Geometric Formulas for Gusset Plate Design

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The Whitmore area is commonly employed to determine the yield and buckling resistances of a gusset plate. The Whitmore area is the product of the Whitmore width, L_w, shown in Figure 1, and the thickness of the gusset plate, t_p. If the Whitmore width extends beyond the borders of the gusset plate, the design resistance area for yielding and buckling needs to be revised. Hence, the lengths, y_c (Figure 2a) or y_{cf} (Figure 2b) and y_b (Figure 2a) or y_{bf} (Figure 2b), must be determined. The buckling resistance of gusset plates of test specimens has been conservatively determined using what shall be referred to herein as the "pseudo-column" approach. The pseudo-column approach has also been referred to as "the equivalent strip method" and the "Thornton method" in the literature. The pseudo-column approach utilizes global buckling stress formulas for columns, the Whitmore area, and several pseudo-column lengths and effective length factors. The average of the lengths shown in Figure 3, [in other words, avg(L_1, L_2, L_3)], the maximum of the lengths, [in other words, max(L_1, L_2, L_3)], or L_2 have been used as pseudo-column lengths. A variety of effective column length factors have been used, ranging from 0.5 to 1.2. The accuracy of this method has proven to be variable when compared to test results, regardless of the pseudo-column length and effective length factor chosen. However, this method has been consistently conservative and has therefore been adopted by industry (Thornton, 1984; Chakrabarti, 1987; Yam and Cheng, 1993; Hu and Cheng, 1987; Rabinovitch, 1993; Walbridge, Grondin, and Chen, 1998; Nast, Grondin, and Cheng, 1999; Dowswell and Barber, 2004). In practice, the lengths, y_c, y_{cf}, y_b, y_{bf}, L_1, L_2, and L_3 are obtained by either drawing the details of the gusset plate to scale and drafting the Whitmore width, drafting the corresponding pseudo-columns, and requesting

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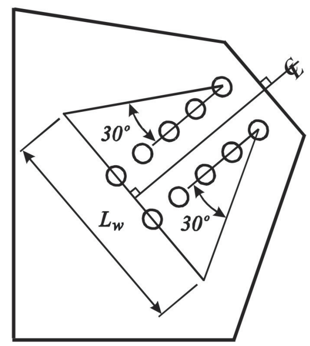

Fig. 1. Whitmore width [adapted from Fig. 9–1 of the Steel Construction Manual (AISC, 2005)].

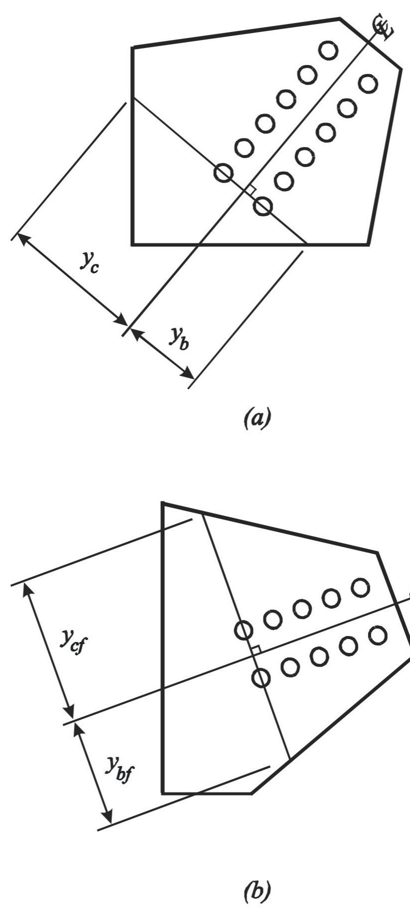

Fig. 2. Lengths needed to determine if Whitmore width extends beyond gusset plate borders.

the digitized distance between pertinent points on the drawing; or by utilizing in-house computer programs, which are essentially black boxes that perform numerical calculations based on the geometry of the gusset plate. For the first time, this paper presents the derivation of the formulas for y_c, y_{cf}, y_b, y_{bf}, L_1, L_2, and L_3 for braces connected to orthogonal beams and columns and then expands them to nonorthogonal connections. Finally, the formulas are validated.

GUSSET PLATE GEOMETRY

Figure 4 presents geometric notation applied herein for a gusset plate used to connect two orthogonal members to a brace. For notation purposes, one member is referred to as "beam" and the other as "column." The positive sense of angles θ_B, θ_b, and θ_c are shown in Figure 4. The angles θ_B and θ_b are measured from a horizontal line, and the angle θ_c is measured from a vertical line. The possible ranges of the angles are

$$0 < \theta_B < 90 \tag{1}$$

$$-\theta_B \le \theta_b \le 90 - \theta_B \tag{2}$$

$$-\theta_B \le \theta_c \le 90 - \theta_B \tag{3}$$

Table 1 presents formulas for the basic dimensions shown in Figures 1, and 5 through 7. These dimensions are needed to determine y_c, y_{cf}, y_b, y_{bf}, L_1, L_2, and/or L_3. Note that only the bolt rows farthest from the corner edge of the gusset plate are shown in Figures 5 through 7. The formulas presented in this paper are only applicable to a brace angle, θ_B, equivalent to the formula shown in Table 1. The dimension c, shown in Figures 5 through 7, must also be equivalent to the value shown in Table 1. That is, the corner edge of the gusset plate must be symmetric about and perpendicular to the centerline of the bolt group. The above gusset plate geometric requirements are generally true in practice. However, the comprehensiveness of the derivation provided in this paper allows for easy adaptation to gusset plate geometries not considered here.

