DESIGN OF FILLET WELDS IN CHS JOINTS FOR THE BRACE CAPACITY

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EN 1993-1-8 and ISO 14346 permit fillet welds in circular hollow section (CHS) joints to be designed as either "fit-for-purpose" or for the brace capacity. For the latter approach, designers often specify the "minimum fillet weld sizes" given in CIDECT Design Guide No. 1. However, these sizes are based on assuming that a CHS brace member is fillet welded at 90° to a flat plate, which in most cases is inaccurate. Moreover, the CIDECT Design Guide No. 1 "minimum sizes" are based on historic values of the base metal ultimate strength and correlation factors for fillet welds that are inconsistent with current Eurocode preNorms. In this paper, an accurate approach to apply the EN1993-1-8 Directional Method to CHS joints is developed, and exemplary new design charts for minimum fillet weld sizes that develop the axial capacity of a brace in a CHS X-, T- and Y-joint are produced, for grade S355 steel.

Keywords: Circular hollow sections, X-joints, fillet welds, design procedures.

1 Introduction

At present, the design of fillet welds in circular hollow section (CHS) joints can be easily carried out by using the "minimum throat thicknesses" for fillet welds given in CIDECT Design Guide No. 1 (Wardenier et al. 2008) (Table 1) to develop the brace capacity. This approach is reflected in EN1993-1-8 Clause 7.3.1(4) (CEN 2010) and ISO 14346 (ISO 2013), and is based on rational analysis of a single-sided fillet weld using the Directional Method (CEN 2010).

Table 1. Minimum fillet weld throat thicknesses to develop the capacity of an EN 10219 cold-formed hollow section brace with $3 \leq t_1 \leq 16$ mm, by CIDECT DG1 and prEN 1993-1-8

Steel Grade	f_y (MPa)	f_u (MPa)	f_y/f_u	β_w[3]	Minimum Throat Thickness (a) CIDECT[1]	Eq. (8)[2,3]
S235JRH	235	360	0.653	0.80	$0.92t_1$	$0.92t_1$
S275J0H/S275J2H	275	410	0.671	0.85	$0.96t_1$	$1.01t_1$
S355J0H/S355J2H	355	470	0.755	0.90	$1.10t_1$	$1.20t_1$
S420NH/S420NLH	420	520	0.808	0.88	$1.42t_1$	$1.26t_1$
S460NH/S460NLH	460	540	0.852	0.85	$1.48t_1$	$1.28t_1$

[1] Wardenier et al. (2008); [2] CEN (2010); [3] CEN (2018).
Note: t_1 = thickness of brace.

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According to the Directional Method (CEN 2010), the design resistance of a fillet weld is sufficient if Eqs. (1) and (2) are satisfied along the weld length:

$$\left[\sigma_{\perp}^2+3\left(\tau_{\perp}^2+\tau_{\parallel}^2\right)\right]^{0.5} \leq \frac{f_u}{\beta_w \gamma_{M2}}, \text{ and} \tag{1}$$

$$\sigma_{\perp} \leq 0.9 f_u / \gamma_{M2} \tag{2}$$

where $\sigma_{\perp}$ = normal stress perpendicular to the throat; $\tau_{\perp}$ = shear stress (in the plane of the throat) perpendicular to the weld axis; $\tau_{\parallel}$ = shear stress (in the plane of the throat) parallel to the weld axis (Fig. 1); γ_{M2} = partial factor for the resistance of the weld equal to 1.25 per EN1993-1-8 Table 2.1 (CEN 2010); f_u = ultimate strength of base metal (weaker part joined); and β_w = correlation factor for fillet welds (which relates f_u to the ultimate strength of the matching filler metal). However, for regular strength steels, Eq. (1) will always govern (Herion et al. 2011).

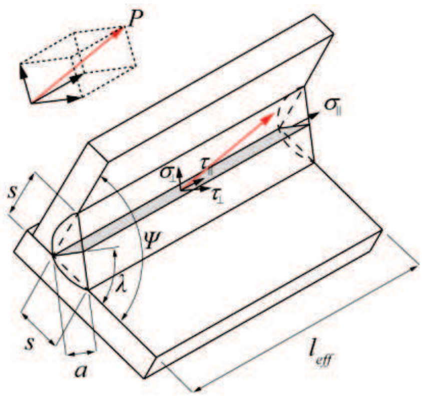

Figure 1. Stress components acting on the plane of the weld throat; weld cross-sectional dimensions.

