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RHS-to-RHS Axially Loaded X-Connections near an Open Chord End

by

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Abstract

In all truss-type welded hollow structural section connection design procedures, the chord member is assumed continuous on both sides of the branch. New limits of applicability have recently been advocated, which specify minimum end distances from an open chord end to achieve the full connection strength. To investigate their suitability for rectangular hollow section (RHS) connections, an experimental program consisting of 12 RHS-to-RHS X-connections subject to branch axial compression was undertaken. For connections near a chord end, a modified yield line mechanism controlled. A proposed analytical model is derived, and by evaluating against the experimental results, is shown to accurately predict the yield loads. An EN 1993-1-8 amendment, transcribed from circular hollow section connections, is deemed excessively conservative, and a closed-form solution for the end distance, presented herein, is recommended for use with RHS connections. Alternatively, providing a cap plate is determined to be an effective stiffening method.

Keywords

Steel structures, hollow structural sections, rectangular hollow sections, truss connections, welded joints, chord end effects, static loading, analytical modelling

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1. Introduction

Specific research on truss-type, welded hollow structural section (HSS) connections has been conducted since the 1960s, resulting in connection design recommendations published in North America (Packer and Henderson 1997; AISC 2010) and internationally (CEN 2005; Packer et al. 2009; ISO 2013). All of these HSS design recommendations presume that the chord member is continuous for a considerable distance beyond the connection region. There is no established guidance for the case when an HSS branch member is near an open end of an HSS chord member in a girder or truss, which is a problem encountered with trusses supported beneath the bottom chord (such as shown in Fig. 1) or with free chord ends unconnected to another member (such as Warren truss bottom chords where the truss is suspended from connections to the ends of the top chord). In this situation, designers typically resort to strengthening the chord ends, such as capping the chord with an end plate or reinforcing the chord face or walls with stiffening plates. However, there should be a minimum end distance, $e_{\min}$, from an open chord end at which full connection strength can be achieved for an unreinforced connection.

Fig. 1. RHS-to-RHS connection near a truss open end, with chord stiffened

Limited research on HSS chord end effects has been performed for circular hollow section (CHS) welded connections. The numerical investigations on CHS-to-CHS T- and X-connections by van der Vegte and Makino (2006; 2010) concluded that chord boundary conditions were not influential if the chord length was greater than 10 times the CHS diameter ($10d_0$) for all connection geometries studied. It was shown that the required chord length was primarily a function of the chord wall slenderness (2γ), where less stiffness was provided to limit chord plastification if the connection had thin chord walls compared to thick chord walls. For shorter chord

lengths, significant differences in the strengths of connections with fixed (capped with end plates) versus free end conditions were determined. Recent numerical studies on transverse branch plate-to-CHS T- and X-connections by Voth and Packer (2012a; 2012b) also substantiated these results.

The recommendations from this research may be employed for the design of isolated connections in experimental or numerical tests, where the behaviour may be different from that of connections which are part of a framed structure. In addition, they are the basis for the minimum end distance proposed for EN 1993-1-8, in the following amendments to Clause 7.1.2 (9):

“For joints with a chord end not connected to other members, the chord end shall be at a distance of at least $(2\gamma/10)d_0$ from the heel or toe of the closest brace, with a minimum of $2.5d_0$. For RHS chords, substitute d_0 by the largest of b_0 or h_0 . Otherwise, the end shall be welded to a cap plate with a thickness of at least $1.5t_0$, at a minimum distance of $0.5d_0(1-\beta)$ or $0.5b_0(1-\beta)$ from the brace toe or heel of the joint.”

This end distance requirement is illustrated in Fig. 2.

Fig. 2. Proposed end distances in EN 1993-1-8 (shown for CHS)

The $(2\gamma/10)d_0$ rule which is derived empirically for CHS chords, with a minimum value of $2.5d_0$ included for good engineering practice, is transcribed for rectangular hollow section (RHS) chords by simply replacing the outside dimensions. Specifically, substituting the CHS diameter (d_0) by the largest of the RHS width and depth (b_0 and h_0) and accounting for the applicable 2γ values lead to a large required end distance of $2.5b_0$ or $2.5h_0$ (the minimum stipulated, as shown in Fig. 2) up to $4b_0$ or $4h_0$ (for the maximum 2γ of 40, as permitted by ISO (2013)

for RHS). However, this end-effects rule accommodates the propagation of ovalization of the complete chord member that occurs in CHS connections, whereas with RHS connections chord member distortion is generally more localized and largely confined to the chord connecting face. Also, the research on chord end effects, on which the EN 1993-1-8 formula is based, considered connections that were symmetrical about the branch, while the behaviour of connections with the branch near a chord end may be different. These assumptions indicate that the estimated end distances may be very conservative, thus further research is needed to develop end distance requirements specific to RHS chord members.

If the branch needs to be closer to a chord end, the use of a cap plate is specified. For this case, the respective minimum distance of $0.5d_0(1-\beta)$ and $0.5b_0(1-\beta)$ for CHS and RHS sections is equal to the distance between the branch and the chord side walls, to ensure a similar stiffness around the branch. While this end distance may be necessary for fabrication details, it should not be an issue for strength. The minimum cap plate thickness of $1.5t_0$ is based on engineering judgement so that it has sufficient stiffness relative to the chord sidewalls (i.e. the ratio of the cap plate to chord sidewall stiffness is $(1.5t_0)^3/t_0^3=3.38$) to restrain local chord deformation and develop the required connection strength.