Whitmore Width beyond Gusset Plate Borders

From Figures 1 and 4 it can be seen that the Whitmore width, L_w, is equivalent to that value given in Table 1. To determine if the Whitmore width is contained within the gusset plate, the lengths, y_c or y_{cf} and y_b or y_{bf} (Figure 2), must be known. A differentiation between y_c and y_{cf} and between y_b and y_{bf} has been established because any portion of the Whitmore area extending beyond a free edge is commonly deducted from the Whitmore area. On the other hand, when any portion of the Whitmore area extends into the beam and/or column, Thornton and Kane recommend computing the Whitmore width using a weighted Whitmore width based on the relative tF_y of the gusset plate and the beam and/or column, where t is the thickness of the gusset plate, beam web, or column web, and F_y is the minimum specified yield strength of the materials (from Chapter 2 of Tamboli, 1999). Williams and Richard (1986) also offer a conservative block shear resistance equation that is equivalent to a Whitmore yield resistance, that is:

$$\begin{aligned} & t\left[2\left(L+L_e\right)0.6F_y + sF_y\right] \\ & \approx t\left[2L\left(\tan 30\right)F_y + sF_y\right] = tL_wF_y \end{aligned} \tag{4}$$

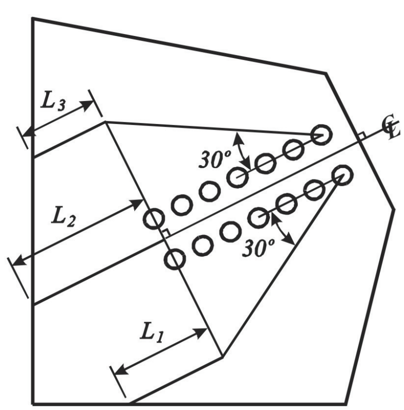

Fig. 3. Pseudo-column lengths.

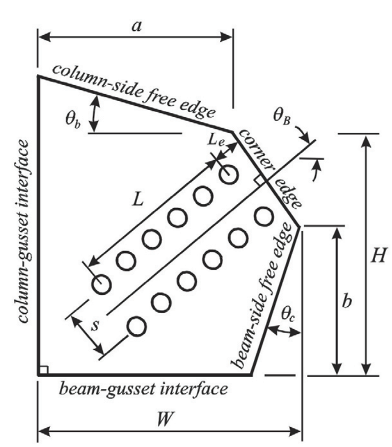

Fig. 4. Gusset plate geometric notation.

Table 1. Basic Geometric Formulas

Parameter	Equation	Parameter	Equation
c	$\frac{1}{2}\sqrt{(W-a)^2+(H-b)^2}$	m	$\frac{b(\cos\theta_B)+2c+g}{\sin\theta_B}$
d	$\sqrt{L_{Le}{}^2+c^2}$	n	$\frac{b(\cos\theta_B)-g}{\sin\theta_B}$
e	$d\frac{\sin\phi}{\sin(\theta_B+\theta_c)}$	L_w	$2L\tan 30+s$
f	$d\frac{\sin\phi}{\cos(\theta_B+\theta_b)}$	L_{Le}	$L_{Le}=L+L_e$
g	$\frac{L_w-2c}{2}$	w	$\frac{b(\cos\theta_B)+c}{\sin\theta_B}$
h	$\frac{a(\sin\theta_B)+c}{\cos\theta_B}$	ϕ	$\cos^{-1}\left(\frac{c}{d}\right)$
j	$\frac{a(\sin\theta_B)+2c+g}{\cos\theta_B}$	θ_B	$\tan^{-1}\left(\frac{W-a}{H-b}\right)$
k	$\frac{a(\sin\theta_B)-g}{\cos\theta_B}$		

Thus, one may reasonably assume that block shear has a lower strength than the Whitmore tension yield load when the Whitmore width extends beyond the gusset plate borders (Williams and Richard, 1986). The buckling resistance should still be considered.

DERIVATION OF FORMULAS

Derivation of y_b, y_{bf}, y_c, and y_{cf}

Referring to Figures 4, 5, and 6 and Table 1, formulas for y_b, y_{bf}, y_c and y_{cf} can be derived as follows:

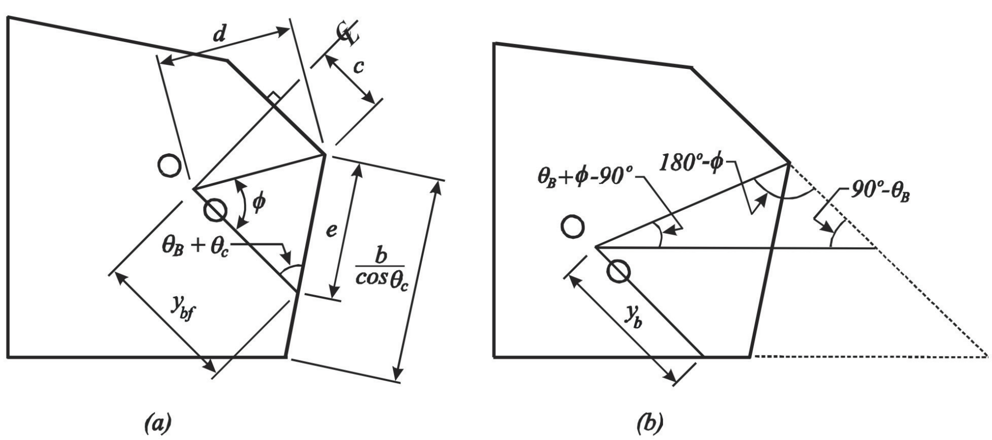

Fig. 5. Parameters needed to determine y_{bf} *and* y_b.

If $e \le b/\cos\theta_c$, the Whitmore width could extend beyond the beam-side free edge, and

$$y_{bf} = d\frac{\sin(\phi + \theta_B + \theta_c)}{\sin(\theta_B + \theta_c)} \tag{5}$$

If $e > b/\cos\theta_c$, the Whitmore width could extend into the beam, and

$$y_b = \frac{b + d\cos(\theta_B + \phi)}{\cos\theta_B} \tag{6}$$

Similarly, for the column side:

$$\text{If } f \le \frac{a}{\cos\theta_b},\ y_{cf} = d\frac{\cos(\theta_B + \theta_b - \phi)}{\cos(\theta_B + \theta_b)} \tag{7}$$

$$\text{If } f > \frac{a}{\cos\theta_b},\ y_c = \frac{a - d\ \sin(\phi - \theta_B)}{\sin\theta_B} \tag{8}$$

Geometric Formulas for Pseudo-Column Lengths

Figure 7 presents the possible termini of pseudo-columns, L_1, L_2, and L_3. The pseudo-column length, L_1, only exists if y_b or y_{bf}, where applicable, is greater than $L_w/2$, and L_3 only exists if y_c or y_{cf}, where applicable, is greater than $L_w/2$. The formulas presented below for L_1 and L_3 are obviously applicable only when they exist.