Assuming a uniform distribution of stress due to a design force (P) acting on the design throat area of the weld ($A_w = al_{eff}$, where a = throat thickness and l_{eff} = weld effective length), it can be shown that:

$$\tau_{\parallel} = \frac{P\cos\theta}{al_{eff}}, \tag{3}$$

$$\sigma_{\perp} = \frac{P\sin\theta\cos\lambda}{al_{eff}}, \text{ and} \tag{4}$$

$$\tau_{\perp} = \frac{P\sin\theta\sin\lambda}{al_{eff}} \tag{5}$$

where θ = angle between the design force and the longitudinal axis of the weld; and λ = angle of inclination of the weld throat plane, measured in a plane perpendicular to the weld axis.

By substituting Eqs. (3) – (5) into Eq. (1), it can be shown that the design resistance of a fillet weld ($F_{w,Rd}$) implied by the Directional Method (CEN 2010) is:

$$F_{w,Rd} = \frac{f_u}{\beta_w \gamma_{M2}} \frac{a l_{eff}}{\left[\sin^2\theta\cos^2\lambda + 3\left(\sin^2\theta\sin^2\lambda + \cos^2\theta\right)\right]^{0.5}} \quad (6)$$

The CIDECT minimum a values in Table 1 are based on setting Eq. (6) equal to the design plastic resistance of the brace cross-section under axial load ($N_{pl,Rd}$):

$$N_{pl,Rd} = \frac{f_{y1}}{\gamma_{M0}} A_1 \approx \frac{f_{y1}}{\gamma_{M0}} t_1 l_1 \quad (7)$$

where f_{y1} = yield strength of the brace; A_1 = cross-sectional area of brace; and γ_{M0} = partial factor for the resistance of the cross-section equal to 1.00 per EN1993-1-8 Table 2.1 (CEN 2010); t_1 = thickness of the brace; and l_1 = perimeter of the brace (= πd_1, where d_1 = diameter of brace).

Values of θ = 90° and λ = 45° are assumed in Eq. (6), along with $l_{eff} = l_1$, such that:

$$a \geq \sqrt{2}\beta_w \frac{f_{y1}}{f_u} \frac{\gamma_{M2}}{\gamma_{M0}} t_1 \quad (8)$$

Eq. (8) is accurate for joints involving a CHS brace member fillet welded at 90° to a flat plate, but inaccurate for CHS-to-CHS joints (since the total weld length > l_1 and brace angle < 90°, typically). Moreover, the values of f_u and β_w that were used by CIDECT to derive the minimum a values in Table 1 (in conjunction with Eq. (8)) are out-of-date. To illustrate this, minimum a values calculated using Eq. (8) with f_u and β_w values from current Eurocode preNorms (CEN 2016, 2018) are tabulated, in Table 1. This paper presents a new approach to: (a) accurately apply the Directional Method (CEN 2010) to fillet welds in CHS joints; and (b) design them for the brace capacity.

2 General Considerations

In a CHS joint, θ and λ change continuously with respect to the "subtended angle" (x), or "the angle measured clockwise around the brace, with 0° and 180° corresponding to the crown points, and 90° corresponding to the saddle points" (Fig. 2). The exact change in θ (angle of the load direction to the local weld axis direction) and λ with x depends on the brace-to-chord inclination angle (θ_1), brace-to-chord width ratio (β), and weld details of a joint. If one assumes that the fillet weld around the brace is made with equal-sized legs (such that $\lambda = \psi/2$ in Fig. 2, where ψ = local dihedral angle), then variations in θ and λ with respect to x can be summarized according to Fig. 3 for joints with different values of θ_1 and β.

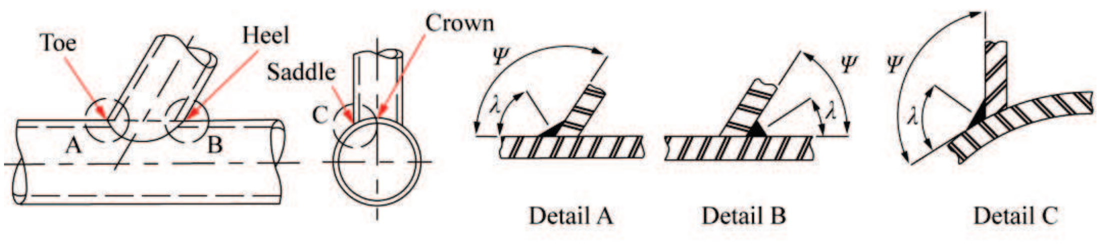

Figure 2. Fillet weld details.

