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Re-evaluation of the shear criterion for RHS overlap joints

This paper deals with a proposal to revise the effective width terms in the brace shear criterion for overlap joints in rectangular hollow sections (RHS). The background to the design equations in ISO 14346 for the failure modes, brace effective width, chord M-N interaction and brace shear are described first. That is followed by the relation between overlap joints in circular hollow sections and those in rectangular hollow sections and those with an I- or H-section chord. Finally, it is shown that the effective width terms in the brace shear criterion can – in the case of 100 % overlap joints – be better related to the thickness of the overlapped brace. In the case of smaller overlaps, $\lambda_{ov,limit} \leq \lambda_{ov} \leq 100$ %, the effective width should also be related to the thickness of the overlapping brace, where $\lambda_{ov,limit}$ depends on whether the hidden seam at the toe of the overlapped brace has been welded.

1 Introduction

This paper deals with the failure modes of overlap joints between rectangular hollow sections (RHS). Fig. 1 shows an overlap joint with the symbols for the dimensions and the definition of the overlap. Within the scope of the update to EN 1993-1-8 [1] “Design of joints”, the brace shear criterion needs to be included for overlap joints between hollow sections and therefore re-evaluated. There is no equation in the current version of EN 1993-1-8 and designers often use the brace shear equation included in ISO 14346 [2], which is also adopted in CIDECT Design Guides 1 and 3 [3], [4]. This brace shear equation for RHS overlap joints is based on the work of Chen et al. [5], [6], [7], [8]. This paper re-evaluates that shear criterion and proposes a more simplified, logical approach.

A numerical investigation was carried out in [5] to determine the strength of multi-planar KK-joints between rectangular hollow sections. In that investigation it was observed that for overlap joints, a chord face local buckling failure could still occur due to the localized brace shear force transfer to the chord. This failure mode was thus at that time not sufficiently covered by the resistance criteria in the codes and recommendations or excluded by the b_0/t_0 limits in the validity range. Therefore, it was decided to investigate 100 % overlap K- and KK-joints in more detail in [6] (i.e. joints where the heel of the overlapping brace meets the toe of the overlapped brace).

2 Background to the EN 1993-1-8 recommendations

Up until 2011 the design recommendations for RHS overlap joints in EN 1993-1-8 [1] only specified that the brace effective width criterion be checked for the overlapping brace (failure mode 1 in Fig. 4). Further, the efficiency of the overlapped brace (i.e. the joint resistance divided by the brace squash load) should not exceed that of the overlapping brace. These recommendations were based on the IIW recommendation of 1989 [9] and the 1st edition of CIDECT Design Guide No. 3 [4].

At the time of drafting those rules, it was known that chord face local buckling failure could occur. This was observed, for example, in the overlap joints in the Pisa girder tests [10], the isolated joint tests in Corby [11] and the Delft tests [12]. Wardenier and de Koning [13] had indicated in 1976 that brace shear failure at the connection with the chord face could also be a possible failure mode, especially when $h_j < b_j$. Packer and Davies [14] and Davies et al. [15] investigated various local buckling failure modes analytically, e.g. using yield line models.

At that time, in all the experimental tests carried out on uni-planar joints, chord face local buckling failure was only observed for overlap joints with chords for $b_0/t_0 > 40$. To avoid this failure mode, this limit of 40, or sometimes 35, was included in the codes and recommendations. Initially, only a brace effective width criterion based on [16] was used to cover the strength of RHS overlap joints, since the moments due to eccentricity would be accounted for in the member check.

3 Investigation in CIDECT programme 5BN and additional investigations

3.1 RHS 100 % overlap joints

Chen et al. [6], [7] investigated 100 % RHS overlap K- and KK-joints in CIDECT programme 5BN, whereas Liu et al. [8] additionally investigated 50 % RHS uni-planar and multi-planar overlap joints. In the basic numerical investigation with 100 % RHS overlap joints, K- and KK-joints were investigated with the parameters $\theta = 45°$, $\beta = 0.6$, $2\gamma = 31.75$, $\tau = 0.79$, S355 steel and an artificial steel S860. Additional investigations [7] were conducted for the pa-

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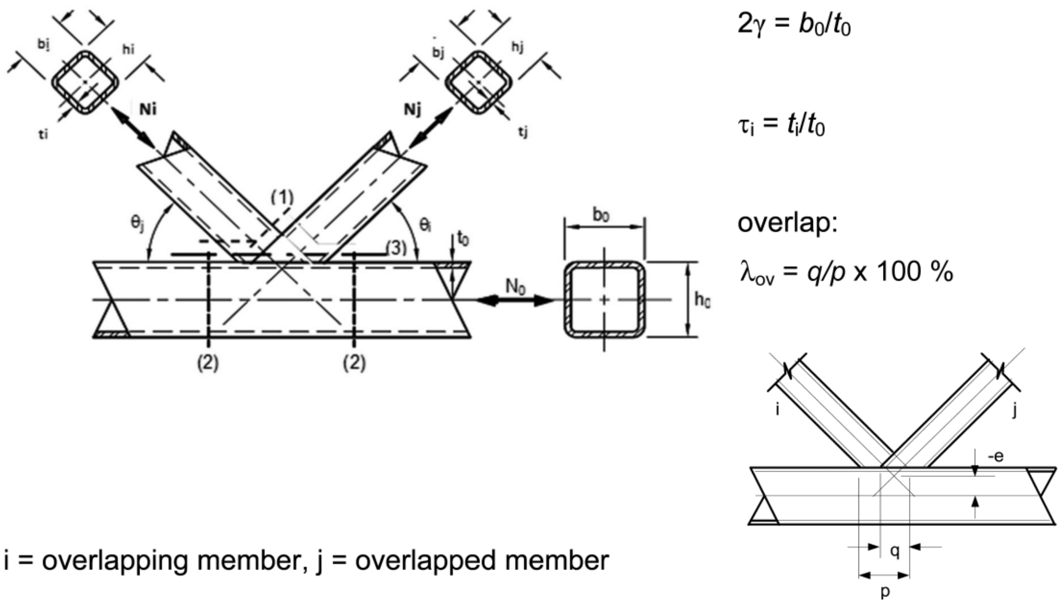