When $W \le w$, L_2 terminates at the column-gusset interface, and

$$L_2 = \frac{W}{\cos\theta_B} - c\tan\theta_B - L_{Le} \tag{9}$$

$$L_3 = L_2 - \frac{L_w}{2}\tan\theta_B \tag{10}$$

When $W \le w$ and $H \ge j$, L_1 terminates at the column-gusset interface, and

$$L_1 = L_2 + \frac{L_w}{2}\tan\theta_B \tag{11}$$

When $W \le w$ and $H < j$, L_1 terminates at the beam-gusset interface, and

$$L_1 = \frac{b - g(\cos\theta_B)}{\sin\theta_B} - L_{Le} \tag{12}$$

Thus, the pseudo-column buckling lengths for the geometries shown in Figures 7a and 7b have been derived.

When $W > w$, L_2 terminates at the beam-gusset interface, and

$$L_2 = \theta\frac{w}{\cos\theta_B} - c\tan\theta_B - L_{Le} \tag{13}$$

$$L_1 = L_2 - \frac{L_w}{2\tan\theta_B} \tag{14}$$

When $W \ge m$, L_3 terminates at the beam-gusset interface, and

$$L_3 = L_2 + \frac{L_w}{2\tan\theta_B} \tag{15}$$

When $W < m$, L_3 terminates at the column-gusset interface, and

$$L_3 = \frac{a - g(\sin\theta_B)}{\cos\theta_B} - L_{Le} \tag{16}$$

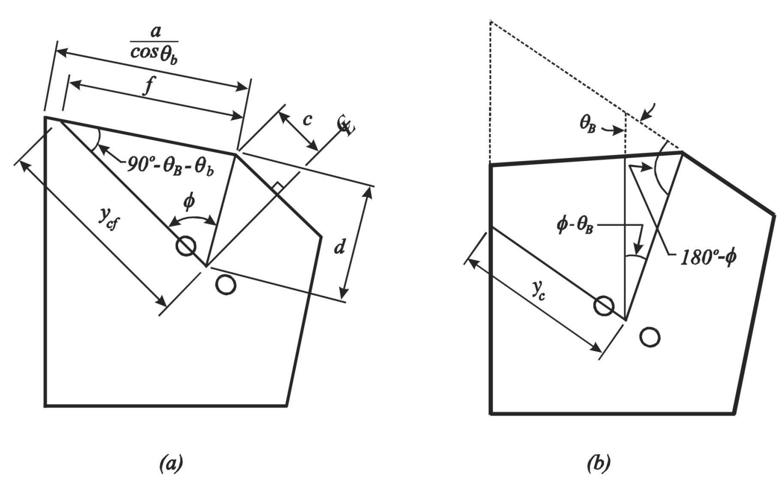

Fig. 6. Parameters needed to determine y_{cf} *and* y_c*.*

Hence, the pseudo-column buckling lengths shown in Figures 7c and 7d have been derived.

Geometric Formulas for Nonorthogonal Column-Gusset and Beam-Gusset Interfaces

The geometric formulas derived above, y_b, y_{bf}, y_c, y_{cf}, L_1, L_2, and L_3, for orthogonal column-gusset and beam-gusset interfaces may be expanded to gusset plate connections for nonorthogonal interfaces by introducing additional terms, θ_{cc} and θ_{bb} (Figure 8), to describe the nonorthogonality of the connection. The positive definitions of θ_{cc} and θ_{bb} are shown in Figure 8, and the limits on these angles are between $-\theta_B$ and 90°.

$$\text{If } e \le \frac{b}{\cos\theta_c} + \frac{\sin\theta_{bb}}{\cos(\theta_{bb}-\theta_c)}(W - b\tan\theta_c),$$

the Whitmore width could extend beyond the beam-side free edge, and y_{bf} is given by Equation 5.

$$\text{If } e > \frac{b}{\cos\theta_c} + \frac{\sin\theta_{bb}}{\cos(\theta_{bb}-\theta_c)}(W - b\tan\theta_c),$$

the Whitmore width could extend into the beam and, after referring to Figures 4, 5, and 8, the expansion of Equation 6 to nonorthogonal interfaces is

$$y_b = \frac{b + d\cos(\theta_B + \phi)}{\cos\theta_B} + \frac{\sin\theta_{bb}}{\cos(\theta_B + \theta_{bb})}\left[W + b(\tan\theta_B) - d\frac{\sin\phi}{\cos\theta_B}\right] \quad (17)$$

$$\text{If } f \le \frac{a}{\cos\theta_b} + \frac{\sin\theta_{cc}}{\cos(\theta_b + \theta_{cc})}(H + a\tan\theta_b),$$

