Design Recommendations for Bolted Rectangular HSS Flange-Plate Connections in Axial Tension

S. WILLIBALD, J.A. PACKER, and R.S. PUTHLI

INTRODUCTION

In recent years the use of closed sections/tubes as structural members has increased significantly. Designers all around the world approve of the advantages that round as well as rectangular hollow structural sections (HSS) can offer, such as uniform strength and stiffness independent of the loading direction, high torsional and buckling strength and the aesthetic appearance. Splicing structural members is a common practice in construction to allow for long spanning trusses, changes in cross sections and transportation to site, to name but a few. Figure 1 shows examples of a bolted flange-plate connection for a rectangular HSS. Although bolting on just two sides of a rectangular hollow section is feasible, most designers prefer the connection to be symmetrical and bolted on all four sides. The most typical loading situation consists of a pure tension load on the member causing prying forces in the connection. The unpredictability of the prying forces is the main obstacle for the use of bolted flange-plate connections. Prying forces occur when deforming end-plates lever against each other. Depending on the flange-plate thickness and the bolt layout, the prying forces can be considerable.

One of the first analytical models describing prying action was developed by Struik and de Back (1969). The prying forces calculated by them were based on an equilibrium analysis of a T-stub connection at different stages of T-stub flange plasticity. Rockey and Griffiths (1970) and Igarashi, Wakiyama, Inoue, Matsumoto, and Murase (1985) subsequently worked on prying models in conjunction with bolted HSS flange-plate connections. That research focussed on flange-plate connections for *circular* hollow sections, for which design recommendations are still evolving (Cao and Packer, 1997). Attention has also expanded to connections for *rectangular* hollow sections, where the initial emphasis was placed on bolt assemblies with bolts on two sides of the hollow section only (Packer and Bruno, 1986; Birkemoe and Packer, 1986; Packer, Bruno, and Birkemoe, 1989). Research on tension-loaded flange-plate connections for square hollow sections with bolts on all four sides has been undertaken by Mang (1980), Kato and Mukai (1982) and Caravaggio (1988).

Recently, the authors have performed an experimental investigation of 16 bolted flange-plate connections for *square* HSS with bolts symmetrically placed on all four sides of the tube. The results of these tests, along with an additional 10 well-documented tests performed internationally, have been compared to existing design models which are mainly derived for connections where the bolts are on two sides of the tube only (Willibald, Packer, and Puthli, 2002). These design models included calculation methods by Packer et al. (1989), Packer, Wardenier, Kuobane, Dutta, and Yeomans (1992) [which is currently also advocated by

S. Willibald is a doctoral candidate, Versuchsanstalt für Stahl, Holz und Steine, University of Karlsruhe, Karlsruhe, Germany, and Research Assistant, Department of Civil Engineering, University of Toronto, Toronto, Ontario, Canada.

J.A. Packer is professor, Department of Civil Engineering, University of Toronto, Toronto, Ontario, Canada.

R.S. Puthli is professor, Versuchsanstalt für Stahl, Holz und Steine, University of Karlsruhe, Karlsruhe, Germany.

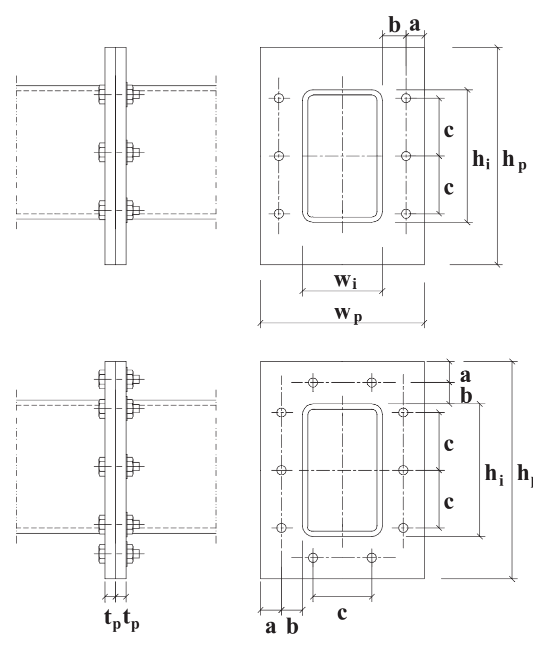

Fig. 1. Typical bolted flange-plate connections for rectangular HSS.

Table 1. Measured Properties of Rectangular HSS Test Specimens

RECTANGULAR SPECIMENS												
Specimen	Tube Properties	n	a (in.)	b (in.)	c (in.)	t_p (in.)	h_p (in.)	w_p (in.)	d' (in.)	F_{yp} (ksi)	F_{up} (ksi)	B_u (kips)
R-1	9.98 x 5.98 x 0.287 in.	10	1.41	1.77	4.31	0.492	16.36	12.33	0.697	55.0[c]	74.8	32.8
R-2	A_i = 8.457 in.^{2} [a]	10	1.42	1.77	4.31	0.624	16.42	12.30	0.695	57.6[c]	74.3	31.7
R-3	F_{yi} = 56.0 ksi [b]	10	1.61	1.56	4.31	0.492	16.43	12.29	0.691	55.0[c]	74.8	32.8
R-4	d = 0.626 in.	10	1.60	1.57	4.32	0.623	16.33	12.36	0.694	57.6[c]	74.3	31.7

