, ksi

H Overall height of rectangular HSS chord member, measured in the plane of the connection, in.

H_b Overall height of rectangular HSS branch member, measured in the plane of the connection, in.

O_v $l_{ov}/l_p \times 100$, %

P Axial force in branch, kips

P_n Nominal available axial strength of connection, expressed as a force in a branch, kips

P_r Required axial strength of connection, expressed as a force in a branch, kips

b_{eoi} Effective width of the rectangular HSS overlapping branch transverse face welded to the chord, in.

b_{eov} Effective width of the rectangular HSS overlapping branch transverse face welded to an overlapped branch, in.

g Gap between toes of branch members in a gapped K-connection, neglecting the welds, in. (negative g = l_{ov} in an overlapped K-connection)

l_{ov} Overlap length measured along the connecting face of the chord beneath two overlapping branches, in.

l_p Projected length of the overlapping branch on the chord connecting face, in.

t Design wall thickness of HSS chord member, in.

t_b Design wall thickness of HSS branch member, in.

Ω Safety factor

β_{eff} Effective width ratio = $\left[(B_b + H_b)_{branch\ 1} + (B_b + H_b)_{branch\ 2}\right]/4B$, for two branches

θ Acute angle between the branch and chord, degrees

ϕ Resistance factor

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