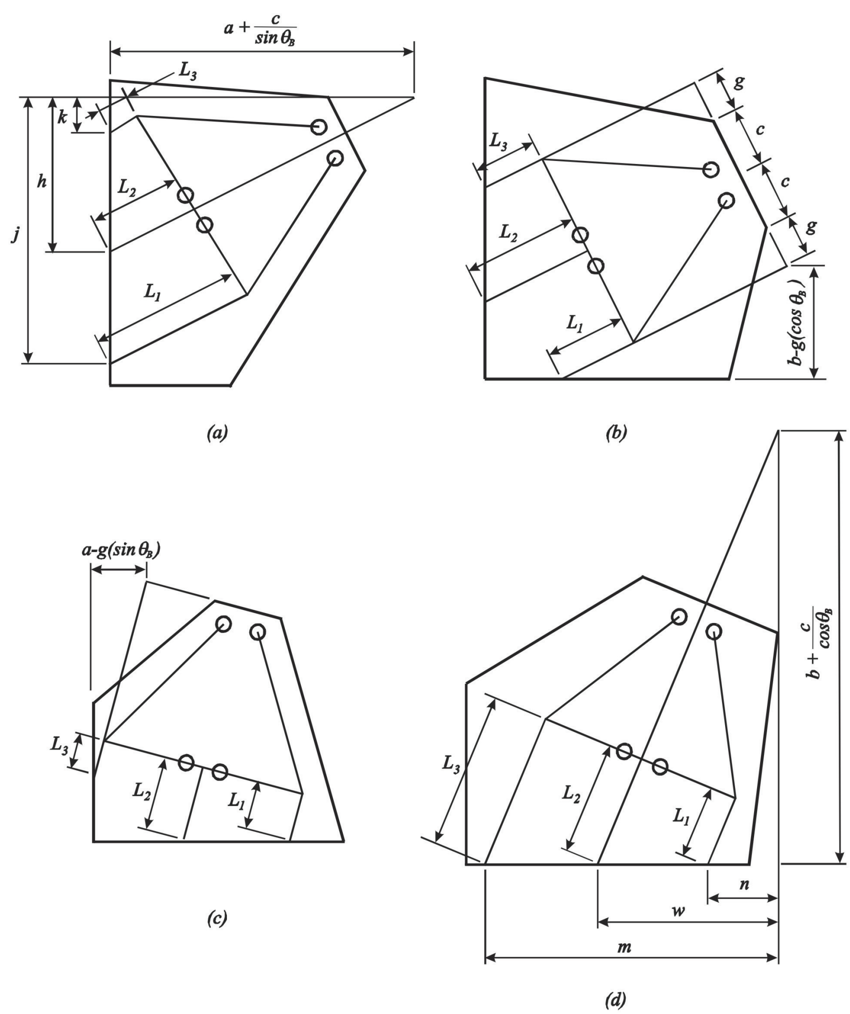

Fig. 7. Pseudo-column lengths.

the Whitmore width could extend beyond the column-side free edge, and y_{cf} is given by Equation 7.

$$\text{If } f > \frac{a}{\cos\theta_b} + \frac{\sin\theta_{cc}}{\cos(\theta_b + \theta_{cc})}(H + a\tan\theta_b),$$

the Whitmore width could extend into the column and, after referring to Figures 4, 6, and 8, the expansion of Equation 8 to nonorthogonal interfaces is

$$y_c = \frac{a - d\sin(\phi - \theta_B)}{\sin\theta_B} + \frac{\sin\theta_{cc}}{\sin(\theta_B - \theta_{cc})}\left(H + \frac{a}{\tan\theta_B} - d\frac{\sin\phi}{\sin\theta_B}\right) \tag{18}$$

The formulas for the pseudo-column lengths of gusset plate connections to nonorthogonal interfaces can be derived by examining Figures 4, 7, and 8, and appending Equations 9 through 16.

When $W \le w$, L_2 terminates at the column-gusset interface, and the expansions of Equations 9 and 10 to nonorthogonal interfaces are

$$L_2 = \frac{W}{\cos\theta_B} + \frac{\sin\theta_{cc}}{\cos(\theta_{cc} - \theta_B)}(H - h) - c\tan\theta_B - L_{Le} \tag{19}$$

$$L_3 = L_2 + \frac{L_w}{2}\left[\frac{\sin\theta_{cc}}{\cos\theta_B\cos(\theta_B - \theta_{cc})} - \tan\theta_B\right] \tag{20}$$

When $W \le w$ and $H \ge j$, L_1 terminates at the column-gusset interface, and the expansion of Equation 11 to nonorthogonal interfaces is

$$L_1 = L_2 + \frac{L_w}{2}\left[\tan\theta_B - \frac{\sin\theta_{cc}}{\cos\theta_B\cos(\theta_B - \theta_{cc})}\right] \tag{21}$$

When $W \le w$ and $H < j$, L_1 terminates at the beam-gusset interface, and the expansion of Equation 12 to non-orthogonal interfaces is

$$L_1 = \frac{b - g(\cos\theta_B)}{\sin\theta_B} + \frac{\sin\theta_{bb}}{\sin(\theta_B + \theta_{bb})}(W - n) - L_{Le} \tag{22}$$

When $W > w$, L_2 terminates at the beam-gusset interface, and the expansions of Equations 13 and 14 to non-orthogonal interfaces are

$$L_2 = \frac{w}{\cos\theta_B} + \frac{\sin\theta_{bb}}{\sin(\theta_{bb} + \theta_B)}(W - w) - c\tan\theta_B - L_{Le} \tag{23}$$

$$L_1 = L_2 + \frac{\sin\theta_{bb}}{\sin(\theta_B + \theta_{bb})}(w - n) - \frac{L_w}{2\tan\theta_B} \tag{24}$$

When $W \ge m$, L_3 terminates at the beam-gusset interface, and the expansion of Equation 15 to non-orthogonal interfaces is

$$L_3 = L_2 + \frac{L_w}{2\tan\theta_B} + \frac{\sin\theta_{bb}}{\sin(\theta_B + \theta_{bb})}(w - m) \tag{25}$$

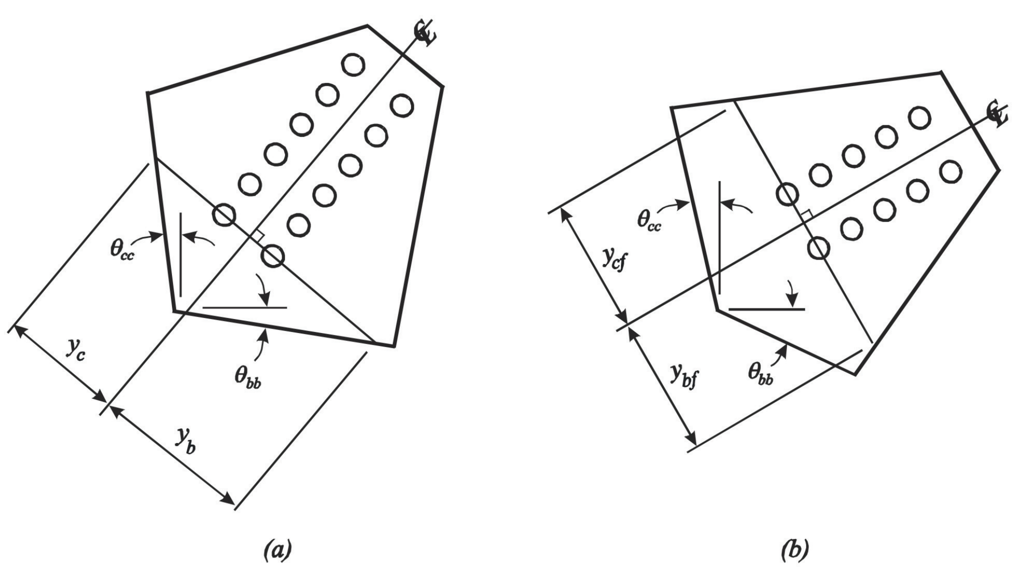

Fig. 8. Gusset plates with non-orthogonal column-gusset and beam-gusset interfaces.