2. Analytical Study (Yield Line Analyses)

Analytical yield line analysis has been used to determine the capacity of flexible HSS connections. When a connection is remote from the RHS chord ends (defined as a “regular” connection), the analytical solution for the yield load P_Y (Eq. (1)), associated with the chord face yielding limit state, can be derived based on a symmetric flexural yield line mechanism developing in the chord connecting face (Fig. 3). Q_f is a function to account for the effect of chord normal stress, which is less than or equal to one. Eq. (1) has been widely adopted in design recommendations for RHS-to-RHS T-, Y-, and X-connections.

$$(1) \quad P_Y \sin \theta_1 = \frac{f_{y0} t_0^2}{(1-\beta)} \left[\frac{2h_1}{b_0 \sin \theta_1} + 4\sqrt{1-\beta} \right] Q_f$$

In Eq. (2), the full dimensions h_1 , b_1 , b_0 and β in Eq. (1) are replaced by the more accurate effective dimensions h_1' , b_1' , b_0' and β' where:

- h_1 is increased to account for the fillet weld size, or $h_1' = h_1/\sin\theta_1 + 2w$

- b_1 is increased to account for the fillet weld size, or $b_1' = b_1 + 2w$
- b_0 is decreased to reflect plastic hinges forming in the centre of the chord walls, or $b_0' = b_0 - t_0$
- branch-to-chord width ratio $\beta = b_1/b_0$ is increased to $\beta' = b_1'/b_0'$

(2)

$$P_Y' \sin \theta_1 = \frac{f_{y0} t_0^2}{(1 - \beta')} \left[\frac{2h_1'}{b_0'} + 4\sqrt{1 - \beta'} \right] Q_f$$

Fig. 3. Yield line mechanism for a regular RHS-to-RHS axially-loaded X-connection

If β approaches unity, the yield load tends to infinity and this limit state is not likely to be critical. $\beta \leq 0.85$ thus represents a practical upper limit for the application of the yield line solution.

When a connection is close to a RHS chord end (termed an “offset” connection), there may not be adequate lengths to develop the traditional yield line mechanism. Potential asymmetric flexural yield line mechanisms are therefore proposed and investigated for their ability to predict the yield loads of the offset connections, where solutions for e_{min} can also be derived by comparison with Eqs. (1) or (2).

A first possible flexural yield line mechanism no. 1 (Fig. 4) is studied. The analytical yield load solution, for a known end distance e from the branch edge to an open chord end, is given by Eq. (3).

100 (3)

$$P_{Y,1} \sin \theta_1 = \frac{f_{y0} t_0^2}{(1-\beta)} \left[\frac{2e}{b_0} + \frac{2h_1}{b_0 \sin \theta_1} + 2\sqrt{1-\beta} \right] Q_f$$

101
102

Fig. 4. Yield line mechanism No. 1 for an offset RHS-to-RHS axially-loaded X-connection

103 It can be shown that this postulated yield line mechanism controls and predicts a lower yield load compared
104 to the traditional yield line mechanism (Eq. (1)) if the end distance is less than:

105 (4)

$$e_{\min} = b_0 \sqrt{1-\beta}$$

106 If $e \geq e_{\min}$, end distance will not be critical and the yield load for the regular T-, Y-, or X-connection
107 represents the minimum connection strength.

108 In Eq. (5), the full dimensions h_1 , b_1 , b_0 , β and e in Eq. (3) are substituted with effective dimensions h_1' , b_1' ,
109 b_0' , β' and e' , where e is reduced to account for the fillet weld size, or $e' = e - w$.

110 (5)

$$P_{Y,1}' \sin \theta_1 = \frac{f_{y0} t_0^2}{(1-\beta')} \left[\frac{2e'}{b_0'} + \frac{2h_1'}{b_0' \sin \theta_1} + 2\sqrt{1-\beta'} \right] Q_f$$

111 The associated minimum end distance is then:

112 (6)

$$e_{\min} = b_0' \sqrt{1-\beta'} + w$$

113 A second possible flexural yield line mechanism no. 2 (Fig. 5) is also investigated in the yield line
 114 predictions (Eq. (7), where m is the slope of the inclined yield line from the branch side to the open chord end).
 115 This mechanism applies only if $e \leq mb_1/2$ or $e \leq mb_1/2 + w$ (i.e. if the yield lines have not converged).

$$116 \quad (7) \quad P_{Y,2} \sin \theta_1 = \frac{f_{y0} t_0^2}{(1-\beta)} \left[\left(2 + \frac{1}{m^2} \right) \frac{e}{b_0} + \frac{2h_1}{b_0 \sin \theta_1} + 2\sqrt{1-\beta} + \frac{1}{2m} \right] Q_f$$

117
 118 **Fig. 5.** Yield line mechanism No. 2 for an offset RHS-to-RHS axially-loaded X-connection

119 This approximate yield line mechanism governs over the regular yield line mechanism (Eq. (1)), if the end
 120 distance is less than:

$$121 \quad (8) \quad e_{\min} = b_0 \left[\sqrt{1-\beta} - 1/(4m) \right] / \left[1 + 1/(2m^2) \right]$$