Fig. 1. RHS overlap joint where cross-sections (1), (2) and (3) have to be checked

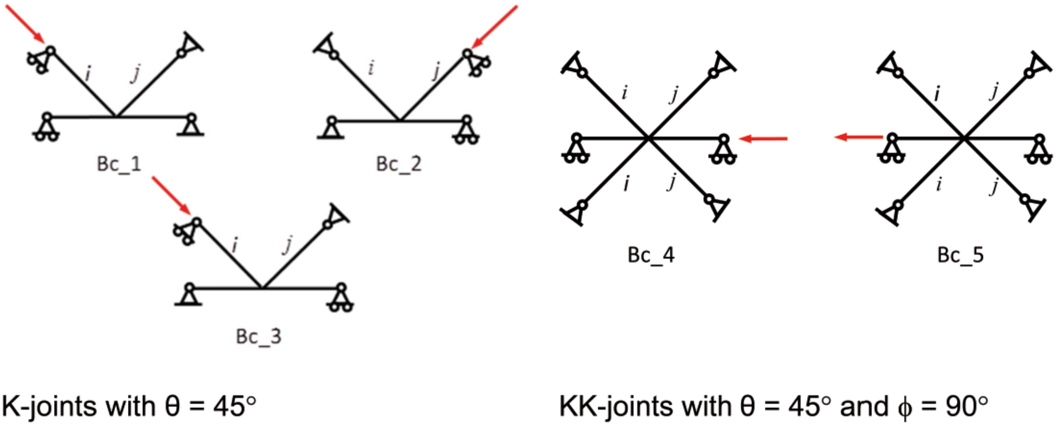


Fig. 2. Boundary conditions used [6], [7]

rameters $2\gamma = 15$ and 35, $\beta = 0.4$ and 0.8, $\tau = 0.55$ and 1.0. Fig. 2 shows the boundary conditions and Fig. 3 shows the element mesh used in [6], [7].

All numerical calculations were performed with the Marc 2003 program with 8-node iso-parametric thick shell elements, which were also used for previous investigations [5]. The Marc input requires true stress–true strain input for the material properties. The three basic failure modes are shown in Fig. 4; the fourth failure mode, strut buckling, is not shown. The capacities of the joints were determined by the maximum load capacity because this appeared before the deformation limit of a 3 % b_0 indentation in the chord face.

In the analyses, the chord at the toe and the heel locations of the overlapped brace have been checked for the interaction between axial load and bending moment. It should be noted that due to induced deformations rather than induced forces, the resulting bending moments in the chords are somewhat larger than the moments due to the resulting brace shear force multiplied by the eccentricity $0.5h_0$ and distributed over both chord ends.

The analysis numbers (u for uniplanar, m for multiplanar), boundary conditions, dimensions, yield stresses and failure modes together with the member efficiencies and the checks for failure modes 1 to 3 are listed in Table 1. Failure modes 1 to 4 (see Fig. 4) in this paper are differently numbered from those in [6]–[8]. Currently, only mode 1 is sufficiently covered in EN 1993-1-8.

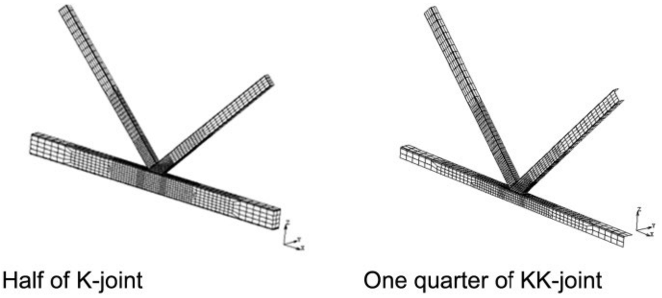
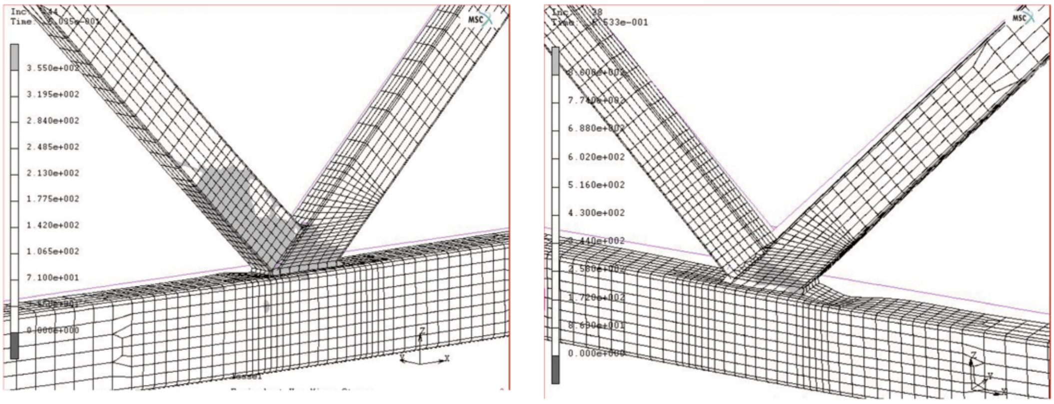


Fig. 3. FE meshes used for overlap joints

Failure mode 1

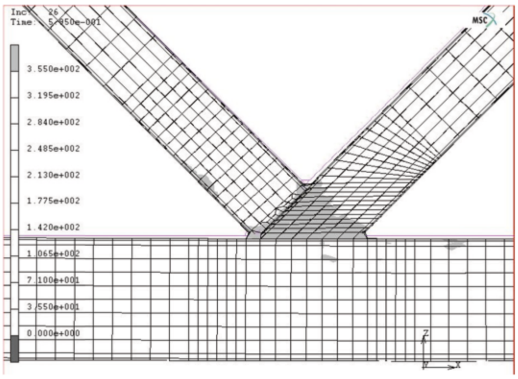
The brace effective width criterion for failure mode 1, included in [1]–[4] and based on [12], [16], for 100 % RHS overlap joints is given by

$$N_{i,Rd} = f_{yi}\, t_i\, (2h_i + b_i + b_{e,ov} - 4t_i) \qquad (1)$$



Mode 1: Overlapping brace yielding and/or local buckling (effective width)