When $W < m$, L_3 terminates at the column-gusset interface, and the expansion of Equation 16 to nonorthogonal interfaces is

$$L_3 = \frac{a - g\sin\theta_B}{\cos\theta_B} - \frac{\sin\theta_{cc}}{\cos(\theta_B - \theta_{cc})}(H - k) - L_{Le} \tag{26}$$

GENERAL ALGORITHM AND VALIDATION

Figure 9 presents the general algorithm to compute y_b, y_{bf}, y_c, y_{cf}, L_1, L_2, and L_3. It is applicable to both orthogonal and nonorthogonal beams and columns. Figure 10 presents the algorithm to compute y_b, y_{bf}, y_c, y_{cf}, L_1, L_2, and L_3 when $\theta_{bb} = \theta_{cc} = 0$. The algorithm was validated for the twelve gusset plates shown in Table 2. The parameters obtained using the algorithm of Figure 9 were compared to the digitized lengths obtained from computer-aided drawing software. In all cases the formulas matched those generated electronically, accurate to 0.001 in.

CONCLUSION

Common approaches to compute the yield and buckling resistances of gusset plates require knowledge of the lengths y_c, y_{cf}, y_b, y_{bf}, L_1, L_2, and L_3, (Figures 2 and 7). While numerical values for these resistances have been presented in the literature, formulas for y_c, y_{cf}, y_b, y_{bf}, L_1, L_2, and L_3 have not been published. This paper presents the derivation and validation of equations to compute these lengths. The equations are summarized in flow charts that can be incorporated into software for practical applications. The formulas provided for y_c, y_{cf}, y_b, y_{bf}, L_1, L_2, and L_3 enable optimization of gusset plate design.

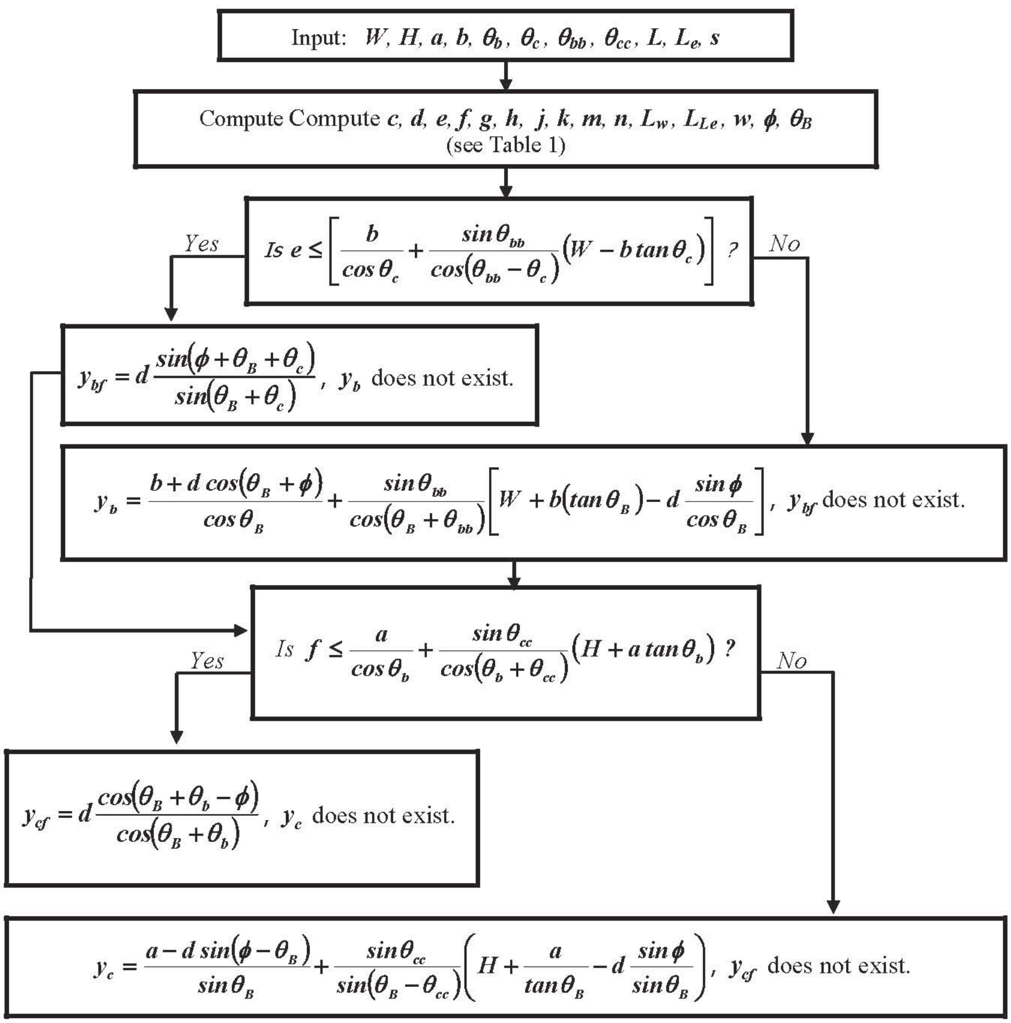

Fig. 9. General algorithm to compute y_c, y_{cf}, y_b, y_{bf}, L_1, L_2, *and* L_3.