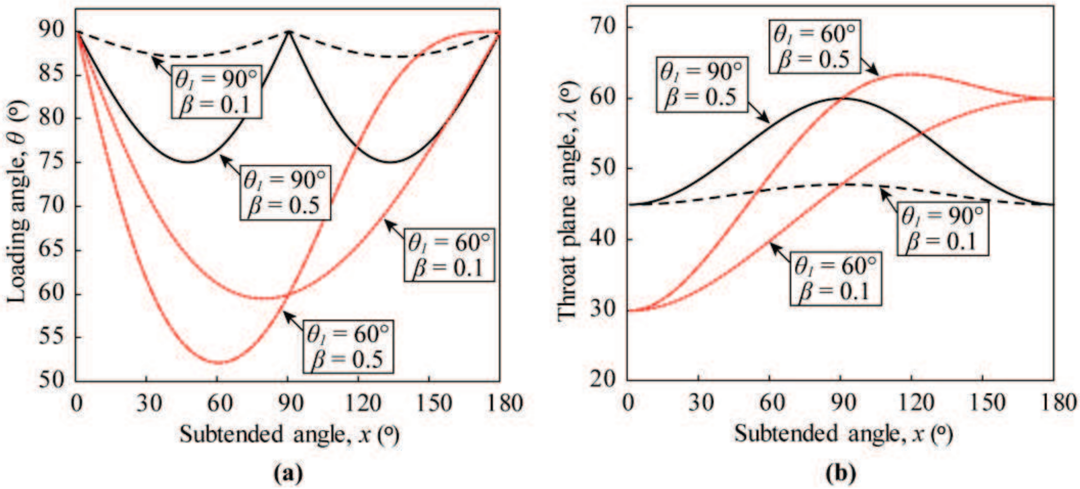

Figure 3. Typical variations in (a) θ and (b) λ with respect to x in a CHS joint.

3 Directional Method Procedure

To accurately apply the Directional Method (CEN 2010) to CHS joints (taking into account variations in θ and λ with respect to x, as shown in Fig. 3) the following procedure can be used:

(i) Calculate the coordinates of the brace/chord intersection at two points corresponding to x and $x+\Delta_x$ to approximate the weld axis $\bar{V}_1$ at $x+\Delta x/2$. In the brace coordinate system (Fig. 4a):

$$\bar{V}_1=\left[\left(-l_{t,x+\Delta x}+l_{t,x}\right),\left(r_1\sin\left(x+\Delta x\right)-r_1\sin x\right),\left(-r_1\cos\left(x+\Delta x\right)+r_1\cos x\right)\right] \tag{9}$$

where r_1 = radius of brace (= $d_1/2$), and:

$$l_{t,x}=\frac{r_1\left(1-\cos x\right)}{\tan\theta_1}+\frac{r_0-\sqrt{r_0^{\,2}-\left(r_1\sin x\right)^2}}{\sin\theta_1} \tag{10}$$

where r_0 = radius of chord (=$d_0/2$). The dimension $l_{t,x}$ denoting "template length" is shown in Fig. 4a; for $l_{t,x+\Delta x}$, substitute $x+\Delta x$ for x in Eq. (10).

(ii) Transform the vector $\bar{V}_1$ into the chord coordinate system (Fig. 4b). The resulting vector $\bar{N}_1$ is the weld axis (Fig. 4c).

(iii) Calculate the magnitude of the vector $\bar{N}_1$ to determine the length of the "linear" weld element i (l_i) between x and $x+\Delta x$ (Fig. 4d). The smaller Δx is, the closer the approximation will be to the actual length.

$$l_i=\left|\bar{N}_1\right| \tag{11}$$

(iv) Repeat the above to calculate l_i again for all values $0° \leq x \leq 360°-\Delta x$, then sum the results to find the total weld length (l_w), i.e.:

$$l_w = \sum l_i \tag{12}$$

(v) Compute the vector normal to the chord at x+Δx/2 ($\bar{N}_2$):

$$\bar{N}_2 = \left[(0),\left(r_1 \sin\left(x+\Delta x/2\right)\right),\left(A\right)\right], \text{ with} \tag{13a}$$

$$A = \sqrt{r_0^{\,2} - \left(r_1 \sin\left(x+\Delta x/2\right)\right)^2} \tag{13b}$$

where A = height from chord centreline (Fig. 4b).