Mode 2: Local chord failure by yielding or local buckling



Mode 3: Overlapped brace shear failure

Fig. 4. Failure modes (mode 4 not shown)

$$\text{where } b_{e,ov} = \left(\frac{10}{b_j/t_j}\right)\left(\frac{f_{yj}t_j}{f_{yi}t_i}\right) b_i \text{ but} \le b_i \tag{1a}$$

Failure mode 2

Owing to a possible shear lag influence, the RHS chord was checked for the interaction between axial load and bending moment. In [14] it is shown that for failure mode 2, a linear interaction (Eq. (2) gives the best fit for the test results:

$$R_{N_0-M_0} = \frac{N_0}{N_{0,Rd}} + \frac{M_0}{M_{0,Rd}} \le 1.0 \tag{2}$$

Failure mode 3

As indicated in Table 1, most K-joints with the chord in compression failed by a combination of failure modes. In some cases, at maximum load on the K-joints and large shear stresses in the overlapped brace (failure mode 3), even the failure criteria for brace effective width (mode 1) and chord M-N interaction (mode 2) can be reached. This may explain why, in the experimental tests, brace shear was initially not reported as a failure mode.

In [6] the brace shear resistance at the chord connecting face was initially based on an effective shear area consisting of the two overlapped brace sides $h_j/\sin\theta_j$ and the brace cross-wall b_j at the connection with the overlapping brace i. Initially, no effective part b_{ej} was assumed for the cross-wall at the heel, which is less effective for shear, therefore $b_{ej} = 0$.

Assuming, conservatively, $f_{uj}/\sqrt{3}$ as the ultimate shear stress, the general equation for the ultimate limit shear resistance is given by

$$N_{S,Rd} = \frac{f_{uj}}{\sqrt{3}} \frac{(2h_j + b_j + b_{ej})\, t_j}{\sin\theta_j} \tag{3a}$$

The actual-to-predicted brace shear capacity checks V_u^* and V_u^{**} in Table 1 [5], [6] are given by Eq. (3b):

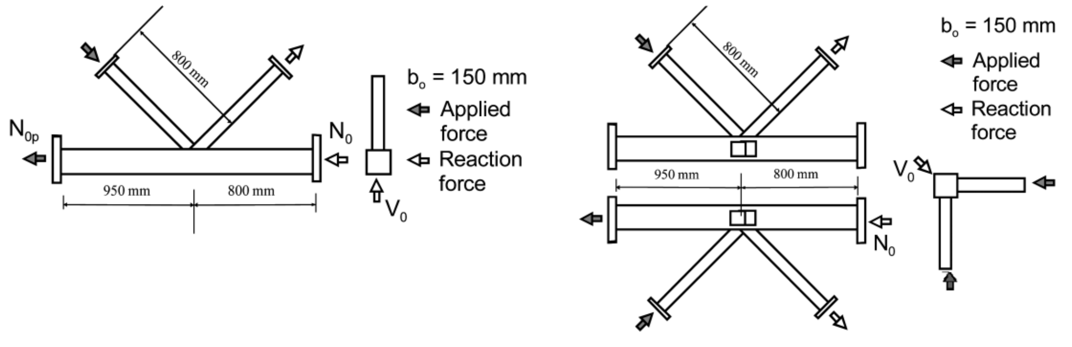
$$V_u = \frac{N_i \cos\theta_i + N_j \cos\theta_j}{\dfrac{f_{uj}}{\sqrt{3}} \dfrac{(2h_j + b_j + b_{ej})\, t_j}{\sin\theta_j}} \tag{3b}$$

As shown in Table 1, the unity check V_u^* for $b_{ej} = 0$ gave conservative results for those cases where mode 3 is absolutely critical (tests U6 and M3 to M9), i.e. high unity checks V_u^* (1.17–1.33). After further analyses and discussions it was decided to include an effective width