122 If $e \geq e_{\min}$, end distance will not be critical.

123 In Eq. (9), the full dimensions h_1 , b_1 , b_0 , β and e in Eq. (7) are substituted with effective dimensions h_1' , b_1' ,
 124 b_0' , β' and e' :

$$125 \quad (9) \quad P_{Y,2}' \sin \theta_1 = \frac{f_{y0} t_0^2}{(1-\beta')} \left[\left(2 + \frac{1}{m^2} \right) \frac{e'}{b_0'} + \frac{2h_1'}{b_0' \sin \theta_1} + 2\sqrt{1-\beta'} + \frac{1}{2m} \right] Q_f$$

126 The corresponding minimum end distance is then:

$$e_{\min} = b_0' \left[\sqrt{1 - \beta'} - 1/(4m) \right] / \left[1 + 1/(2m^2) \right] + w$$

A third possible flexural yield line mechanism no. 3 (Fig. 6) is considered as well (Eq. (11), where x is the distance required for the inclined yield lines from the branch side to the open chord end to converge). This mechanism applies only if $e > x$ or $e > x' + w$ (i.e. if the yield lines have converged).

$$P_{Y,3} \sin \theta_1 = \frac{f_{y0} t_0^2}{(1 - \beta)} \left[\frac{2e}{b_0} + \frac{2h_1}{b_0 \sin \theta_1} + 2\sqrt{1 - \beta} + \frac{b_1(1 + \beta)}{4x} \right] Q_f$$

Fig. 6. Yield line mechanism No. 3 for an offset RHS-to-RHS axially-loaded X-connection

Since mechanism no. 3 applies only for $e > x$ or $e > x' + w$, the yield load predicted by this yield line mechanism in the applicable range will generally be greater than the yield load predicted by the regular yield line mechanism. Thus, it is not a critical mechanism for end effects, and a minimum end distance does not apply.

In Eq. (12), the full dimensions h_1 , b_1 , b_0 , β , e and x in Eq. (11) are substituted with effective dimensions h_1' , b_1' , b_0' , β' , e' and x' , where x is reduced to account for the fillet weld size, or $x' = x - w$.

$$P_{Y,3}' \sin \theta_1 = \frac{f_{y0} t_0^2}{(1 - \beta')} \left[\frac{2e'}{b_0'} + \frac{2h_1'}{b_0' \sin \theta_1} + 2\sqrt{1 - \beta'} + \frac{b_1'(1 + \beta')}{4x'} \right] Q_f$$

140 The ratios of $e_{\min}/b_0$, calculated for mechanisms nos. 1 and 2 using Eqs. (4) and (8), are plotted against β (i.e.
141 represented by the two lines) in Fig. 7, which shows that $e_{\min}$ is always less than b_0 for all values of β . Thus,
142 according to the yield line solution, a conservative end distance equal to the chord member width can be used for
143 a branch connected close to an open chord end.

Fig. 7. $e_{\min}/b_0$ vs. β based on postulated yield line mechanisms

144 However, as the minimum end distances are derived analytically, they have not been substantiated by
145 experimental evidence. The formulae are also only a function of β , the branch-to-chord width ratio, and do not
146 account for the possible influence of other connection parameters (e.g. 2γ , the chord slenderness ratio). Further, a
147 yield line mechanism, which is based on a chord face flexure limit state, may not always govern. For $\beta > 0.85$,
148 which is outside the yield line theory applicability, a sidewall failure limit state may control.

149 **2.1. Ultimate Deformation Limit Applied to Tests**

150 The connection capacity at the ultimate limit state can be determined from experimental or numerical load-
151 displacement results as the lower of, as implemented by IIW (2012) and shown in Fig. 8:

- 152 (a) The maximum load resulting from ultimate failure if this load occurs at a lower displacement than (b); or
153 (b) The load corresponding to an ultimate deformation limit

154 A connecting face deformation equal to 3% of the RHS chord width ($0.03b_0$) or 3% of the CHS chord
155 diameter ($0.03d_0$) has generally been used as the ultimate deformation limit in (b), as proposed by Lu et al.
156 (1994). The applicability of this ultimate deformation limit for various RHS welded connections has previously

been investigated (Zhao 2000; Kostas and Packer 2003a, 2003b; Kostas et al. 2003). As the 3% b_0 ultimate deformation limit load $N_{1,3\%}$ was shown to agree well with the analytical yield load P_Y for these regular connections, it will also be used as a limit to the connection capacity and to validate the proposed yield line formulae for the offset connections.

Fig. 8. Failure criteria (adapted from Wardenier et al., 2010)

3. Experimental Program

An experimental program was undertaken to investigate the behaviour of connections near an open chord end, evaluate the proposed yield line models, and assess the EN 1993-1-8 amendments for RHS welded connections.