(vi) Compute the vector in the plane tangent to the chord and perpendicular to the weld axis at $x+\Delta x/2$ ($\bar{N}_3$ in Fig. 4c):

$$\bar{N}_3 = \bar{N}_1 \times \bar{N}_2 \tag{14}$$

(vii) Compute the vector normal to the brace at $x+\Delta x/2$ in the brace coordinate system ($\bar{V}_4$):

$$\bar{V}_4 = \left[(0),\left(r_1 \sin\left(x+\Delta x/2\right)\right),\left(-r_1 \cos\left(x+\Delta x/2\right)\right)\right] \tag{15}$$

(viii) Transform the vector $\bar{V}_4$ into the chord coordinate system, giving the vector $\bar{N}_4$ (Figs. 4b and 4c).

(ix) Compute the vector in the plane tangent to the brace and perpendicular to the weld axis ($\bar{N}_5$ in Fig. 4c), using the cross product of vectors $\bar{N}_4$ and $\bar{N}_1$:

$$\bar{N}_5 = \bar{N}_4 \times \bar{N}_1 \tag{16}$$

(x) Compute ψ (Fig. 4c) using the dot product of vectors $\bar{N}_3$ and $\bar{N}_5$:

$$\psi = \cos^{-1}\left(\frac{\bar{N}_5 \bullet \bar{N}_3}{\left|\bar{N}_5\right|\left|\bar{N}_3\right|}\right) \tag{17}$$

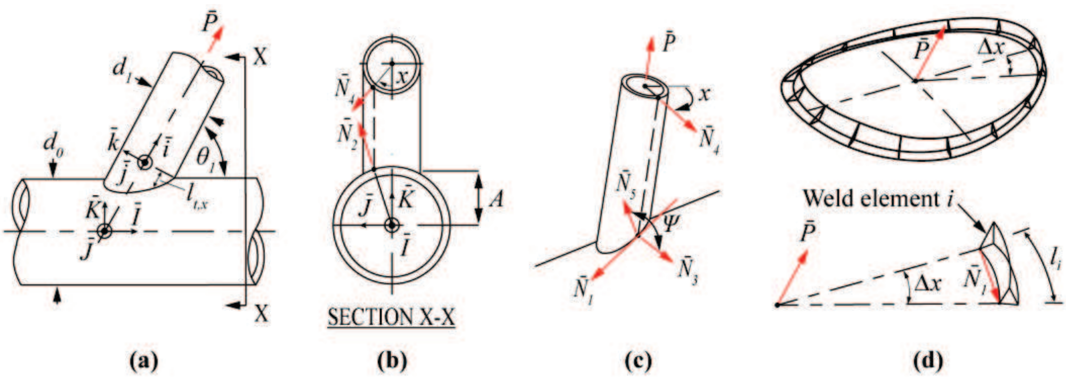

Figure 4. Vectors and notation.

(xi) Compute the vector that defines the direction of the design force ($\bar{P}$) in the chord coordinate system.

$$\bar{P} = \left[(\cos\theta_1), (\sin\theta_1), (0) \right] \tag{18}$$

(xii) Compute the angle of loading of each weld element i (θ_i):

$$\theta_i = \cos^{-1}\left(\frac{\bar{P} \bullet \bar{N}_1}{|\bar{N}_1||\bar{P}|} \right) \tag{19}$$

(xiii) Define a "directional method factor" ($K_{CHS,DM}$) by writing Eq. (3) as:

$$F_{w,Rd} = \frac{f_u}{\beta_w \gamma_{M2}} \left(K_{CHS,DM} \right) \left(l_{eff} \right) a, \text{ with} \tag{20a}$$

$$K_{CHS,DM} = \frac{1}{\left[\sin^2\theta \cos^2\lambda + 3\left(\sin^2\theta \sin^2\lambda + \cos^2\theta \right) \right]^{0.5}} \tag{20b}$$