Table 1. Numerical models, dimensions and failure modes of K- and KK-joints

											Mode 3: Actual-to-predicted brace shear capacity for 4 conditions of b_e			
Tes t No.	Boundary	Chord	Braces	f_y chord	f_y braces	Failure mode	$N_{i,max}/A_if_{yi}$ *	N_0/A_0f_{y0}	$N_{i,max}/N_{i,eff.width}$	$R_{N0\text{-}M0}$	V_u *	V_u **	corrected	corrected
		bxhxt	bxhxt	N/mm²	N/mm²				mode 1	mode 2	$b_{ej} = 0$	$b_{ej} = b_e$	$b_{ej} = 6t_j$	$b_{ej} = 10t_j$
u1	Bc-1	200×200×6.3	120×120×5	355	355	2,3	0.78	–0.51	0.92	**1.07**	1.16	1.03	1.07	1.02
u2	Bc-1	200×200×6.3	120×120×**6.3**	355	355	2	0.69	–0.57	0.78	**1.07**	1.04	0.93	0.94	0.89
u3	Bc-2	200×200×6.3	120×120×**3.5**/5	355	355	2,1	0.90/0.74	–0.46	**1.00**	**1.07**	1.06	0.9	0.98	0.93
u4	Bc-1	200×200×6.3	120×120×5	355	**860**	2	0.37	–0.59		**1.11**	0.72	0.68	0.66	0.63
u5	Bc-1	200×200×6.3	120×120×5	**860**	355	1,4	0.83	–0.22	**0.98**	no data	1.19	0.94	1.10	1.04
u6	Bc-1	200×200×6.3	120×120×5	**860**	**860**	**3,2**	0.66	–0.43	0.77	0.95	**1.27**	**1.12**	**1.17**	**1.12**
u7	Bc-2	200×200×6.3	120×120×5	355	355	2,3	0.81	–0.51	0.95	**1.08**	1.17	1.04	1.08	1.03
u8	Bc-3	200×200×6.3	120×120×5	355	355	4,3	0.82	0.51	0.96	tension	**1.17**	**1.04**	**1.08**	**1.03**
u9	Bc-1	200×100×6.3	120×60×**6.3**	355	355	4,2,3	0.69	–0.57	0.83	**1.04**	1.14	1.00	0.98	0.90
u10	Bc-1	200×100×6.3	**60**×120×**6.3**	355	355	2,3	0.81	–0.70	0.80	**1.02**	1.14	1.07	1.01	0.98
M1	Bc-4	200×200×6.3	120×120×5	355	355	4,3	0.74/0.72	**–0.98**	0.87		1.13	1.00	1.04	0.99
M2	Bc-5	200×200×6.3	120×120×5	355	355	4,3	0.73/0.74	**0.99**	0.85		1.13	1.00	1.04	0.99
M3	Bc-4	200×200×6.3	120×120×5	**860**	355	**3,1**	0.82/0.91	–0.48	0.96		**1.32**	**1.04**	**1.22**	**1.16**
M4	Bc-5	200×200×6.3	120×120×5	**860**	355	**3,4**	0.81/0.93	0.48	0.95		**1.33**	**1.05**	**1.23**	**1.17**
M5	Bc-4	200×200×6.3	120×120×5	**860**	**860**	**3,4**	0.63/0.64	–0.85	0.73		**1.25**	**1.10**	**1.15**	**1.10**
M6	Bc-5	200×200×6.3	120×120×5	**860**	**860**	**3**	0.64/0.67	0.88	0.75		**1.30**	**1.15**	**1.20**	**1.14**
M7	Bc-4+Bc-5	200×200×6.3	120×120×5	355	355	**3,4**	0.81/0.87	0.56/–0.56	0.95		**1.27**	**1.12**	**1.17**	**1.12**
M8	Bc-4+Bc-5	200×200×6.3	120×120×5	355	355	**3,4**	0.81/0.85	0.99/–0.13	0.96		**1.27**	**1.12**	**1.17**	**1.12**
M9	Bc-4+Bc-5	200×200×6.3	120×120×5	355	355	**3,4**	0.82/0.80	0.20/–0.89	0.96		**1.23**	**1.09**	**1.14**	**1.08**

* pairs of results in u3 and M1–M9 indicate results for overlapping and overlapped brace, respectively



Uni-planar K-joint

Multi-planar KK-joint with ϕ = 90°

Fig. 5. Numerical models of uni-planar K- and multi-planar KK-joint with 50 % overlap [8]

b_{ej} at the heel of the overlapped brace. For simplicity, b_{ej} was taken to be similar to that given in Eq. (1a) for the brace effective width $b_{e,ov}$ but now related to the connection between overlapped brace j and chord 0, giving Eq. (3c):

$$b_{ej} = \left(\frac{10}{b_0/t_0}\right)\left(\frac{f_{y0}t_0}{f_{yj}t_j}\right) b_j \text{ but} \le b_j \tag{3c}$$

Now, for the tests where failure mode 3 is absolutely critical (tests U6 and M3 to M9), the unity checks V_u** with b_{ej} according to Eq. (3c) are reduced from 1.23–1.33 to 1.04–1.15. Chen et al. [7] also carried out additional numerical calculations for uni-planar K-joints with β ratios of 0.4 and 0.8, with lower 2γ ratios of 16 and 25 and varying τ ratios; however, these all failed either by brace member failure (mode 4) or by chord M-N interaction (mode 2).

3.2 Additional analyses for 50 % uni-planar and multi-planar overlap joints

Liu et al. [8] analysed K- and KK-type overlap joints with $\phi = 90°$ and 50 % overlap, as shown in Fig. 5. That investigation covers chord slendernesses b_0/t_0 of 15, 25 and 35 and brace-to-chord width ratios $\beta = 0.4$, 0.6 and 0.8. Additional tests were carried out with different steel grades for chord and braces as well as analyses with different chord preloads. In the analyses, a similar approach was used as for the 100 % overlap joints.

Eq. (1b), which is already included in [1], was used for the brace effective width criterion (failure mode 1):

$$N_{i,Rd} = f_{yi}\, t_i\, (2h_i + b_{eff} + b_{e,ov} - 4t_i) \tag{1b}$$

$$\text{where } b_{eff} = \left(\frac{10}{b_0/t_0}\right)\left(\frac{f_{y0}t_0}{f_{yi}t_i}\right) b_i \text{ but} \le b_i \tag{1c}$$

For failure mode 2, Eq. (2) applies as used for 100 % overlap joints.

For failure mode 3, besides the sides of the overlapped brace, parts of the sides of overlapping brace i are now also effective for shear. Also effective are b_{ei} at the heel of the overlapping brace and, for the overlapped brace, b_{ej} at the heel and for the hidden seam at the toe of the overlapped brace j if this seam is welded, resulting in Eq. (3d) [8]:

$$N_{S,Rd} = \frac{f_{ui}}{\sqrt{3}} \frac{\left[\left(\frac{100-\lambda_{ov}}{100}\right)2h_i + b_{ei}\right]t_i}{\sin\theta_i} + \frac{f_{uj}}{\sqrt{3}} \frac{(2h_j + c_s b_{ej})\, t_j}{\sin\theta_j} \tag{3d}$$

$$\text{with } b_{ei} = \left(\frac{10}{b_0/t_0}\right)\left(\frac{f_{y0}t_0}{f_{yi}t_i}\right) b_i \text{ but} \le b_i \tag{3e}$$

If the hidden seam is welded, $c_s = 2$ in Eq. (3d), and if the hidden seam is not welded, $c_s = 1$. Fig. 6 shows the model representing the effective parts used in Eqs. (3a) and (3d) for the brace shear criterion.