[a] Determined by weighing a certain length of HSS and using a known steel density

[b] Determined by tensile coupons from the flat, using the 0.2% offset method, as material was cold-formed

[c] Determined by tensile coupons, using the 0.2% offset method, as material was cold-formed

CIDECT], Kato and Mukai (1982), Timoshenko and Woinowsky-Krieger (1959), as well as AISC (1997). It was found that these 26 tests on *square* HSS flange-plate connections indicated that the equations provided by the AISC HSS Connections Manual (AISC, 1997) were the preferred ones for determining the connection capacity. This, however, was with the provision that one uses the flange-plate width to calculate the bolt pitch. Unfortunately, the AISC HSS Connections Manual (Example 6.6) illustrates the use of p' (see Figure 2) instead of p (see Figure 2) for the bolt pitch in the calculations, but the latter was advocated since it was more accurate. It is worthwhile noting that the use of p' was found to be safe, but excessively conservative, for the 26 *square* HSS flange-plate connections studied (Willibald et al., 2002).

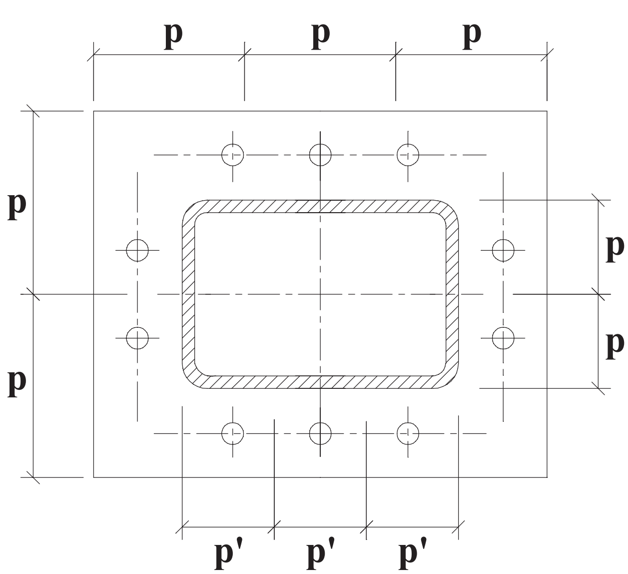

Fig. 2. Bolt pitch definitions.

EXPERIMENTAL PROGRAM ON RECTANGULAR HSS FLANGE-PLATE CONNECTIONS

Scope of Testing

The experimental work consisted of four rectangular HSS flange-plate connection tests. Rectangular ASTM A500 hollow structural sections 10 in. × 6 in. × 5/16 in. with a nominal yield strength of 50 ksi (Grade C) were used throughout. The flange-plate material was grade 44W with a nominal yield strength of 44 ksi. The flange-plate thickness was varied, using 1/2-in. and 5/8-in. plate, while the width and height were kept constant in all four tests (16.4 in. × 12.3 in.). Table 1 shows the measured dimensions and material properties of the four specimens. In each of the four tests 10 ASTM A325 bolts 5/8 in. in diameter were used. Besides changing the flange-plate thicknesses, the ratio of edge distance, a, to distance from bolt line to rectangular hollow section face, b (see Figure 1), was varied in the tests to study the influence of this parameter.

Testing Procedure

All splices were tested in axial tension applied by a 619 kips (2750 kN) capacity MTS Universal testing machine (see Figure 3). The specimens were loaded under displacement control in a quasi-static manner until failure. The testing procedure consisted of two stages. In the first stage the bolts were pretensioned up to 70 percent of their ultimate load, then the specimen was gripped and in the second testing stage the tensile loading was applied to the splice through the tongue plates in the tubes.

Prying action in the specimens can be found by comparing the bolt loads with the applied load of the MTS machine. To study the bolt loads an ultrasonic bolt gage (Bolt Gage 3, Power-Dyne, Bidwell Industrial Group, Inc.) was used. During the tests the loading was stopped at certain load steps and a transducer was placed on each of the

Table 2. Actual and Predicted Failure Loads of Rectangular HSS Specimens

Specimen	Actual strength		CONNECTION STRENGTH AS PREDICTED BY											
			Packer et al. (1989)		Packer et al. (1992)		AISC (1997) $p' = w_i / 2$ $p' = h_i / 3$		AISC (1997) $p = w_{p/} 2$ $p = h_p / 3$		AISC (1997) $p' = 2(h_i + w_i)/n$		AISC (1997) $p = 2(h_p + w_p)/n$	
	R_{ux} (kips)	β_{ux} (%)	$R_u{}^b$ (kips)	R_{ux}/R_u	$R_u{}^b$ (kips)	R_{ux}/R_u	$R_u{}^b$ (kips)	R_{ux}/R_u	$R_u{}^b$ (kips)	R_{ux}/R_u	$R_u{}^b$ (kips)	R_{ux}/R_u	$R_u{}^b$ (kips)	R_{ux}/R_u
R-1 S[a]	231.8	41.7	171	1.36	225	1.03	126	1.84	245	0.95	135	1.71	240	0.96
R-1 L[a]			184	1.26	203	1.14	142	1.63	237	0.98				
R-2 S[a]	259.5	22.2	185	1.40	260	1.00	210	1.23	284	0.91	226	1.15	277	0.94
R-2 L[a]			205	1.27	249	1.04	233	1.12	272	0.96				
R-3 S[a]	248.7	32.1	190	1.31	244	1.02	147	1.69	266	0.93	158	1.57	262	0.95
R-3 L[a]			204	1.22	232	1.07	165	1.50	259	0.96				
R-4 S[a]	279.0	13.6	203	1.38	279	1.00	243	1.15	304	0.92	249	1.12	296	0.94
R-4 L[a]			222	1.26	266	1.05	252	1.11	290	0.96				
Mean of governing S or L values	-	-	-	1.36	-	1.08	-	1.48	-	0.96	-	1.39	-	0.95
Coefficient of Variation (%)	-	-	-	2.6	-	3.7	-	19.9	-	0.8	-	27.4	-	0.7