(xiv) Calculate the value of $K_{CHS,DM}$ for each weld element i by substituting λ_i and θ_i for λ and θ in Eq. (20b). With Fig. 3 weld details, $\lambda_i = \psi/2$. Then, calculate the value of $K_{CHS,DM}$ for the entire weld by taking a weighted average of the $K_{CHS,DM}$ values for each weld element i (to account for variations in l_i); i.e.:

$$K_{CHS,DM} = \frac{1}{l_w} \sum \frac{l_i}{\left[\sin^2\theta_i \cos^2\lambda_i + 3\left(\sin^2\theta_i \sin^2\lambda_i + \cos^2\theta_i \right) \right]^{0.5}} \tag{21}$$

The foregoing procedure is valid for CHS joints with $\theta_1 \geq 60°$ and $\beta \leq 0.5$ (Luyties and Post 1988; Tousignant and Packer 2017, 2018) because prEN1993-1-8 (CEN 2018) Clause 6.3.2.1(1) restricts the use of fillet welds to connecting parts where $60° \leq \psi \leq 120°$, and for fillet welds having a constant throat thickness (a in Fig. 1) and equal leg sizes (s in Fig. 1). The use of details A, B and C in Fig. 2 have also been assumed. For connections meeting these criteria, solutions for values of $K_{CHS,DM}$ are given in Table 2.

Table 2. Values of $K_{CHS,DM}$ for a fillet weld in a CHS joint, for use in Eq. (20a).

Brace-to-chord width ratio, β	Brace inclination angle, θ_1			
	90°	80°	70°	60°
0	0.707	0.705	0.700	0.691
0.1	0.698	0.697	0.692	0.683
0.2	0.690	0.688	0.684	0.676
0.3	0.681	0.680	0.676	0.668
0.4	0.673	0.672	0.668	0.661
0.5	0.664	0.663	0.660	0.654

Note: The above values for $K_{CHS,DM}$ assume a constant weld throat thickness and equal leg sizes (a and s, respectively, in Fig. 1), and use of welding details A, B and C shown in Fig. 2.

4 Application to Design of Fillet Welds for the Brace Capacity

Using Eq. (20a,b) and Table 2, a new approach can be taken to derive "minimum throat thicknesses" for fillet welds, to potentially replace those given by CIDECT in Design Guide No. 1 (Wardenier et al. 2008) (Table 1). By substituting the following expression for l_{eff} into Eq. (20a) (AWS 2015):

$$l_{eff} = \pi d_1 K \text{, with} \tag{22a}$$

$$K = \frac{1}{2\pi \sin\theta_1} + \frac{1}{3\pi}\frac{3-\beta^2}{2-\beta^2} + 3\sqrt{\left(\frac{1}{2\pi \sin\theta_1}\right)^2 + \left(\frac{1}{3\pi}\frac{3-\beta^2}{2-\beta^2}\right)^2} \tag{22b}$$

and setting Eq. (20a) equal to or greater than the brace axial load capacity $N_{pl,Rd}$ (Eq. (7)), a new equation (analogous to Eq. (8), but more accurate) can be derived; i.e.:

$$a \geq \left(1 - 2\gamma_1^{-1}\right)\beta_w \frac{1}{K(K_{CHS,DM})} \frac{f_{y1}}{f_u} \frac{\gamma_{M2}}{\gamma_{M0}} t_1 \tag{23}$$

where γ_1 = half diameter-to-thickness ratio of the brace.

Eq. (23) is a function of numerous variables, including f_{y1}, f_u, and β_w, joint parameters γ_1, β and θ_1 (via K and $K_{CHS,DM}$), and t_1. As a result, most engineers would likely prefer to apply Eq. (23) in design by using design charts, rather than solving it directly. Exemplary design charts for applying Eq. (23) to CHS joints with θ_1 = 90° and 60° made from grade S355 steel (with f_y/f_u = 0.755 and β_w = 0.90) (CEN 2016, 2018) (Table 1) are presented in Fig. 5a,b. Where applicable, the recommended minimum fillet weld throat thicknesses given by CIDECT (Wardenier et al. 2008) and Eq. (8) are also shown in Fig. 5a,b – by bold, red (dashed or solid) lines.