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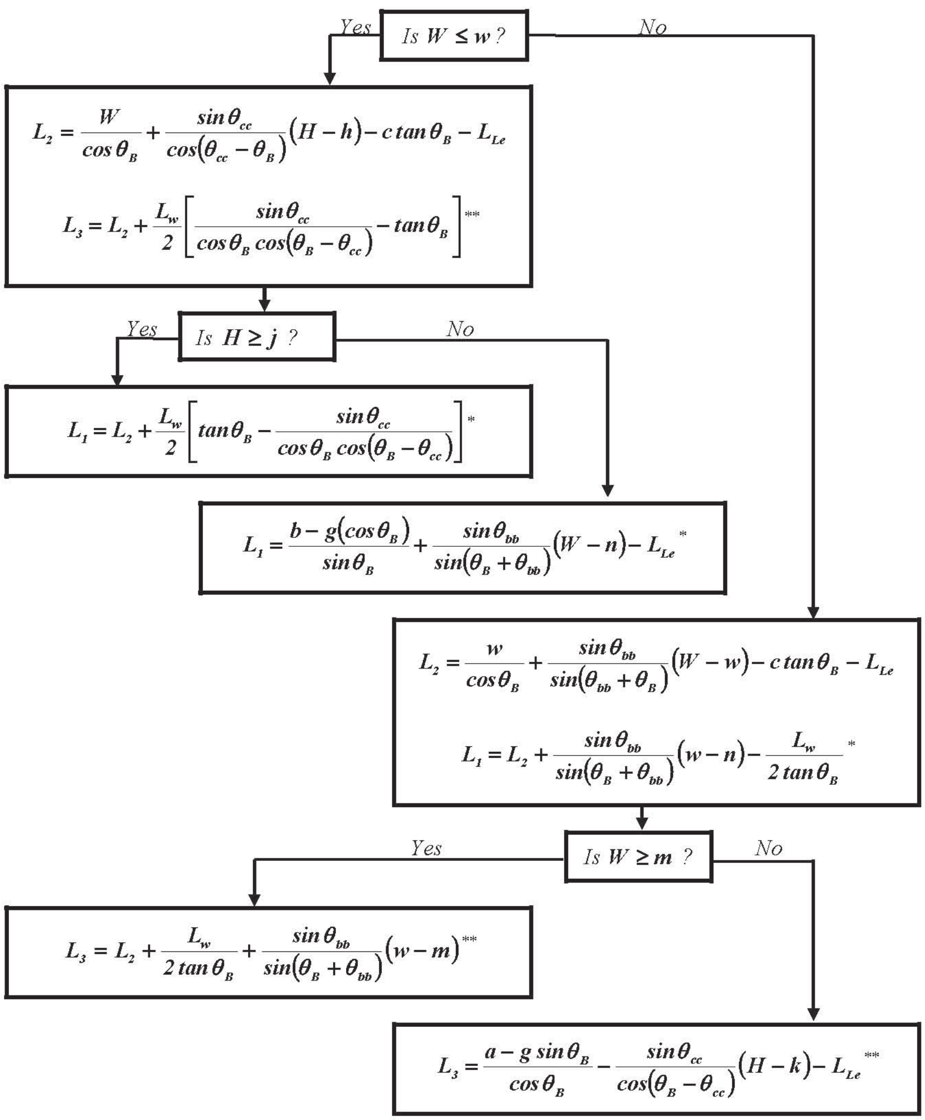

* *If* y_b or $y_{bf} < \frac{L_w}{2}$, L_1 does not exist. ** *If* y_c or $y_{cf} < \frac{L_w}{2}$, L_3 does not exist.

Fig. 9 (cont'd). General algorithm to compute y_c, y_{cf}, y_b, y_{bf}, L_1, L_2, *and* L_3.

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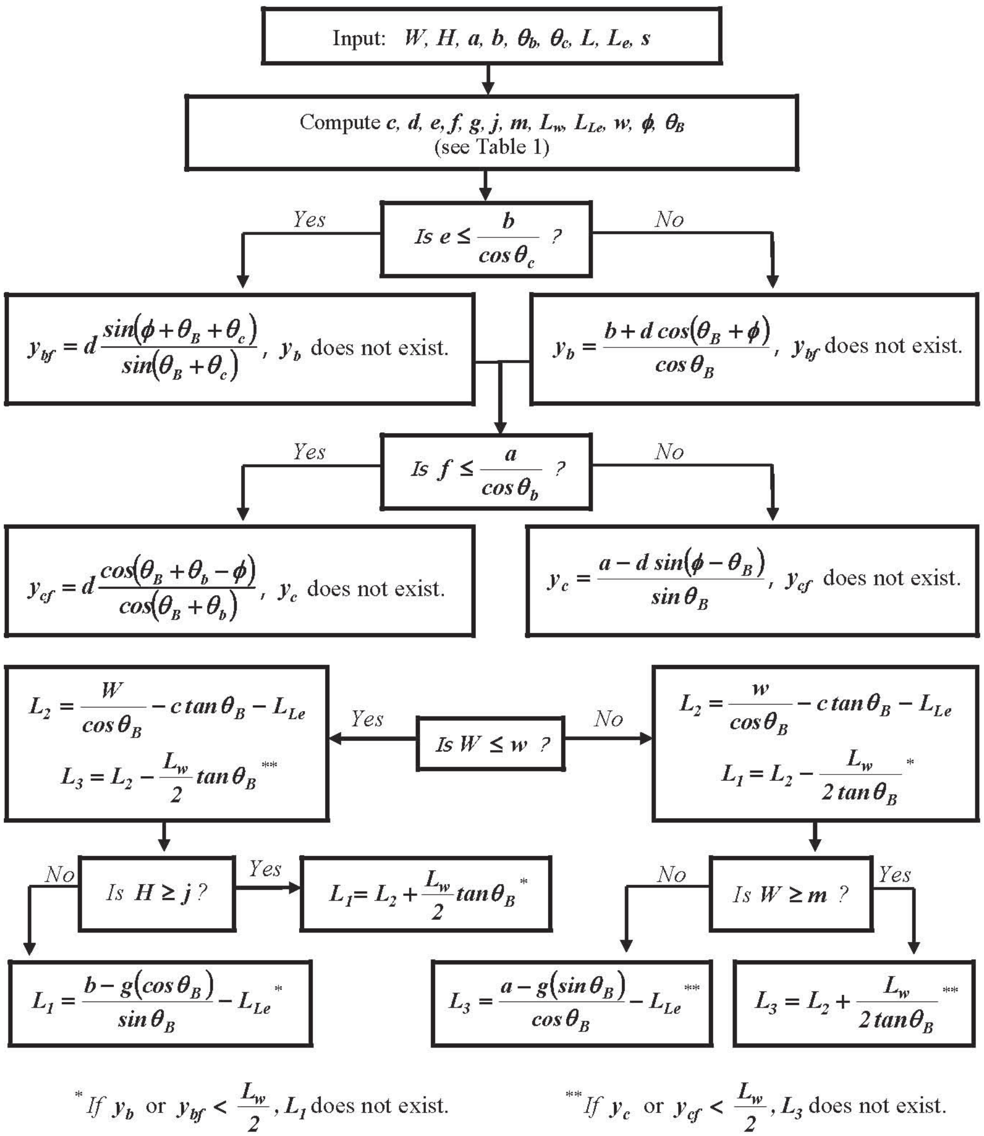
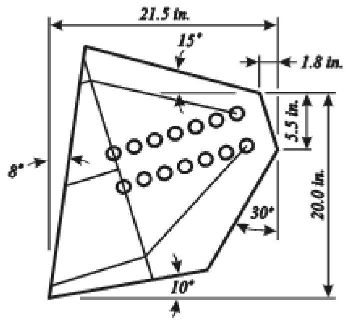
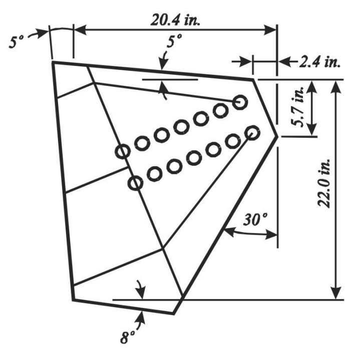
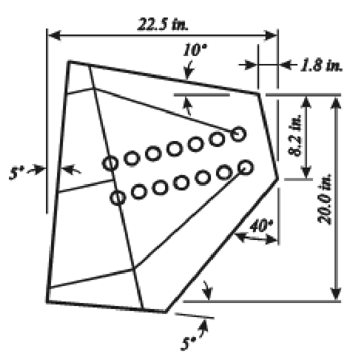