[a]S and L refer to the calculations being performed for the short side of the HSS/plate only (S) or the long side of the HSS/plate only (L)

[b]R_u values calculated with all resistance factors (ϕ) removed

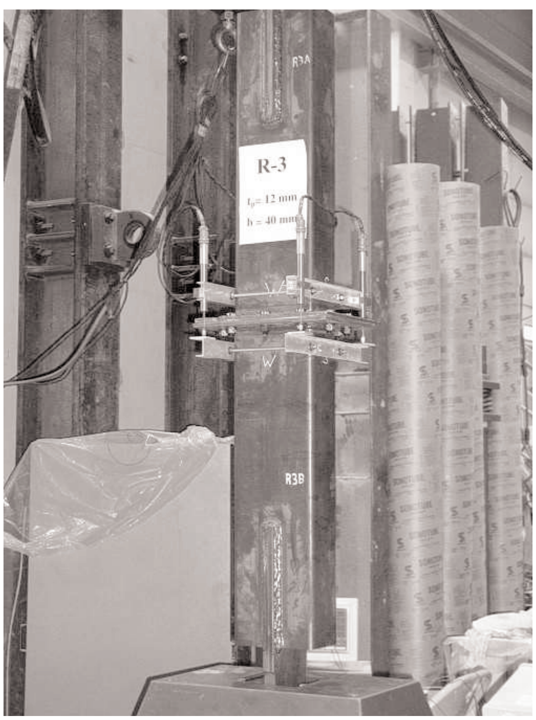

Fig. 3. Typical specimen in testing machine.

bolts. The transducer emits a shock wave that travels along the bolt axis and thereby measures the bolt length. With the knowledge of the force-elongation relationship (see Figure 4) the exact bolt forces were known at any time during the test. Before the actual tests the bolt gage was calibrated by tension tests on individual bolts. The overall connection elongation was measured over a distance of 4.88 in. + $2t_p$ by LVDTs which were mounted on all four sides of the connection.

Discussion of Test Results

Table 2 shows the test results and the respective prying ratios for the rectangular HSS specimens. The prying ratio bux is calculated as follows:

$$\beta_{ux} = \frac{Q_{ux}}{R_{ux}} = \frac{\sum B_u - R_{ux}}{R_{ux}} \tag{1}$$

All specimens of the test program failed by some or all of the bolts breaking. The prying action ranged between 13.6 and 41.7 percent. Despite the significant prying ratios in the four specimens no significant visible separation of the flange-plates along the edges of the connection could be reported. Yet, the bending in the unbroken bolts (see Figure 5) suggests deformation of the flange-plates. The position of each bolt within the bolt layout (i.e. whether at a middle or corner location) did not have an influence on the load distribution for the individual bolt (see Figure 6). However, one should note that all the bolts were located within the width or height of the HSS member, which was found to be the preferred bolting arrangement in previous research (Willibald et al., 2002).

Figure 7 shows the influence of the bolt layout and flange-plate thickness on the prying action. The flange-plate thickness is the main influencing parameter. As the flange-plate thickness increases, the flexural strength of the flange-plates increases accordingly, which lessens the prying effect and thus increases the connection capacity. Another important factor is the ratio of edge distance, *a*, to distance from bolt line to tube face, *b*. It is confirmed that a higher *a/b*-ratio results in a lower prying ratio (see Figure 7), as is expected from traditional two-dimensional prying models developed for T-stubs (Struik and de Back, 1969), however previous researchers have found that there is no advantage (in decreased prying) for *a/b* > 1.25.

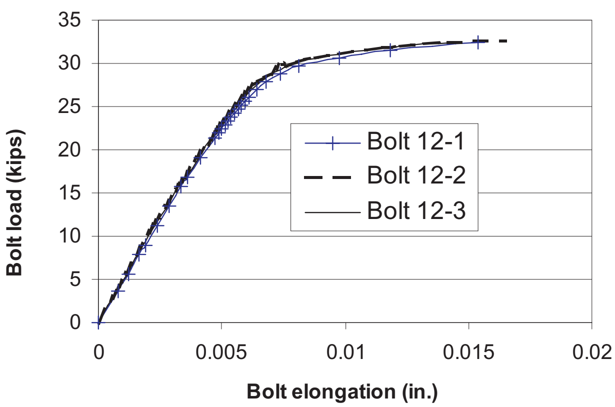

Fig. 4. Bolt gage calibration curve.

Fig. 5. Bending in a typical (unbroken) bolt after testing of a connection.