However, for the 50 % overlap joints, all numerical tests failed either by brace effective width (mode 1), chord M-N interaction (mode 2), member yield or buckling failure (mode 4). This is partly due to the different boundary conditions, shown in Fig. 7, which resulted in larger bending moments in the chord compared with those that occur with the boundary conditions of Fig. 2, so mode 2 governs in most cases for the multi-planar joints with 50 % overlap. The results are not discussed here, as the details can be obtained from [8]. Later analyses of overlap joints between circular hollow sections [17] showed that mode 3 only governs for larger overlaps.

4 Overlap joints between circular hollow sections

For CHS overlap joints, [17] and [18] follow the same principles as for RHS joints and the criteria are directly related to those of RHS joints. For the effective width criterion of the overlapping brace, the equations for overlap joints with RHS braces are used with all b and h dimensions in the formulae replaced by d and the equation is multiplied by π/4, which is the ratio of the cross-sectional areas of thin-walled CHS and RHS braces with d = b = h and the same thickness t.

Since the local stiffness of CHS-to-CHS connections is more uniform than that of RHS-to-RHS connections, the constant in the effective width terms of Eqs. (1a), (3c) and (3e) for brace effective width and brace shear is increased by 20 %, i.e. changes from 10 to 12. This increase is also found when comparing the efficiency of CHS X-joints with

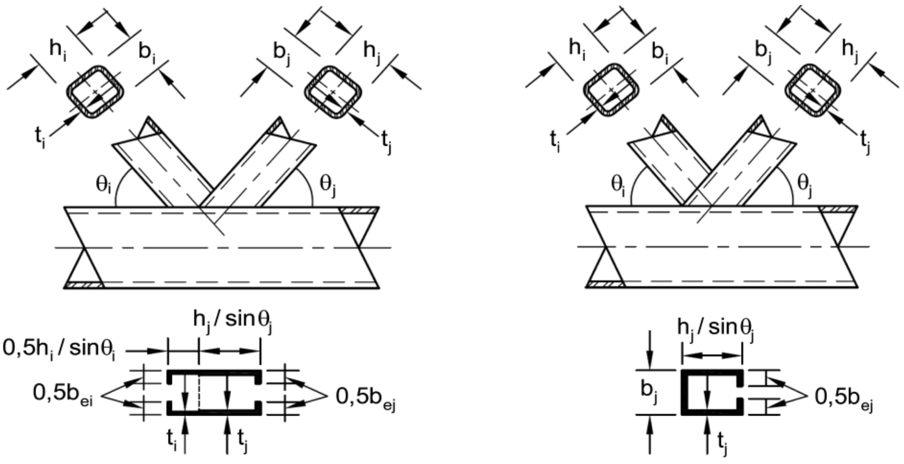


Fig. 6. Effective shear areas for RHS joints with 50 % (no hidden weld) and 100 % overlap

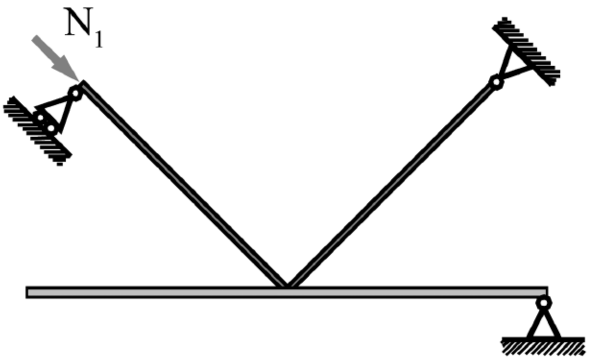


Fig. 7. Boundary conditions used in [8]

that of RHS X-joints. Adopting these modifications in Eqs. (3a) and (3d) results in the functions given in [2]. Numerical data [17], [18] showed that owing to the more uniform stiffness distribution in CHS overlap joints, a single expression, related to the expression for RHS joints with 50 % ≤ λ_{ov} < 100 %, can be used to describe the brace effective width criterion of CHS joints with overlaps 25 % ≤ λ_{ov} < 100 %.

Further, [17] and [18] determined when brace shear may become critical compared with the criteria for brace effective width or chord M-N interaction, resulting in the following limits:

$\lambda_{ov,limit} \geq 60$ % when the hidden toe of the overlapped brace is not welded.

$\lambda_{ov,limit} \geq 80$ % when the hidden toe of the overlapped brace is welded.

The local chord yield interaction criterion for CHS chords in [2] for CHS overlap joints is based on [19].

5 Overlap joints between CHS or RHS braces and I- or H-section chords

The criteria for brace effective width (failure mode 1) is already included in EN 1993-1-8. For the interaction between N and M in the chord (failure mode 2) and brace shear (failure mode 3), in principle, similar equations can be used as for overlap joints with an RHS chord, i.e. Eqs. (2), (3a) and (3d).

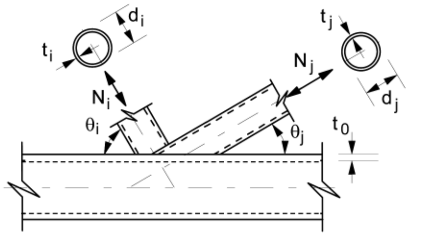
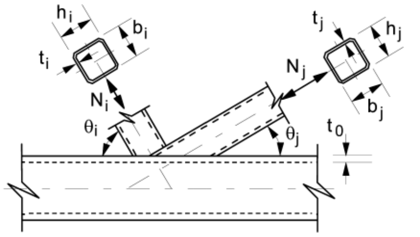
6 Evaluation for inclusion in EN 1993-1-8

Eq. (1) with (1a) for the brace effective width criterion is commonly accepted and already included in [1]. The material reduction factor included in EN 1993-1-8 for criteria based on deformation or fracture for steels with a yield stress exceeding 355 N/mm^2 has been taken into account for brace failure by a factor C_f. Eq. (2) for the chord M-N interaction is also logical, although for tension chords it is more restrictive than the current rule in [1]. Considering the stiffness, the effective width term b_{ej} in the brace shear criterion Eq. (3a) for 100 % overlap joints should, physically and logically, only be a function of the overlapped brace thickness t_j and should not be a function of the parameters used in Eq. (3c). Therefore, Table 1 also gives the shear capacity checks for two alternative cases, i.e. for $b_{ej} = 6t_j$ and for $b_{ej} = 10t_j$. The value $b_{ej} = 6t_j$ is based on an RHS inner corner radius $r_i = t_j$ and a 1:2.5 spread on both sides, and $b_{ej} = 10t_j$ seems too optimistic theoretically but gives about the same correlation as the current equation Eq. (3b) with b_{ej} as in Eq. (3c). It is already included in ISO 14346 [2] and in CIDECT Design Guides 1 and 3 [3], [4].