Fig. 10. Algorithm to compute y_c, y_{cf}, y_b, y_{bf}, L_1, L_2, *and* L_3 *when* $\theta_{bb} = \theta_{cc} = 0$.

Table 2. Validation of Formulas[a]			
Ex.	**Gusset Plate**	**Input[b]**	**Output**
1		H = 20.0 W = 21.5 a = 19.7 b = 14.5 θ_b = 15.0 θ_c = 30.0 θ_{bb} = –10.0 θ_{cc} = –8.0	y_b = 11.406 y_c = 10.291 L_1 = 9.462 L_2 = 5.046 L_3 = 0.630
2		H = 22.0 W = 20.4 a = 18.0 b = 16.3 θ_b = 5.0 θ_c = 30.0 θ_{bb} = 8.0 θ_{cc} = 5.0	y_{bf} = 14.464 y_{cf} = 11.012 L_1 = 9.743 L_2 = 6.846 L_3 = 3.948
3		H = 20.0 W = 22.5 a = 20.7 b = 11.8 θ_b = 10.0 θ_c = 40.0 θ_{bb} = 5.0 θ_{cc} = –5.0	y_b = 13.875 y_{cf} = 10.374 L_1 = 8.914 L_2 = 6.095 L_3 = 3.276

[a] All units are in inches (in.) and radians; 1 in. = 25.4 mm.
[b] L = 13 in., L_e = 2 in., and s = 3 in. for all gusset plates.