HISTORY AND OVERVIEW OF DESIGN METHODS FOR BOLTED RECTANGULAR HSS FLANGE-PLATE CONNECTIONS

One of the first simple models to describe prying action was produced by Struik and de Back (1969), analyzing a T-stub connection at different stages of T-stub flange plasticity. The yield lines in their design model are parallel to the web and the bolt line, forming a two-dimensional yield line pat-

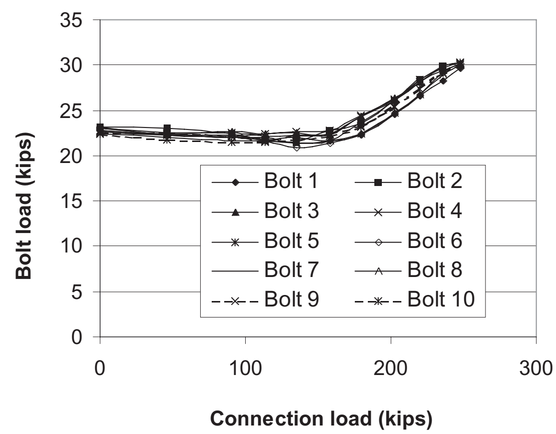

Fig. 6. Bolt loads during testing of connection R-4.

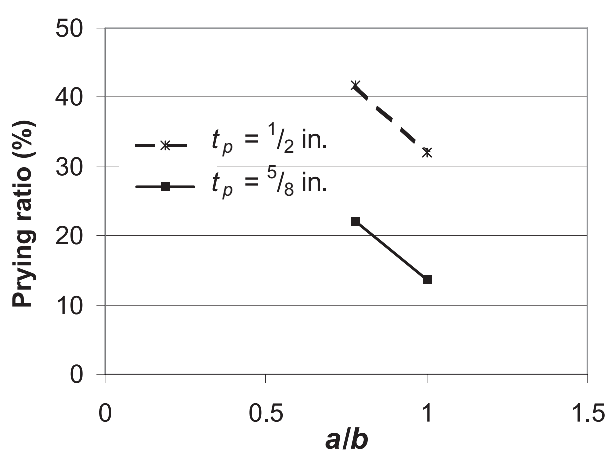

Fig. 7. Influence of the bolt layout and the flange-plate thickness on the prying ratio.

tern. Based on the traditional prying action model of the T-stub connection, Birkemoe and Packer (1986) and later Packer et al. (1989) established a theoretical model for flange-plate connections bolted along just *two* sides of a hollow section. In contrast to the early general model (for a T-stub), the location of the inner plastic hinge was not fixed at the hollow section outer wall but could form anywhere within the width of the tube. Unfortunately, some of their postulated limit states could not be verified in tests. Generally, the design equations of this method require considerable effort and an easier approach for calculating prying action for bolted rectangular HSS flange-plate connections having bolts along *two* sides of the hollow section was sought.

The latest pertinent design guides on tubular structures provided by CIDECT (Packer et al., 1992) and the Canadian Institute of Steel Construction (Packer and Henderson, 1997) possess formulas that are also based on the model of Struik and de Back (1969). The location of the inner plastic hinge is fixed at the inside wall of the hollow section and a resistance factor ϕ_p is introduced (with ϕ_p taken as 0.9) when calculating the required flange-plate thickness for limit states design (LRFD). Table 2 shows the load predictions of the methods that were originally derived for connections with bolts on two sides only but can also be applied to the current experimental program. The model by Packer et al. (1992) agrees well with the test results (see Table 2 and Figure 8) while the earlier model (Packer et al., 1989) gives less favorable results. The best agreement between connection strength predictions and the test results of this study can be found for the design method of the AISC HSS Connections Manual (AISC, 1997). This is consistent with the results of a study on bolted flange-plate connections for square HSS with bolts on all four sides (Willibald et al., 2002).

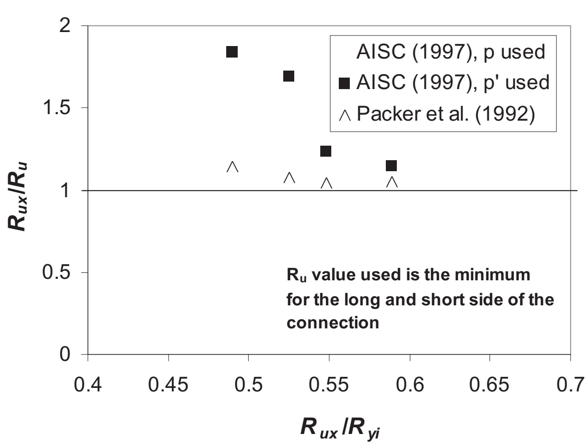

Fig. 8. Comparison between selected calculation methods.

The AISC HSS Connections Manual (1997) extends the applicability of their design procedure to square and rectangular hollow section connections bolted along all *four* sides. The equations in the AISC HSS Connections Manual (1997) are also derived from the original T-stub model by Struik and de Back (1969) and will be discussed in detail in the following section.

Contrary to the two-dimensional yield line approach (linear yield lines all parallel to the face of the HSS) Kato and Mukai (1982) developed an analytical model based on a three dimensional yield line pattern. The method generally gives good agreement to test data for bolted flange-plate connections for square HSS (Willibald et al., 2002). Unfortunately, their model covers only two different bolt layouts (four and eight bolts) and does not include rectangular HSS flange-plate connections. Moreover, due to the high number and unwieldy nature of their design formulas it does not seem advisable to extend their three-dimensional yield line approach to rectangular HSS flange-plate connections.