In fact, for $b_{ej} = 6t_j$, the mean is 1.18, and for $b_{ej} = 10t_j$ it is 1.12, whereas for both cases COV = 2.7 % applies. Since $b_{ej} = 6t_j$ agrees better with the mathematical model and may be more appropriate for overlap joints with the overlapped brace at 90°, this value is preferred. The characteristic value of the numerical results for RHS joints with a mean of 1.18 and CoV = 2.7 % results in – using $b_{ej} = 6t_j$ in Eq. (3b) – a reserve > 1.1.

In [1] it is common practice to use $\gamma_M = 1.0$ for yield and $\gamma_M = 1.25$ if based on ultimate stresses. However, local strain hardening occurs here in a part of the joint with small deformations, not resulting in fracture in the end but in a chord local buckling failure. Thus, if according to [1] $\gamma_{M2} = 1.25$ should be used, it would be far too conservative and therefore it has to be compensated for by a model factor of 1.25 effectively restoring the γ_M to 1.0. However, to be in line with the presentation of other equations in

Table 2a. Design axial resistance of welded uni-planar overlap joints with CHS, RHS, I or H section chord

Type of joint	Design axial resistance	
Axially loaded overlap joints	Overlapping brace failure	Overlapped brace failure
 	$N_{i,Rd} = C_f f_{yi}\, t_i\, \ell_{b,eff.} / \gamma_{M5}$ (1,2) (for $\ell_{b,eff.}$, see Table 2b)	$N_{j,Rd} = N_{i,Rd}\left(\frac{A_j f_{yj}}{A_i f_{yi}}\right)$
	Chord member failure	
	$\left(\frac{N_{0,Ed}}{N_{0,Rd}}\right)^c + \frac{M_{0,Ed}}{M_{0,Rd}} \le 1.0$	c = 1.7 for CHS chord c = 1.0 for RHS, I or H section chord
	Brace shear failure (check for $\lambda_{ov,limit} < \lambda_{ov} \le 100\ \%$) (3) $\lambda_{ov,limit}$ = 60 % when hidden toe of the overlapped brace is not welded. $\lambda_{ov,limit}$ = 80 % when hidden toe of the overlapped brace is welded.	
	$N_{i,Ed}\cos\theta_i + N_{j,Ed}\cos\theta_j \le N_{S,Rd}$ (for $N_{S,Rd}$, see Table 2c)	

(1) $\gamma_{M5} = 1.0$

(2) C_f is a material factor, being 1.0 for $f_{y0} \le 355$ N/mm^2; 0.9 for 355 N/mm$^2 < f_{y0} \le 460$ N/mm^2 and 0.8 for 460 N/mm$^2 < f_{y0} \le 700$ N/mm^2.

(3) If the braces are rectangular sections with $h_i < b_i$ and/or $h_j < b_j$, the connection between the braces and chord face has always to be checked for shear.

Table 2b. Effective perimeter length $l_{b,eff.}$ for overlapping brace failure

	CHS braces	RHS braces
$25\ \% \le \lambda_{ov} < 50\ \%$	$\ell_{b,eff.} = \frac{\pi}{4}(2d_i + d_{eff} + d_{e,ov} - 4t_i)$	$\ell_{b,eff.} = (\frac{\lambda_{ov}}{50})2h_i + b_{eff} + b_{e,ov} - 4t_i$
$50\ \% \le \lambda_{ov} < 100\ \%$		$\ell_{b,eff.} = 2h_i + b_{eff} + b_{e,ov} - 4t_i$
$\lambda_{ov} = 100\ \%$	$\ell_{b,eff.} = \frac{\pi}{4}(2d_i + 2d_{e,ov} - 4t_i)$	$\ell_{b,eff.} = 2h_i + b_i + b_{e,ov} - 4t_i$

Factors for CHS braces	
Overlapping CHS brace to CHS chord $d_{eff} = \left(\frac{12}{d_0/t_0}\right)\left(\frac{f_{y0}t_0}{f_{yi}t_i}\right) d_i$ but $\le d_i$ Overlapping CHS brace to overlapped CHS brace $d_{e,ov} = \left(\frac{12}{d_j/t_j}\right)\left(\frac{f_{yj}t_j}{f_{yi}t_i}\right) d_i$ but $\le d_i$	Overlapping CHS brace to RHS chord $d_{eff} = \left(\frac{10}{b_0/t_0}\right)\left(\frac{f_{y0}t_0}{f_{yi}t_i}\right) d_i$ but $\le d_i$ Overlapping CHS brace to I-section chord $d_{eff} = t_w + 2r + 7t_0\frac{f_{y0}}{f_{yi}}$ but $\le d_i$ r = web-to-flange fillet radius of I-section

Factors for RHS braces	
Overlapping RHS brace to RHS chord $b_{eff} = \left(\frac{10}{b_0/t_0}\right)\left(\frac{f_{y0}t_0}{f_{yi}t_i}\right) b_i$ but $\le b_i$ $b_{e,ov} = \left(\frac{10}{b_j/t_j}\right)\left(\frac{f_{yj}t_j}{f_{yi}t_i}\right) b_i$ but $\le b_i$	Overlapping RHS brace to I section chord $b_{eff} = t_w + 2r + 7t_0\frac{f_{y0}}{f_{yi}}$ but $\le b_i$ r = web-to-flange fillet radius of I-section

EN 1993-1-8, it was decided to present the equations in Table 2c based on the yield stress f_y with a factor $C_u = f_u/f_y$ (for the steel grade used), in combination with $\gamma_{M5} = 1.0$, which gives the same result. Based on the above considerations, the b_{ei} and b_{ej} terms in the proposed brace shear equations for all overlap joints in Table 2 are proposed to be modified to $b_{ei} = 6t_i$ and $b_{ej} = 6t_j$, and to $d_{ei} = 7.2t_i$ and $d_{ej} = 7.2t_j$ for CHS brace and chord members.