3.1. Test Specimens and Measured Dimensions

Twelve isolated, square HSS-to-HSS X-connection tests were performed, with the branch loaded in axial compression and centred laterally on the chord. The connections were designed with “thick branches welded to thin chords” in order to generate connection failure before reaching the branch member capacity. This is against tubular design principles in practice, when the objective would be to avoid a connection failure. All chord and branch members were made of cold-formed HSS sections. The branch members were produced to ASTM A847 (2014), which is a weathering steel grade, but has similar strength properties as ASTM A500 Grade C. The cap plate materials were made to CSA G40.21 (2013) Grade 350W. Two chord sizes (HSS 203x203x6.35 and HSS 203x203x9.53) and one branch size (HSS 102x102x9.53) were selected, enabling one branch-to-chord width ratio (nominal $\beta = 0.5$) and two chord slenderness ratios (nominal $2\gamma = 32$ and 21). An empirical parametric

study was performed with the clear end distance (e) from the HSS branch to the open chord end being the primary variable (Fig. 9 (a)), and ranging from almost zero (but still sufficient to accommodate the welds) up to slightly over $e_{\min} = b_0 \sqrt{1 - \beta} = 144 \text{ mm}$ (the yield line solution for mechanism no. 1, Eq. (4)). The chord length on the other side of the branch was made sufficiently long to minimize the influence of chord end conditions and was estimated from the EN 1993-1-8 formula. The effect of welding a chord end cap plate, for when the branch is very close to the chord end (Fig. 9 (b)), was also investigated. The end distance and plate thickness for this case satisfy the EN 1993-1-8 requirements. Since the top of the branch was uniformly compressed, shear lag was not a problem and a branch height of four times the branch width ($4b_1$) was considered adequate. Details of the test specimens, including the measured dimensions, are tabulated in Table 1.

A 0.045" (1.2mm) diameter AWS A5.18 E70C-6M H4 (CSA W48 E491C-6M-H4) gas-shielded metal-cored wire (Metal-Cor 6-L) with a minimum specified tensile strength of 70ksi (480MPa) was used to weld the test specimens. The branches, with both ends machined normal to the member axis, were welded to the flat faces of the chord members with a continuous fillet weld around the branch perimeter. Two specimens had a 1-in. thick cap plate welded to the chord end closest to the branch, with the weld ground flush at the bottom. Single-pass welds were used and the average horizontal leg size for each series of six specimens using the $2\gamma=34$ and 23 HSS chords was determined to be 7.8mm and 7.9mm, respectively.

Fig. 9. Square HSS-to-HSS X-connection test specimens

195 **Table 1.** Test specimens and measured dimensions

Specimen no.	Specimen identification	2γ	End distance e [mm]	Chord length l_0 [mm]
1	X-0.5-32-25O	34	24	827
2	X-0.5-32-55O	34	55	764
3	X-0.5-32-100O	34	100	796
4	X-0.5-32-160O	34	160	875
5 (control)	X-0.5-32-700O	34	714	1530
6 (+cap plate)	X-0.5-32-55C	34	55	759
7	X-0.5-21-25O	23	25	687
8	X-0.5-21-55O	23	54	718
9	X-0.5-21-100O	23	101	771
10	X-0.5-21-160O	23	160	828
11 (control)	X-0.5-21-550O	23	560	1222
12 (+cap plate)	X-0.5-21-55C	23	55	731

196 Note: measured $\beta = 0.50$ for all specimens.

197 3.2. Test Setup and Instrumentation

198 The experiments were performed using a 5000kN-capacity Baldwin testing frame. The connection was
 199 supported on a pedestal, which was secured to the laboratory floor. A steel collar was fitted around the branch at
 200 the top to prevent any lateral movement and the steel collar was welded to a steel plate, which was then bolted to
 201 the machine head. The branch could then be centred vertically with the load application and support points. The
 202 X-connection was thus tested under direct transverse compression rather than as a simply supported T-
 203 connection, which removed any chord normal stress effects on the connection results and hence $Q_f = 1.0$
 204 (discussed further by Packer et al., 2017). This configuration also enabled the end distance to be varied for the
 205 different test specimens.

206 All connections were instrumented with a linear variable differential transformer (LVDT) placed between
 207 the top of the pedestal and the bottom of the machine head to monitor the total branch elastic deformation and
 208 connection local deformation. A system, which consisted of a K610 optical camera that recorded the global
 209 coordinates of light-emitting-diode (LED) targets positioned on the test specimens, was used to measure the
 210 vertical connection displacements and chord face deformation profiles. For four connections, when the branch
 211 was very close to the chord end ($e = 25\text{mm}$) and when the branch was in the middle of the chord length (control),

for both HSS chord sizes, strain gauges were installed around the branch perimeter to measure the non-uniform strain distribution close to the connection and the bending moment distribution along the branch height. Typical test setups are shown in Fig. 10.

Fig. 10. Typical test setups

4. Experimental Results

4.1. Geometric and Material Properties

Cross sections of the RHS branch and chord members were cut with a thickness of 1 in., machined, and traced in AutoCAD to obtain the outside dimensions, inside/outside corner radii, as well as the cross-sectional areas of the flat faces, corners, and full sections of the RHS members. The wall thicknesses were measured with a 1-in. Mitutoyo micrometer. The average geometric properties are given in Tables 2 and 3. Since the measured thickness of the chord members exceeds the 5% tolerance on the wall thickness for CSA G40 grade, it was likely made to ASTM A500 grade.