A very fast method of calculating flange-plate connections for any type of hollow section can be found in the Stelco Manual (Stelco, 1981). The equations are based on research done by Timoshenko and Woinowsky-Krieger (1959). A flange-plate thickness is calculated for which no prying action occurs. Unfortunately, the design procedure is kept very general resulting in very large flange-plate thicknesses if used for routine structural design.

RECOMMENDED DESIGN METHOD FOR RECTANGULAR HSS FLANGE-PLATE CONNECTIONS

According to the results of a study on bolted flange-plate connections for square hollow sections (Willibald et al., 2002) as well as the results of the current experimental program on connections for rectangular hollow sections (see Table 2) the advocated design procedure is based on the equations provided by the AISC HSS Connections Manual (1997).

In a typical design procedure the factored load as well as the size of the HSS are known (and also the outer dimensions of the flange-plate may be chosen), before designing the connection. The unknowns of the connection are hence the number of bolts, their diameter and grade and locations on the plate, as well as the flange-plate thickness.

As a first LRFD step the load per bolt can be calculated assuming that no prying action is taking place in the connection:

$$r_{ut} = \frac{P_{ut}}{n} \tag{2}$$

Bolts of the right size and grade have to be chosen so that

$$\phi r_n \geq r_{ut} \tag{3}$$

The trial selection now has to be checked and the required flange-plate thickness has to be found. The design method reverts back to the original T-stub model by Struik and de Back (1969) with the inner yield line forming adjacent to the HSS outer face and the outer yield line following the bolt line. From test results it is deduced that the bolt forces act somewhere between the bolt axis and the edge of the bolt head, resulting in a slight shift of the outer yield line. Thus, the effective dimensional parameters a' and b' are calculated as follows:

$$a' = a + \frac{d}{2} \tag{4}$$

with a limited to a maximum of 1.25 b in the calculations (but not necessarily for the plate dimensions), and:

$$b' = b - \frac{d}{2} \tag{5}$$

Using the effective parameters a' and b' the coefficient ρ can be determined:

$$\rho = \frac{b'}{a'} \tag{6}$$

A "temporary prying factor" β', which uses the comparison of the existing to the required bolt strength, has to be calculated:

$$\beta' = \frac{1}{\rho}\left(\frac{\phi r_n}{r_{ut}} - 1\right) \tag{7}$$

The next step, in order to calculate the required flange-plate thickness, is to determine the coefficient δ which includes the influence of the bolt pitch p:

$$\delta = 1 - \frac{d'}{p} \tag{8}$$

Contrary to the example provided by the AISC HSS Connections Manual (AISC, 1997) the bolt pitch p is calculated as the *flange* height/width divided by the number of bolts parallel to the flange height/width on one side. In the AISC Manual the bolt pitch (p') is calculated using the HSS height/width instead of the flange-plate height/width resulting in very conservative load predictions (see Table 2 and Figure 8). The AISC HSS Connections Manual (AISC, 1997) does not state if it is necessary to calculate the connection for the long and short side of rectangular connections individually or if it is possible to use averaged values for a', b', and p. The experimental program indicates that the best agreement is found for the minimum values of the load predictions for the short and long side (see Table 2), with a mean ratio of actual to predicted load of 0.96 and a coefficient of variation of 0.8. The resistance predictions using the "averaged" values for p err slightly more on the unconservative side, (mean ratio of actual to predicted load of 0.95) with a comparable coefficient of variation (0.7 compared to 0.8). For subsequent calculations p should therefore be chosen as the minimum value of the bolt pitch for the long and the short side (assuming equal values of a and b for the short and long side of the rectangular HSS flange-plate connection):

$$p = \min.\left(\frac{h_p}{n_h}, \frac{w_p}{n_w}\right) \tag{9}$$

Using the results of Equations 7 and 8 the coefficient α' is calculated:

$$\alpha' = \frac{1}{\delta}\left(\frac{\beta'}{1-\beta'}\right) \tag{10}$$

The coefficient a can be found in the original prying model based on T-stub analysis. The term α is the ratio of moment per unit plate width at the bolt line to moment at the stem of the tee. Two limit state extremes exist, one with a rigid plate, corresponding to $\alpha = 0$, and the other with a flexible plate in double curvature, corresponding to $\alpha = 1$. The value α' calculated in equation 10 represents an upper limit of this coefficient α for this specific connection. The exact value for α can only be found with the knowledge of the flange-plate thickness.

Finally, by comparing the plastic moment per unit plate width $\left(m_p = \frac{1}{4} t_p^2 F_{yp}\right)$ of the flange-plate with the bolt strength and the level of prying α', the required flange-plate thickness can be calculated as follows (AISC, 1997):

$$t_{req} = \sqrt{\frac{4.44 r_{ut} b'}{p F_{yp}(1 + \delta\alpha')}} \tag{11}$$

The factor of 4.44 in the formula for the required flange-plate thickness is caused by the inclusion of the resistance factor in the equation:

$$4.44 = \frac{4}{0.9} = \frac{4}{\phi_p}$$

DESIGN EXAMPLES

Design Example 1: Bolted flange-plate connection for a square HSS with bolts on all four sides.