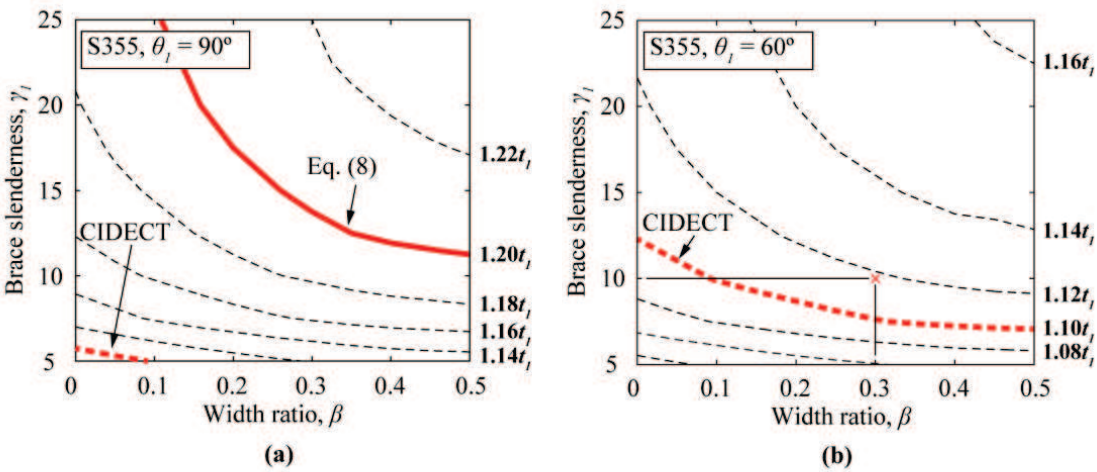

Figure 5. Minimum throat thicknesses, a, for fillet welds in CHS-to-CHS X-, T- and Y-joints made from grade S355 steel with: (a) θ_1 = 90° and (b) θ_1 = 60°

Fig. 5a,b illustrates that CIDECT's (Wardenier et al. 2008) minimum a = 1.10t_1 for grade S355 steel is generally unconservative (i.e. it is smaller than most sizes that would be given by

Eq. (23)). In contrast, the Eq. (8) minimum $a = 1.20t_1$ for grade S355 steel is generally conservative (i.e. it is larger than most sizes that would be given by Eq. (23)). If one considers a joint with $\theta_1 = 60°$, $\gamma_1 = 10$ and $\beta = 0.3$, made from grade S355 steel (with $f_y/f_u = 0.755$ and $\beta_w = 0.90$), then $a = 1.12t_1$ using Eq. (23) (Fig. 5b), which is 2% larger than $a = 1.10t_1$ given by CIDECT (Wardenier et al. 2008) (Table 1) and 6% smaller than $a = 1.20t_1$ using Eq. (8) (Table 1). Alternatively, if one considers a joint with $\theta_1 = 60°$, $\gamma_1 = 10$ and $\beta = 0.3$, made from grade S460 steel (with $f_y/f_u = 0.853$ and $\beta_w = 0.85$), for which design charts are not shown, then $a = 1.19t_1$ using Eq. (23), which is 20% smaller than $a = 1.48t_1$ given by CIDECT (Wardenier et al. 2008) (Table 1) and 7% smaller than $a = 1.28t_1$ given by Eq. (8) (Table 1). By comparing the results of Eq. (23) and Eq. (8) in the preceding examples (since it was already shown that CIDECT's minimum a values are out-of-date), it can be seen that this new approach (Eq. (23)) can lead to smaller prequalified sizes for fillet welds in CHS joints (in particular, those made of higher strength steels).

5 Conclusions

A procedure has been developed to accurately apply the Directional Method of EN1993-1-8 (CEN 2010) to fillet welds in CHS joints; it has thereafter been used in conjunction with modern values of f_u and β_w from current Eurocode preNorms (CEN 2016, 2018) to derive new "minimum throat thicknesses" for fillet welds to develop the capacity of an axially loaded CHS brace. These new "minimum sizes" are believed to represent optimal sizes achievable for fillet welds in conjunction with the requirements of EN1993-1-8 (CEN 2010).

Typical design charts for selecting prequalified fillet weld sizes according to this new approach were produced for axially loaded CHS X-, T-, and Y-joints with $\theta_1 = 90°$ and 60°, made from grade S355 steel (Figs. 5a and 5b). However, the recommendations in this paper are applicable to other axially loaded CHS X-, T- and Y-joints, for geometric combinations of members where fillet welding is permissible (i.e. $\theta_1 \geq 60$ degrees and $\beta \leq 0.5$).

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