7 Recommendations and relevance

The recommended resistance equations for hollow section overlapped joints for next editions of EN 1993-1-8 and ISO 14346 are given in Tables 2a to 2d with the effective perimeter $l_{b,eff}$ for the brace effective width criterion in Table 2b. The recommendations (if not the presentation) in Tables 2a and 2b are consistent with

Table 2c. Design brace shear resistance of uni-planar overlap joints with CHS, RHS, I or H section chord

<table>
<tr><td colspan="3">$N_{s,Rd}$ for brace shear criterion $^{(1,2)}$ (check for $\lambda_{ov,limit} < \lambda_{ov} \leq 100$ % and for h_i/b_i and/or $h_j/b_j < 1.0$)</td></tr>
<tr><td rowspan="2">CHS braces</td><td>$\lambda_{ov,limit} < \lambda_{ov} < 100$ %</td><td>$N_{S,Rd} = \frac{\pi}{4}\left[[0.58C_{ui}f_{yi}t_i \frac{\left[\left(\frac{100-\lambda_{ov}}{100}\right)2d_i + 7.2t_i\right]}{\sin\theta_i} + 0.58C_{uj}f_{yj}t_j \frac{(2d_j + c_s d_{ej})}{\sin\theta_j}] \right] / \gamma_{M5}$</td></tr>
<tr><td>$\lambda_{ov} = 100$ %</td><td>$N_{S,Rd} = 0.58C_{uj}f_{yj}t_j \frac{\pi}{4} \frac{(3d_j + 7.2t_j)}{\sin\theta_j} / \gamma_{M5}$</td></tr>
<tr><td rowspan="2">RHS braces</td><td>$\lambda_{ov,limit} < \lambda_{ov} < 100$ %</td><td>$N_{S,Rd} = \left[0.58C_{ui}f_{yi}t_1 \frac{\left[\left(\frac{100-\lambda_{ov}}{100}\right)2h_i + 6t_i\right]}{\sin\theta_i} + 0.58C_{uj}f_{yj}t_j \frac{(2h_j + c_s b_{ej})}{\sin\theta_j} \right] / \gamma_{M5}$</td></tr>
<tr><td>$\lambda_{ov} = 100$ %</td><td>$N_{S,Rd} = \left[0.58C_{uj}f_{yj}t_j \frac{(2h_j + b_j + 6t_j)}{\sin\theta_j} \right] / \gamma_{M5}$</td></tr>
</table>

(1) C_{ui}, $C_{uj} = f_u/f_y$ for the steel grade used: f_{ui}/f_{yi} for the overlapping member; f_{uj}/f_{yj} for the overlapped member

(2) $c_s = 1$ when hidden toe of the overlapped brace is not welded, and $c_s = 2$ when hidden toe of the overlapped brace is welded

Table 2d. Validity range for the design axial resistance of welded uniplanar overlap joints with CHS, RHS, I or H section chord

<table>
<tr><td colspan="8">Range of validity</td></tr>
<tr><td colspan="2" rowspan="2">General</td><td colspan="2" rowspan="2">d_i/d_0 and $d_j/d_0 \geq 0.20$
b_i/b_0 and $b_j/b_0 \geq 0.25$
d_i/b_0 and $d_j/b_0 \geq 0.25$</td><td rowspan="2">$d_i/d_j \geq 0.75$
$b_i/b_j \geq 0.75$</td><td rowspan="2">t_i and $t_j \leq t_0$
$t_i \leq t_j$</td><td>θ_i and $\theta_j \geq 30°$</td><td rowspan="2">f_{yi} and $f_{yj} \leq f_{y0}$</td></tr>
<tr><td>Ov ≥ 25 %</td></tr>
<tr><td rowspan="8">Chord</td><td rowspan="2">CHS</td><td colspan="2">Compression</td><td colspan="4">class 1 or 2 and $d_0/t_0 \leq 50$</td></tr>
<tr><td colspan="2">Tension</td><td colspan="4">$d_0/t_0 \leq 50$</td></tr>
<tr><td rowspan="3">RHS</td><td colspan="2">Compression</td><td colspan="4">class 1 or 2 and $b_0/t_0 \leq 35$ and $h_0/t_0 \leq 35$</td></tr>
<tr><td colspan="2">Tension</td><td colspan="4">$b_0/t_0 \leq 35$ and $h_0/t_0 \leq 35$</td></tr>
<tr><td colspan="2">Aspect ratio</td><td colspan="4">$0.5 \leq h_0/b_0 \leq 2.0$</td></tr>
<tr><td rowspan="3">I or H section</td><td rowspan="2">Compression</td><td>Flange</td><td colspan="4">class 1 or 2</td></tr>
<tr><td>Web</td><td colspan="4">class 1 or 2 and $h_w \leq 400$ mm</td></tr>
<tr><td colspan="2">Tension</td><td colspan="4">none</td></tr>
<tr><td colspan="4"></td><td colspan="4">CHS, RHS and I or H section chord</td></tr>
<tr><td rowspan="5">Braces</td><td rowspan="2">CHS</td><td colspan="2">Compression</td><td colspan="4">class 1 or 2 and d_i/t_i and $d_j/t_j \leq 50$</td></tr>
<tr><td colspan="2">Tension</td><td colspan="4">d_i/t_i and $d_j/t_j \leq 50$</td></tr>
<tr><td rowspan="3">RHS</td><td colspan="2">Compression</td><td colspan="4">class 1 or 2 and b_i/t_i, h_i/t_i, b_j/t_j and $h_j/t_j \leq 35$</td></tr>
<tr><td colspan="2">Tension</td><td colspan="4">b_i/t_i, h_i/t_i, b_j/t_j and $h_j/t_j \leq 35$</td></tr>
<tr><td colspan="2">Aspect ratio</td><td colspan="4">$0.5 \leq h_i/b_i \leq 2.0$ and $0.5 \leq h_j/b_j \leq 2.0$</td></tr>
</table>

those in [2], [3] and [4]. The resistance equations for brace shear are given in Table 2c and the proposed validity ranges in Table 2d.