Determine the flange-plate thickness and size of ASTM A325 bolts required to resist a factored tension load of 150 kips on an ASTM A500 Grade C HSS 5 × 5 × ¼. The flange-plate has a yield strength of 36 ksi. The bolt layout and plate dimensions chosen are shown in Figure 9. One should note that the bolt centers are located within the HSS width/depth dimension.

Determine the size of the ASTM A325 bolts:

$$r_{ut} = \frac{P_{ut}}{n} = \frac{150}{8} = 18.75 \text{ kips}$$

⇒ Use 8 ASTM A325 ⅝-in. bolts.
$\phi r_n = 20.7$ kips > 18.75 kips

Check trial selection:

$a = 1.25$ in. ≤ 1.25 b = 1.25 (1.25) in., so use effective $a = 1.25$ in.

$$a' = a + \frac{d}{2} = 1.25 + \frac{5/8}{2} = 1.56 \text{ in.}$$

$$b' = b - \frac{d}{2} = 1.25 - \frac{5/8}{2} = 0.94 \text{ in.}$$

$$\rho = \frac{b'}{a'} = \frac{0.94}{1.56} = 0.600$$

$$\beta' = \frac{1}{\rho}\left(\frac{\phi r_n}{r_{ut}} - 1\right) = \frac{1}{0.600}\left(\frac{20.7}{18.75} - 1\right) = 0.173$$

$$p = \frac{4h_p}{n} = \frac{4 \times 10}{8} = 5 \text{ in., } p \text{ is the same for all four sides.}$$

$$\delta = 1 - \frac{d'}{p} = 1 - \frac{\left(5/8 + 1/8\right)}{5} = 0.850$$

$$\alpha' = \frac{1}{\delta}\left(\frac{\beta'}{1-\beta'}\right) = \frac{1}{0.850}\left(\frac{0.173}{1-0.173}\right) = 0.246 \le 1$$

$$t_{req} = \sqrt{\frac{4.44 r_{ut} b'}{p F_{yp}(1+\delta\alpha')}} = \sqrt{\frac{4.44 \times 18.75 \times 0.94}{5 \times 36 \times (1 + 0.850 \times 0.246)}} = 0.60 \text{ in.}$$

⇒ Use ⅝-in. flange-plate, $t_p = 0.625$ in. > 0.60 in.; bolt check not required.

Design Example 2: Bolted flange-plate connection for a rectangular HSS with bolts on all four sides.

Determine the flange-plate thickness and size of ASTM A325 bolts required to resist a factored tension load of 250 kips on an ASTM A500 Grade C HSS 8 × 6 × ¼. The flange-plate has a yield strength of 36 ksi. The bolt layout and plate dimensions chosen are shown in Figure 10. One should again note that the bolt centers are located within the HSS width/depth dimension.

Determine the size of the ASTM A325 bolts:

$$r_{ut} = \frac{P_{ut}}{n} = \frac{250}{10} = 25 \text{ kips}$$

⇒ Use 10 ASTM A325 ¾-in. bolts.
$\phi r_n = 29.8$ kips > 25 kips

Check trial selection:

$a = 1.50$ in. ≤ 1.25 b = 1.25 (1.50) in., so use effective $a = 1.50$ in.

$$a' = a + \frac{d}{2} = 1.5 + \frac{3/4}{2} = 1.88 \text{ in.}$$

$$b' = b - \frac{d}{2} = 1.5 - \frac{3/4}{2} = 1.13 \text{ in.}$$

$$\rho = \frac{b'}{a'} = \frac{1.13}{1.88} = 0.600$$

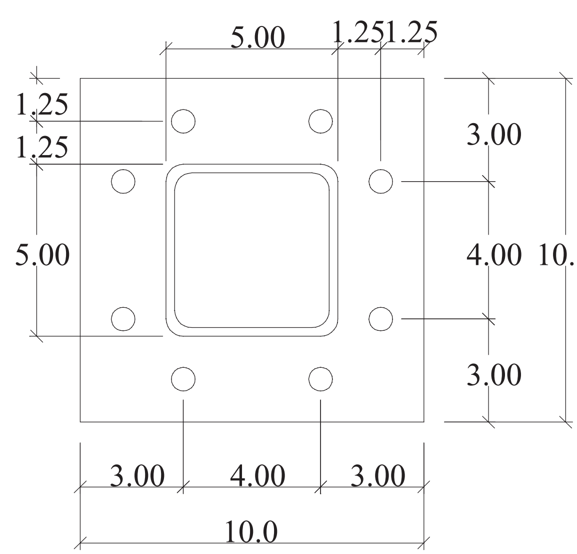

Fig. 9. Bolt layout and plate dimensions for square flange-plate connection design example.

$$\beta' = \frac{1}{\rho}\left(\frac{\phi r_n}{r_{ut}} - 1\right) = \frac{1}{0.600}\left(\frac{29.8}{25} - 1\right) = 0.320$$

$$p = \min.\left(\frac{h_p}{n_h}, \frac{w_p}{n_w}\right) = \min.\left(\frac{14}{3}, \frac{12}{2}\right) = 4.7 \text{ in.}$$

$$\delta = 1 - \frac{d'}{p} = 1 - \frac{\left(3/4 + 1/8\right)}{4.7} = 0.813$$

$$\alpha' = \frac{1}{\delta}\left(\frac{\beta'}{1-\beta'}\right) = \frac{1}{0.813}\left(\frac{0.320}{1-0.320}\right) = 0.579 \leq 1$$

$$t_{req} = \sqrt{\frac{4.44 r_{ut} b'}{p F_{yp}(1+\delta\alpha')}} = \sqrt{\frac{4.44 \times 25 \times 1.12}{4.7 \times 36 \times (1 + 0.813 \times 0.579)}}$$

$$= 0.71 \text{ in.}$$

⇒ Use ¾-in. flange-plate, $t_p = 0.750$ in. > 0.71 in.; bolt check not required.