Table 2. Average measured RHS cross-sectional dimensions

Designation [mm]	Width and height h and b [mm]	Wall thickness t [mm]	Corner radius	
			Out., r_o [mm]	In., r_i [mm]
HSS 203x203x6.35 Chord	203.6	5.96	14.98	8.99
HSS 203x203x9.53 Chord	203.1	8.85	23.82	14.98
HSS 102x102x9.53 Branch	101.7	8.74	18.62	9.68

Table 3. Measured RHS cross-sectional areas

Designation [mm]	2γ	Cross-sectional area, A [mm ²]		
		Flat	Corner	Total
HSS 203x203x6.35 Chord	34	4046	446	4492
HSS 203x203x9.53 Chord	23	5405	1090	6495
HSS 102x102x9.53 Branch	12	2225	755	2980

Standard longitudinal tensile coupons, taken from the three flat sides at least 90° from the weld seam and from three corners of each of the two RHS chord members used for the connection tests, were cut, machined, and tested in accordance with ASTM E8 (2013). The average material properties, including the yield strength (f_y), ultimate strength (f_u), and rupture strain (ϵ_{rup}) are summarized in Table 4.

The strengths of the corners are increased relative to the flats (the yield strengths are increased significantly and the ultimate strengths are increased moderately), while the ductility in the corners is reduced (the rupture strains are reduced) due to the greater amount of cold-working. Typical stress-strain plots for the flats and corners of the HSS 203x203x9.53 chord member are shown in Fig. 11 (a) and (b), respectively.

Table 4. Average measured RHS chord material properties

Designation [mm]	f_y [MPa]*	f_u [MPa]	ϵ_{rup}
HSS 203x203x6.35 flat	388.8	508.7	0.287
HSS 203x203x6.35 corner	540.5	598.9	0.176
HSS 203x203x9.53 flat	398.1	519.8	0.306
HSS 203x203x9.53 corner	513.8	604.4	0.219

* Yield strength determined by the 0.2% offset method.

(a) HSS 203x203x9.53 flat coupons

(b) HSS 203x203x9.53 corner coupons

Fig. 11. Typical stress-strain curves from tensile coupon tests

4.2. Connection Test Results

Testing was quasi-static and displacement-controlled to connection failure. Failure of all 12 connections was governed by the chord plastification limit state, which was exhibited by flexural deformation of the chord connecting face. For the connection with a cap plate, the chord face eventually failed in punching shear at the junction with the cap plate. Typical failure modes are illustrated in Fig. 12.

Fig. 12. Typical failure modes

To obtain the connection load-deformation curve, the branch load was measured by the testing machine's load cell and vertical connection deformation was determined from the global vertical displacement of the LED located close to the connection (on the branch, 50mm above the chord face), which also represented the local deformation because the bottom of the HSS chord was restrained from vertical displacement. Typical load-displacement behaviours are illustrated in Fig. 13 (a) and (b) for the HSS chords with $2\gamma = 34$ and 23, respectively.

The ultimate connection capacities of all 12 tests were controlled by the 3% b_0 deformation limit. The connections exhibited considerable deformation and ductility beyond this point, and strength continued to increase with strain hardening of the HSS material and membrane action in the chord. After punching shear occurred for the connection with a cap plate, the load dropped but the cap plate continued to provide restraint to the chord sidewalls.

Based on the plots, it was found that when the connection is very close (24-25 mm) to an open chord end, there is a reduction in strength of approximately 27-29% compared to the regular connection without chord end

effects. Alternatively, if the chord end is welded with a cap plate, there is an increase in strength of about 27-30% compared to the regular connection.

Fig. 13. Typical load-displacement curves

The local vertical deformation along the centerline of the top chord face was processed from the LED readings. Typical graphs of these profiles, for various branch loads, are presented in Fig. 14 for the $2\gamma = 34$ HSS chord. The theoretical transverse yield lines at a distance of $0.5b_0\sqrt{1-\beta}$, modified slightly to account for the weld size w , from the edges of the branch are also plotted.

It is shown that deformations were concentrated near the connection and extended for a length of approximately 400mm ($\approx 2b_0$) and 300mm ($\approx 1.5b_0$), from the branch edge for the $2\gamma = 34$ and 23 HSS chords, respectively, beyond which there is almost no deformation. This indicates that the chord lengths used, based on the EN 1993-1-8 formula, are conservative in excluding any chord end effects on the connection results.

Fig. 14. Typical chord face deformation profiles for HSS chord with $2\gamma = 34$

273 The normal stress distributions around the branch perimeter were processed from the strain gauge readings.
274 Typical plots of these distributions just above the chord face, at the connection load of $N_{1,3\%}$, are presented in
275 Fig. 15 for the HSS chord with $2\gamma = 34$. The branch remained elastic under all applied loads, with the stresses
276 being well below the nominal yield stress of 345MPa.

277 It is observed that the branch stress distribution is highly non-uniform near the connection. Maximum
278 compressive stress is seen in the two branch walls parallel to the chord, while minimum compressive stress (or
279 even tensile stress in this case) is seen in the two branch walls transverse to the chord. This shows that the axial
280 load is resisted primarily by the two branch walls parallel to the chord, due to the stiffness of the HSS chord
281 walls. The two branch walls transverse to the chord are much less effective in resisting the load, because of the
282 flexibility of the HSS chord face.

283 **Fig. 15.** Typical branch stress distribution close to the connection at $N_{1,3\%}$ for HSS chord with $2\gamma = 34$

284 The tensile stresses seen in the branch transverse walls are likely due to interference afforded by the branch
285 against chord face deformation. Specifically, as the chord face, which is supported at the chord walls, attempts to
286 deform in the transverse direction, it is restrained by the branch. Therefore, the branch pulls up, through the
287 weld, on the chord face; and the chord face, through the weld, pulls down on the branch, resulting in the
288 observed tensile stresses in the middle of the transverse branch walls, as illustrated in Fig. 16.