The current RHS chord and brace slenderness limits used in EN 1993-1-8 [1] are still recorded in Table 2d although the general limit of 35 differs from that in ISO 14436 [2] and in the CIDECT Recommendations [4] which are updated to 40.

The proposed effective width terms $b_{ei} = 6t_i$, $b_{ej} = 6t_j$, $d_{ei} = 7.2t_i$ and $d_{ej} = 7.2t_j$ for brace shear are now directly included in the equations in Table 2c.

This paper has demonstrated that the limit state of brace shear is a viable controlling failure mode for overlapped hollow section joints. To illustrate the relevance of the brace shear check, consider a uniplanar 90 % overlap RHS-to-RHS K-joint, with braces at 40°, having 100×50×4.0 mm braces (b×h×t) welded to a 150×150×10.0 mm chord. The hidden toe is left unwelded and all members are fabricated from EN10210 S355J2H steel. The K-joint is subjected to brace axial loads of 300 kN (one in compression, one in tension) resulting in an equilibrating compression force of 459.6 kN in the chord. It can be shown that the joint resistance for the limit state of local yielding of the overlapping (and overlapped) brace is adequate, per Tables 2a and 2b. Similarly, the check for chord member local yielding in Table 2a is satisfied. However, the brace shear resistance (Tables 2a and 2c) is exceeded by 72 %, which illustrates the importance of inclusion of this limit state in future design codes.

Notation

A_0	cross-sectional area of chord
A_i	cross-sectional area of overlapping brace
A_j	cross-sectional area of overlapped brace
C_f	material factor
C_u	ratio ultimate tensile strength to yield strength f_u/f_y
M	moment (general)
M_0	moment in chord (general)
$M_{0,Ed}$	design value of bending moment in chord
$M_{0,Rd}$	design moment resistance of a chord cross-section
N	axial force (general)
N_i	load in overlapping brace (general)
N_0	load in chord (general)
$N_{0,Ed}$	design value of chord axial load
$N_{0,Rd}$	design value of chord axial load resistance
$N_{i,eff.width}$	resistance in brace i based on effective width criterion
$N_{i,Ed}$	design value of applied axial load in overlapping brace
$N_{i,Rd}$	design axial load resistance of a joint based on load in overlapping brace i
N_j	load in overlapped brace (general)
$N_{j,Ed}$	design value of applied axial load in overlapped brace
$N_{j,Rd}$	design axial load resistance of a joint based on load in overlapped brace j
$N_{S,Rd}$	axial shear resistance between braces and chord
$R_{N0\text{-}M0}$	interaction equation between chord axial load N_0 and chord bending moment M_0
V_u^*, V_u^{**}	unity checks for shear criterion
b_e	effective width (general)
b_{eff}	effective width of overlapping RHS brace member for effective width criterion
b_{ei}	effective width of overlapping RHS brace member for shear at chord connection
b_{ej}	effective width of overlapped RHS brace member for shear at chord connection
$b_{e,ov}$	effective width of overlapping RHS brace member at connection to overlapped brace
b_0	external width of chord
b_i	external width of overlapping brace i
b_j	external width of overlapped brace j
c	constant in chord M-N interaction equation
c_s	factor considering the condition (welded or unwelded) at hidden toe of overlapped brace
d_0	external diameter of chord
d_i	external diameter of overlapping brace i
d_j	external diameter of overlapped brace j
d_{eff}	effective width term of overlapping CHS brace member for effective width criterion
d_{ei}	effective width term of overlapping CHS brace member for shear at chord connection
d_{ej}	effective width term of overlapped CHS brace member for shear at chord connection
$d_{e,ov}$	effective width term of overlapping CHS brace member at connection to overlapped brace
e	eccentricity
f_y	yield stress (general)
f_{ui}	ultimate tensile strength of overlapping brace i
f_{uj}	ultimate tensile strength of overlapped brace j
f_{y0}	design yield strength of chord
f_{yi}	design yield strength of overlapping brace i
f_{yj}	design yield strength of overlapped brace j
h_0	external depth of chord
h_i	external depth of overlapping RHS brace i
h_j	external depth of overlapped RHS brace j
h_w	depth of web between flanges of I- or H-section
$l_{b,eff.}$	effective perimeter for local brace failure
p	length of contact area of overlapping brace projected onto face of chord, without the presence of the overlapped brace
q	projected length of overlap between braces at chord face
r	inside corner radius of rectangular or square hollow section, radius of I- or H-section
t_0	wall thickness of CHS or RHS chord or flange thickness of H-section chord
t_i	wall thickness of overlapping brace i
t_j	wall thickness of overlapped brace j
t_w	thickness of H-section web
i	integer, used for overlapping brace
j	integer, used for overlapped brace
β	average width or diameter ratio between braces and chord of a K-joint $(b_i + b_j)/2b_0$ or $(d_i + d_j)/2b_0$ or $(d_i + d_j)/2d_0$
ϕ	angle between two planes in a multi-planar joint
γ	half chord width or half chord diameter-to-thickness ratio, $2\gamma = b_0/t_0$ or d_0/t_0
γ_M	partial factor (general)
τ	thickness ratio, $\tau_i = t_i/t_0$, $\tau_j = t_j/t_0$
θ_i	acute angle between overlapping brace i and chord 0
θ_j	acute angle between overlapped brace j and chord 0
λ_{ov}	overlap, $\lambda_{ov} = q/p \times 100$ %
$\lambda_{ov,limit}$	limit for overlap, critical for brace shear check

Abbreviations

CIDECT	Comité International pour le Développement et l'Etude de la Construction Tubulaire
IIW	International Institute of Welding
ISO	International Organization for Standardization
CHS	circular hollow section
RHS	rectangular hollow section

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