When calculating the required flange-plate thickness the temporary prying factor, β', was calculated on the basis of a comparison between bolt strength and bolt load due to connection load. It is thereby assumed that the bolt strength equals the bolt load due to connection load plus the additional forces due to prying. The required flange-plate thickness was then calculated so that the flange-plate connection will not have more prying action than the calculated temporary prying factor β'.

To do a bolt check the actual prying factor β of the connection would have to be calculated based on the chosen flange-plate thickness t_p, number of bolts, bolt strength and bolt layout. Then the actual prying forces could be calculated. Finally the bolts would be checked against the sum of connection load and actual prying forces.

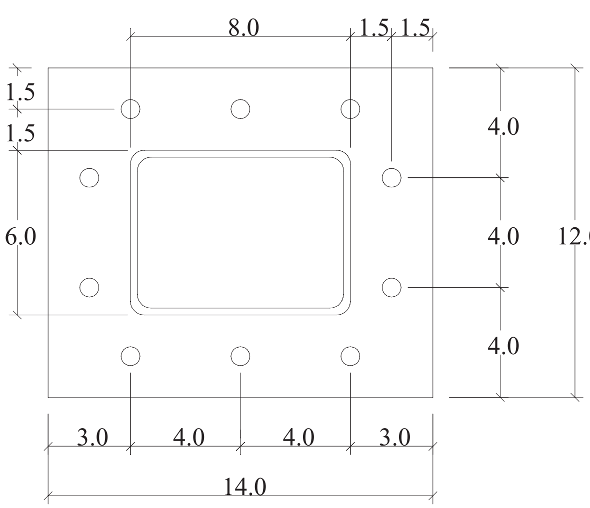

Fig. 10. Bolt layout and plate dimensions for rectangular flange-plate connection design example.

CONCLUSIONS

The results of an experimental investigation of four bolted flange-plate connections between rectangular hollow structural sections, with bolts on all four sides, have been presented. A brief overview of different design methods for bolted flange-plate connections for square and rectangular hollow structural sections under tension load has also been given. A comparison of the load predictions of the various methods for the specimens in the experimental program supports the use of the design procedure that can be found in the AISC HSS Connections Manual (AISC, 1997). However, this is provided that the flange-plate width/height is used to calculate the bolt pitch. Unfortunately, the AISC HSS Connections Manual illustrates the (more conservative) use of the HSS width/height instead of the flange-plate width/height for determining the bolt pitch, but the latter is hereby advocated. Moreover, the results of this experimental study on rectangular HSS connections suggest that the connection strength should be calculated for both the short and long side individually, using the minimum of both values as the actual connection resistance. Provided that the edge distance, a, and the distance from bolt line to tube face, b, are the same for the short and long side of the connection, the side having the smaller bolt pitch p will govern. Using the "averaged" values for the bolt pitch p will always result in slightly less conservative predictions for the connection resistance. It might be conceivable to use the "averaged" bolt pitch instead, considering that the load predictions for all test specimens were done with all resistance factors removed in the calculations. For design purposes the bolt capacity as well as the flange-plate capacity are reduced by the inclusion of resistance factors, $\phi = 0.75$ and $\phi_p = 0.9$ respectively, providing a fair safety margin. All the given design recommendations should be restricted to the range of experimental verification, which is for up to 10 bolts and for rectangular HSS up to 10 in. in size and with aspect ratios up to 1.7.

NOMENCLATURE

a	=	Edge distance (see Figure 1)
a'	=	Effective value of $a\left(= a + \frac{d}{2}\right)$
A_i	=	Cross-sectional area of rectangular HSS
b	=	Distance from bolt line to rectangular hollow section face (see Figure 1)
b'	=	Effective value of $b\left(= b - \frac{d}{2}\right)$
B_u	=	Measured bolt tensile strength in bolt tension test
c	=	Distance between bolts parallel to rectangular hollow section face (see Figure 1)