289 The differences in the stresses between the transverse walls suggest the presence of branch in-plane bending,
290 which may have been caused by branch initial out-of-straightness (for both the offset and regular connections) as
291 well as rotation applied at the branch base and lateral force induced at the branch top, thus leading to higher
292 tensile stresses in the transverse wall closest to the open chord end (for the offset connections). Nevertheless,

comparable compressive stress distribution along the branch longitudinal walls is seen for both the offset connections ($e = 25\text{mm}$) and the regular connections (control).

Fig. 16. Geometric compatibility for RHS-to-RHS connection

5. Evaluation of Results

5.1. Comparison with Yield Line Predictions

In order to evaluate the proposed analytical models, the experimentally-determined yield loads $N_{1,3\%}$ (the loads at the 3% b_0 ultimate deformation limit) are plotted against the end distance e and compared with the different yield line predicted strengths, calculated using measured chord yield strengths (f_{y0}), based on the chord flat faces, and with effective dimensions for the chord width (b_0'), branch width (b_1'), width ratio (β'), and end distance (e'). The average weld sizes were used in the calculations. The comparisons for the two sets of six tests using the HSS 203x203x6.35 and HSS 203x203x9.53 chords, with an actual chord slenderness (2γ) of 34 and 23, are presented in Fig. 17 (a) and (b), respectively.

The calculation using effective dimensions is more accurate and increases the yield load value. Since the yield line method is an upper bound method, mechanism no. 1, which computes the lowest yield load, is the critical mechanism. Mechanisms no. 2 and 3, plotted respectively in Fig. 17 for $m = 3$ and $x_1' = b_1'$ to match experimental observations (Fig. 18 (c) and (d)), never govern. $m = 3$ is also used to plot $e_{\min}/b_0$ vs. β in Fig. 7 using Eq. (8), but it is again not critical. The plots show that the experimental loads agree well with the resulting predicted loads and demonstrate a similar trend. Specifically, for end distances less than approximately $e_{\min}$ (Eq.

(4), the yield line solution based on mechanism no. 1), the strengths of connections near an open chord end are reduced relative to their “regular connection” counterparts. For end distances greater than about $e_{\min}$, the strengths of such connections reach those of their regular counterparts (control specimens). While the test results are very close to the predicted P_{Y1}' values for the $2\gamma = 34$ chord (Fig. 17 (a)), they are slightly higher (but within 10%) for the $2\gamma = 23$ chord (Fig. 17 (b)), which indicates that mechanism no. 1 is still conservative. Thus, overall, the comparison justifies yield line model no. 1 as an accurate predictor of the yield load for the offset connections, with a mean actual/predicted strength of 1.04 and an associated coefficient of variation (COV) of 0.035. Results for connections with a cap plate are not included in the statistical calculation. It is also observed that $e_{\min}$ does not seem to be affected by the chord wall slenderness, based on the trends for the two HSS chords.

Fig. 17. $N_{1,3\%}$ or P_Y vs. e (using effective dimensions)

As designers do not know the weld sizes until the connections have been detailed, design recommendations typically use full dimensions which do not account for the chord wall thickness t_0 and weld size w in the calculations. The predicted yield line strengths are thus re-calculated using measured chord yield strengths (f_{y0}), with full dimensions for the chord width (b_0), branch width (b_1), width ratio (β), and end distance (e). The resulting computed values for mechanism no. 1 (P_{Y1}) are found to be always less than the experimental results ($N_{1,3\%}$) for both the $2\gamma = 34$ and 23 chords, with an overall actual/predicted mean value of 1.29 and a corresponding COV of 0.053. This shows that yield line model no. 1, used in conjunction with full (or nominal) dimensions as a simplification, is a conservative predictor of the yield load for the offset connections, and can thus be used for design. This also validates the corresponding yield-line solution for the minimum end distance,

331 $e_{\min} = b_0 \sqrt{1 - \beta}$, to develop the full connection strength, provided $\beta \leq 0.85$ and chord plastification is the
 332 governing failure mode.

333 5.1.1. Observed Yield Line Patterns

334 Application of the analytical yield line patterns to the deformed chord face for four of the tested connections
 335 is shown in Fig. 18. While the rectilinear yield lines can only approximate the curved deformed surface, the
 336 general yield line mechanisms can still be seen. The traditional mechanism is associated with the control
 337 specimen with a large e , and mechanisms no. 1, 2, and 3 are observed for the end connections, with $e \leq 55\text{mm}$
 338 (shown for $e = 55\text{mm}$), $e = 100\text{mm}$, and $e = 160\text{mm}$, respectively.