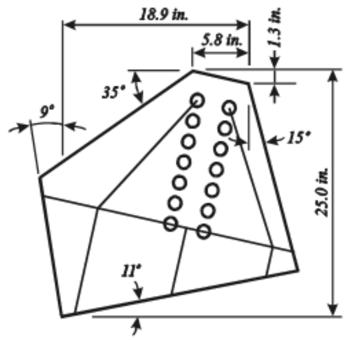
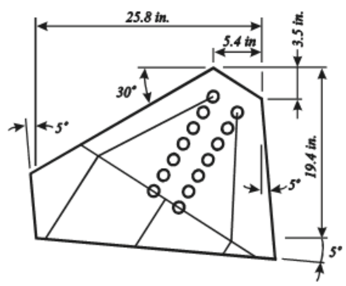
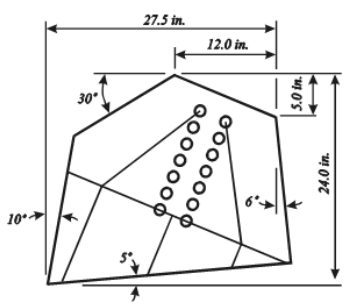
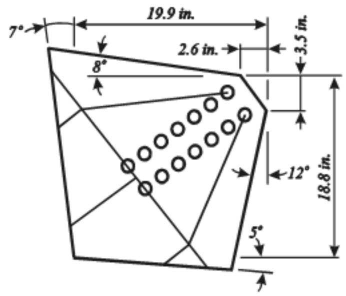
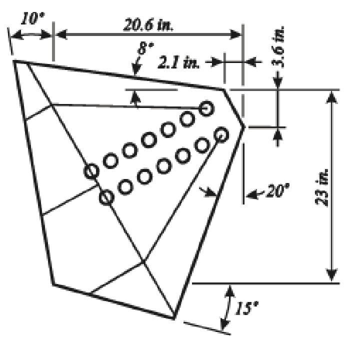
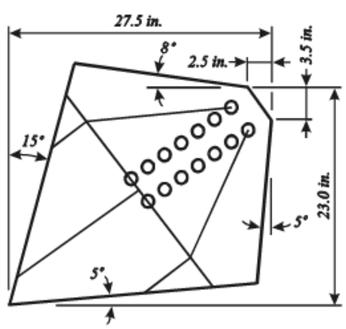
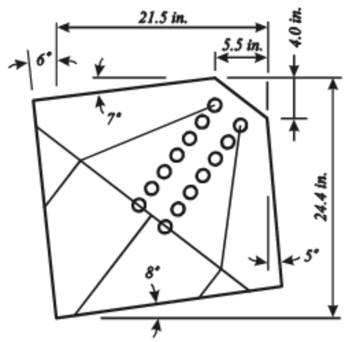
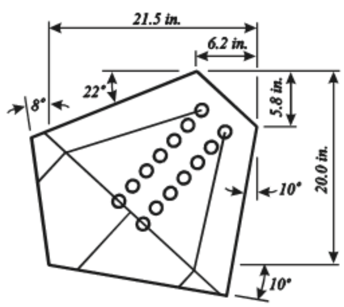
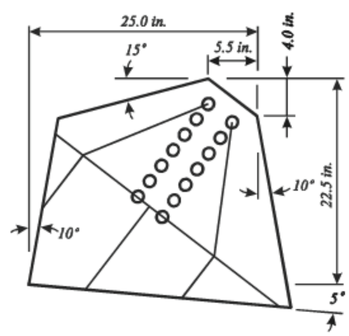
<table>
<tr><th colspan="4">Table 2 (cont'd). Validation of Formulas[a]</th></tr>
<tr><th>Ex.</th><th>Gusset Plate</th><th>Input[b]</th><th>Output</th></tr>
<tr><td>4</td><td>
</td><td>$H = 25.0$
$W = 18.9$
$a = 13.1$
$b = 23.7$
$\theta_b = -35.0$
$\theta_c = -15.0$
$\theta_{bb} = -11.0$
$\theta_{cc} = -9.0$</td><td>$y_{bf} = 10.825$
$y_c = 15.149$
$L_1 = 3.818$
$L_2 = 7.758$
$L_3 = 11.699$</td></tr>
<tr><td>5</td><td>
</td><td>$H = 19.4$
$W = 25.8$
$a = 20.4$
$b = 15.9$
$\theta_b = -30.0$
$\theta_c = -5.0$
$\theta_{bb} = 5.0$
$\theta_{cc} = 5.0$</td><td>$y_b = 13.539$
$y_{cf} = 10.877$
$L_1 = 2.405$
$L_2 = 7.184$
$L_3 = 11.962$</td></tr>
<tr><td>6</td><td>
</td><td>$H = 24.0$
$W = 27.5$
$a = 15.5$
$b = 19.0$
$\theta_b = -30.0$
$\theta_c = -6.0$
$\theta_{bb} = -5.0$
$\theta_{cc} = -10.0$</td><td>$y_b = 13.489$
$y_c = 14.513$
$L_1 = 2.346$
$L_2 = 7.058$
$L_3 = 11.770$</td></tr>
<tr><td colspan="4">[a] All units are in inches (in.) and radians; 1 in. = 25.4 mm.
[b] L = 13 in., L_e = 2 in., and s = 3 in. for all gusset plates.</td></tr>
</table>

Table 2 (cont'd). Validation of Formulas[a]			
Ex.	**Gusset Plate**	**Input[b]**	**Output**
7		H = 18.8 W = 19.9 a = 17.3 b = 15.3 θ_b = 8.0 θ_c = 12.0 θ_{bb} = 5.0 θ_{cc} = 7.0	y_b = 11.563 y_c = 15.176 L_1 = 2.880 L_2 = 8.624 L_3 = 3.506
8		H = 23.0 W = 20.6 a = 18.5 b = 19.4 θ_b = 8.0 θ_c = 20.0 θ_{bb} = 15.0 θ_{cc} = 10.0	y_{bf} = 14.556 y_c = 13.912 L_1 = 12.030 L_2 = 9.446 L_3 = 6.123
9		H = 23.0 W = 27.5 a = 25.0 b = 19.5 θ_b = 8.0 θ_c = 5.0 θ_{bb} = –5.0 θ_{cc} = –15.0	y_b = 13.073 y_c = 13.370 L_1 = 6.895 L_2 = 16.241 L_3 = 5.301

[a]All units are in inches (in.) and radians; 1 in. = 25.4 mm.
[b]L = 13 in., L_e = 2 in., and s = 3 in. for all gusset plates.

<table>
<tr><th colspan="4">Table 2 (cont'd). Validation of Formulas[a]</th></tr>
<tr><th>Ex.</th><th>Gusset Plate</th><th>Input[b]</th><th>Output</th></tr>
<tr><td>10</td><td>
</td><td>$H = 24.4$
$W = 21.5$
$a = 16.0$
$b = 20.4$
$\theta_b = -7.0$
$\theta_c = -5.0$
$\theta_{bb} = -8.0$
$\theta_{cc} = 6.0$</td><td>$y_b = 12.644$
$y_c = 14.736$
$L_1 = 3.517$
$L_2 = 12.222$
$L_3 = 6.358$</td></tr>
<tr><td>11</td><td>
</td><td>$H = 20.0$
$W = 21.5$
$a = 15.3$
$b = 14.2$
$\theta_b = -22.0$
$\theta_c = 10.0$
$\theta_{bb} = 10.0$
$\theta_{cc} = 8.0$</td><td>$y_b = 13.679$
$y_{cf} = 11.211$
$L_1 = 3.045$
$L_2 = 8.914$
$L_3 = 4.205$</td></tr>
<tr><td>12</td><td>
</td><td>$H = 22.5$
$W = 25.0$
$a = 14.5$
$b = 18.5$
$\theta_b = -15.0$
$\theta_c = -10.0$
$\theta_{bb} = 5.0$
$\theta_{cc} = -10.0$</td><td>$y_b = 18.445$
$y_c = 13.099$
$L_1 = 5.678$
$L_2 = 11.095$
$L_3 = 8.382$</td></tr>
<tr><td colspan="4">[a]All units are in inches (in.) and radians; 1 in. = 25.4 mm.
[b]L = 13 in., L_e = 2 in., and s = 3 in. for all gusset plates.</td></tr>
</table>