CIDECT = Comité International pour le Développement et l'Etude de la Construction Tubulaire
d = Nominal bolt diameter
d' = Bolt hole diameter
F_{up} = Ultimate tensile stress of flange-plate material
F_{yi} = Yield tensile stress of hollow section material
F_{yp} = Yield tensile stress of flange-plate material
h_i = External height of rectangular hollow section (see Figure 1)
h_p = Flange-plate height (see Figure 1)
HSS = Hollow Structural Section
LVDT = Linear Variable Differential Transformer
m_p = Plastic moment of flange-plate per unit length $\left(=\frac{1}{4}t_p^2 F_{yp}\right)$
n = Number of bolts in a connection
n_h = Number of bolts on one side parallel to flange-plate height
n_w = Number of bolts on one side parallel to flange-plate width
p = Tributary flange-plate width per bolt (see Figure 2)
p' = Tributary HSS width per bolt (see Figure 2)
P_{ut} = Factored Connection load
Q_{ux} = Measured total prying force at ultimate load
r_{ut} = Required tensile strength of each bolt if no prying occurred $\left(r_{ut}=\frac{P_{ut}}{n}\right)$
r_n = Nominal tensile bolt strength
R_u = Theoretical predicted connection strength
R_{ux} = Measured connection strength
R_{yi} = Yield load of square hollow section
t_p = Flange-plate thickness
t_{req} = Required flange-plate thickness
w_i = External width of rectangular hollow section (see Figure 1)
w_p = Flange-plate width (see Figure 1)
α' = Coefficient for prying action (see Equation 10)
β' = "Temporary prying factor" for calculating the required flange-plate thickness
β_{ux} = Measured prying ratio at ultimate load $\left(=\frac{\sum B_u - R_{ux}}{R_{ux}}=\frac{Q_{ux}}{R_{ux}}\right)$
δ = Coefficient $\left(=1-\frac{d'}{p}\right)$
ϕ = Resistance factor
ϕ_p = Flange-plate resistance factor (taken as 0.9 in flexure)
ρ = Coefficient $\left(=\frac{b'}{a'}\right)$

ACKNOWLEDGMENTS

The research was undertaken at the University of Toronto within the framework of the Baden-Württemberg (Germany)/Ontario (Canada) Exchange Program. Financial support for this project has been provided by CIDECT Programs 8D and 8E (Comité International pour le Développement et l'Etude de la Construction Tubulaire), NSERC (Natural Sciences and Engineering Research Council of Canada), CANAM Steel Works and the DFG (Deutsche Forschungsgemeinschaft). The provision of HSS material by LTV Copperweld and plate material by IPSCO is gratefully acknowledged.

REFERENCES

AISC (1997), *Hollow Structural Sections Connections Manual*, American Institute of Steel Construction, Chicago, Illinois.

Birkemoe, P.C. and Packer, J.A. (1986), "Ultimate Strength Design of Bolted Tubular Tension Connections," *Proceedings, Steel Structures—Recent Research Advances and their Application to Design*, Budva, Yugoslavia, pp. 153-168.

Cao, J. and Packer, J.A. (1997), "Design of Tension Circular Flange Joints in Tubular Structures," *Engineering Journal*, AISC, Vol. 34, No. 1, 1st Quarter, pp. 17-25.

Caravaggio, A. (1988), "Tests on Steel Roof Joints for Toronto SkyDome," Master of Applied Science thesis, University of Toronto, Ontario, Canada.

Igarashi, S., Wakiyama, K., Inoue, K., Matsumoto, T., and Murase, Y. (1985), "Limit Design of High Strength Bolted Tube Flange Joints-Parts 1 and 2," *Journal of Structural and Constructional Engineering*, Transactions of AIJ, Department of Architecture Reports, Osaka University, Japan.

Kato, B. and Mukai, A. (1982), "Bolted Tension Flanges Joining Square Hollow Section Members," CIDECT Report 8B -82/3 E, University of Tokyo, Japan.

Mang, F. (1980), "Investigation of Standard Bolted Flange Connections for Circular and Rectangular Hollow Sections," CIDECT Report 8A-81/7 E, University of Karlsruhe, Germany.

Packer, J.A. and Bruno, L. (1986), "Behaviour of Bolted Flange-Plate Connections in Rectangular Hollow Section Tension Members," *Proceedings, 10th Australasian Conference on the Mechanics of Structures and Materials*, Adelaide, Australia, pp. 45-50.

Packer, J.A., Bruno, L., and Birkemoe, P.C. (1989), "Limit Analysis of Bolted RHS Flange Plate Joints," *Journal of Structural Engineering*, ASCE, Vol. 115, No. 9, pp. 2226-2242.

Packer, J.A., Wardenier, J., Kurobane, Y., Dutta, D., and Yeomans, N. (1992), "Design Guide for Rectangular Hollow Section (RHS) Joints Under Predominantly Static Loading," CIDECT (ed.) and Verlag TÜV Rheinland GmbH, Köln, Germany.

Packer, J.A., and Henderson, J.E. (1997), *"Hollow Structural Section Connections and Trusses—A Design Guide,"* 2nd ed., Canadian Institute of Steel Construction, Toronto, Ontario, Canada.

Rockey, K.C., and Griffiths, D.W. (1970), "The Behaviour of Bolted Flange Joints in Tension," *Proceedings, Conference on Joints in Structures*, Sheffield, U.K.

STELCO (1981), *"Hollow Structural Sections—Design Manual for Connections,"* 2nd ed. Stelco Inc., Hamilton, Ontario, Canada.

Struik, J.H.A., and de Back, J. (1969), "Tests on Bolted T-stubs with respect to a Bolted Beam-to-Column Connection," Stevin Laboratory Report 6-69-13, Delft University of Technology, The Netherlands.

Timoshenko, S. and Woinowsky-Krieger (1959), *Theory of Plates and Shells*, 2nd ed., McGraw Hill.

Willibald, S., Packer, J.A., and Puthli, R.S. (2002), "Experimental Study of Bolted HSS Flange-Plate Connections in Axial Tension," *Journal of Structural Engineering*, ASCE, Vol. 128, No. 3, pp. 328-336.