(a) Traditional mechanism (control specimen)

(b) Mechanism 1 ($e = 55\text{mm}$)

(c) Mechanism 2 ($e = 100\text{mm}$)

(d) Mechanism 3 ($e = 160\text{mm}$)

Fig. 18. Observed yield line patterns for HSS chord with $2\gamma = 34$

5.2. Evaluation of EN 1993-1-8 Amendments

In the proposed amendment to EN 1993-1-8, an end distance greater than the maximum of $(2\gamma/10)d_0$ or $2.5d_0$, measured from the edge of the branch, is required for CHS connections, in order for the strengths to be predicted by traditional design equations. To assess the applicability of this end distance rule for RHS connections, the diameter (d_0) of the CHS chord is replaced by the width (b_0) of the square HSS chord studied in this research. Substituting $2\gamma = 34$ and 23 for the two HSS chords gives a minimum required end distance of $3.4b_0$ and $2.5b_0$, respectively. This is much larger than that predicted by the yield-line solution of $b_0\sqrt{1-\beta}$ or $0.71b_0$, computed with $\beta = 0.5$ for both chords, which was found to agree well with experimental results. Thus, the EN 1993-1-8 formula is excessively conservative, and not particularly suitable for estimating the minimum required connection end distances for open-ended chord members used in RHS trusses and girders.

The end connections found in practical applications are typically *asymmetrical* about the branch. However, the research on end distance effects, on which the EN 1993-1-8 formula is based, examined connections that are *symmetrical* about the branch. Thus, the recommended EN end distance or chord length is specifically relevant for the design of isolated connections in experimental or numerical tests, in order to develop the traditional yield line mechanism and exclude the influence of chord boundary conditions on the connection strength. In this respect, based on the chord face deformation profiles on both sides of the branch for the regular connections, or on the long-chord side of the branch for the offset connections, a chord length of approximately $2.0b_0$ and $1.5b_0$ was determined to be adequate for the two HSS chords with $2\gamma = 34$ and 23 , respectively (see Fig. 14 for the $2\gamma = 34$ chord profiles). These observed values are still less than $3.4b_0$ and $2.5b_0$, calculated above, as the maximum of $(2\gamma/10)b_0$ or $2.5b_0$. Hence, the EN 1993-1-8 formula is reasonably conservative, and still suitable for determining the minimum required chord lengths of RHS chord members used for isolated “symmetrical” connections in experimental or numerical research.

5.3. Influence of Providing a Chord End Cap Plate

As illustrated by the load-displacement curves in Fig. 13 for both HSS chords, adding a cap plate to the chord end restrains chord deformation and increases the connection stiffness. As such, the connection loads at

the 3% b_0 deformation limit exceed that of the control specimens, thus indicating that welding a cap plate to the chord end is effective in achieving the full strength of a regular connection.

5.4. Weld Effective Length for Offset Connections

Welds may be designed to resist the actual forces in the branch. This requires the use of weld effective lengths, which account for the non-uniform load transfer around the weld perimeter. Suitable effective lengths for RHS T-, Y-, or X-connections subjected to a branch axial load are provided in Table K5.1 of AISC 360-16 (Eq. K5-5) and illustrated in Fig. 19 (a). The effective length is given by:

$$(13) \quad l_e = \frac{2h_1}{\sin \theta_1} + 2b_e \quad (\text{Regular RHS connection})$$

Both Eq. (13) and Fig. 19 (a) show that, for a regular RHS connection associated with a large end distance, it is primarily the two walls or the two welds in the longitudinal direction which are considered effective in resisting the applied loads. This agrees with the branch stress distribution observed for the control specimens at the connection load of $N_{1,3\%}$ (see Fig. 15 (b) for the $2\gamma = 34$ chord). In Eq. (13), an effective weld length in the transverse direction, taken the same as the effective branch width b_e (given by Eq. K1-1 of AISC 360-16) used for checking local yielding of a branch, is also included, where $b_e/2$ cannot exceed $b_1/4$ when $\beta > 0.85$ or $\theta_1 > 50^\circ$. Thus, it is acknowledged that a portion of the branch or weld transverse lengths may be considered effective.

(a) Regular connection

(b) Offset connection

Fig. 19. Effective weld lengths for RHS-to-RHS X-connections ($\theta_1 = 90^\circ$)

As described earlier, the offset connections with $e = 25\text{mm}$ show a similar compressive stress distribution along the branch longitudinal walls, at the connection yield load, as the control specimens for both HSS chords (compare Fig. 15 (a) with (b) for the $2\gamma = 34$ chord). For the offset connections, the tensile stresses seen in the branch transverse wall closest to the open chord end may render the transverse weld length b_e along this side to be ineffective. Thus, for the case of branch axial loading, the weld effective length developed for a regular RHS connection may be applied, with a slight modification, to an offset RHS connection, as presented by Eq. (14) and Fig. 19 (b).

$$l_e = \frac{2h_1}{\sin \theta_1} + b_e \quad (\text{Offset RHS connection})$$

6. Conclusions and Recommendations

Based on the results for the 12 connection tests, shown in Fig. 20, the following conclusions and recommendations are made for RHS-to-RHS axially-loaded T-, Y-, and X-connections:

- When a connection has a small end distance, e , to an open chord end, a modified yield line mechanism controls connection failure and produces a connection strength lower than that associated with “regular” connections (remote from the chord ends). The proposed closed-form analytical model herein, which is evaluated against the experimentally-determined 3% b_0 deformation limit load, is shown to be an accurate predictor of the yield load P_Y for “offset” connections (near an open chord end), and P_Y can be conservatively estimated from:

$$P_Y \sin \theta_1 = \frac{f_{y0} t_0^2}{(1-\beta)} \left[\frac{2e}{b_0} + \frac{2h_1}{b_0 \sin \theta_1} + 2\sqrt{1-\beta} \right] Q_f \quad \text{for } e < e_{\min}$$

where $e_{\min} = b_0 \sqrt{1-\beta}$ represents the critical end distance at which full connection capacity is achieved.

This minimum end distance, $e_{\min}$, has also been adopted in Table K3.2A of AISC 360-16, as a requirement for the application of traditional design rules for RHS connections. Alternatively, an end distance equal to the chord member width, or $e_{\min} = b_0$, is conservative.

- The proposed amendment to EN 1993-1-8, requiring an end distance as the maximum of $(2\gamma/10)b_0$ or $2.5b_0$ in order to achieve full connection strength, is deemed excessively conservative and not suitable for open-ended RHS chord members in real structures. It is, however, considered suitable (and conservative) for determining the minimum chord lengths of RHS chord members used for isolated, “symmetrical” connections in experimental or numerical tests.
- When a connection is closer to an open chord end than $e_{\min}$, reducing the strength predicted by traditional yield line equations for RHS connections by 50%, in lieu of a detailed calculation, as recommended by the AISC 360-16 Commentary, is safe for design.
- Stiffening the chord end with a cap plate is effective in developing the strength of the connected face against chord plastification. A minimum end distance, $e_{\min}$, does not apply for this case.
- The branch member in an end connection needs to be laterally restrained (which is typically the case when it is connected to the rest of the frame in a real structure) to prevent lateral movement at the branch top, due to a rotation applied at the branch base.
- The weld effective lengths provided for a regular connection, which are used to proportion welds for the actual forces in the branch, can also be applied to an offset connection with a slight modification of $l_e = 2h_1/\sin \theta_1 + b_e$, for the case of branch axial loading.

The conclusions summarized above, which are all associated with the chord plastification limit state, only apply if $\beta \leq 0.85$. They can be extended to T- and Y-connections, since flexure of the chord connecting face should produce the same effects in these connections as in the X-connections studied in this research. For a Y-connection with $\theta_1 < 90^\circ$, the connection capacity depends on the component of the branch load normal to the chord, $P_Y \sin \theta_1$, with a branch footprint of $h_1/\sin \theta_1$, which has been accounted for in the equations above.

6.1.1. Application to Other Connection Types

The minimum end distance developed for the RHS-to-RHS X-connections should be applicable to the following connection types, for the case of branch axial loading:

- Gapped and overlapped K- and N-connections, which consist of a compression branch member pushing into the chord face and a tension branch member pulling out. Compared to X-connections, the resulting chord face deformations are expected to be less.
- Longitudinal plate-to-RHS connections, as the same limit state of chord plastification governs. For these plate-to-RHS connections, β would equal t_1/b_0 (typically varying between 0.05 to 0.25) and the end distance would be $e_{\min} = b_0\sqrt{1-t_1/b_0}$, where t_1 is the plate thickness.
- Transverse plate-to-RHS connections, which are generally not governed by chord plastification for practical values of β and low compressive stresses in the chord connecting face. However, if either local yielding of the plate or punching shear in the chord is critical, the associated local deformations are expected to be more confined than those produced by chord face plastification.

Fig. 20. 12 tested specimens

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496 **List of Symbols**

A	Cross-sectional area (mm^2)
b_e	Effective branch width (mm)
b_0, b_0'	Nominal/full (out-of-plane) width of RHS chord, effective width ($= b_0 - t_0$) (mm)
b_1, b_1'	Nominal/full (out-of-plane) width of RHS branch, effective width ($= b_1 + 2w$) (mm)
d_0	Outside diameter of CHS chord (mm)
E	Modulus of elasticity (MPa)
$e, e', e_{\min}$	End distance from edge of branch to chord end, measured from edge of weld ($= e - w$), minimum required end distance (mm)
f_y, f_{y0}	Yield stress of material, yield stress of RHS chord (MPa)
f_u	Ultimate stress of material (MPa)
h_0	Outside (in-plane) depth of RHS chord (mm)
h_1, h_1'	Nominal/full (in-plane) depth of RHS branch, effective depth ($= h_1/\sin\theta_1 + 2w$) (mm)
l_e	Effective weld length (mm)
l_0	Chord length (mm)
m	Mechanism 2: slope of inclined yield lines from branch side to open chord end
N_1	Branch axial load (N)
$N_{1,3\%}$	Connection load at an ultimate deformation of 3% b_0 (N)
P_Y, P_Y'	Connection load predicted by yield line mechanisms using full, effective dimensions (N)
Q_f	Chord stress function
t_0, t_1	Wall thickness of HSS chord, wall thickness of HSS/plate branch (mm)
w	Measured fillet weld size (horizontal leg length) (mm)
x, x'	Mechanism 3: distance required for inclined yield lines from edge of branch to open chord end to converge, measured from edge of weld ($= x - w$) (mm)
β, β'	Nominal/full width ratio ($= b_1/b_0$ for RHS), effective width ratio ($= b_1'/b_0'$ for RHS)
δ	Vertical connection displacement (mm)
ε_{rup}	Rupture strain of material
2γ	Chord width (diameter)-to-thickness ratio ($= 2b_0/t_0$ for RHS, $= 2d_0/t_0$ for CHS)
θ_1	Included angle between branch and chord ($^\circ$)

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