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Recent Research Advances and Development of ISO 14346 Design Standard for Failure Modes of RHS Joints

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Abstract. In recent years, considerable research efforts have been devoted to rectangular hollow section (RHS) joints, aiming to re-examine suitability of codified design provisions for steel grades up to S460 and to extend the validity range beyond S460. Within the research framework of drafting the next-generation international design standard ISO 14346 for hollow section joints, this paper presents recent research advances and improved design methods for RHS joints under brace axial compression or tension, failing by essential failure modes. For chord sidewall failure, the representative modified IIW method and an alternate Lan-Kuhn method together with the subsequently proposed Kim-Lee method are compared and evaluated against existing test and numerical evidence. Further, an upper limit of the codified chord sidewall bearing length is proposed to avoid overestimations for thick-walled RHS joints. For interactive chord sidewall and chord face failure, more-suitable limiting beta ranges for the occurrence of this failure mode and a linear interpolation design method are suggested. Design rules and recommendations are then proposed for chord sidewall failure and interactive failure, which have been approved to be included in the next draft of ISO 14346.

Keywords: Brace axial loading · Design standard · Failure mode · Limit state · RHS joint

1 Introduction

Substantial research efforts have been recently devoted to evaluating the suitability of design rules for tubular joints, such as those in ISO 14346 (ISO 2013), in particular for steel grades of S460 and higher. Within the research framework for updating codified design rules, Wardenier et al. (2020, 2021) and Lan et al. (2021, 2022) re-assessed representative design methods for chord sidewall failure in rectangular hollow section (RHS)

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X joints under brace axial loading, prior to 2021, and proposed a modified International Institute of Welding (IIW) method and an alternate Lan-Kuhn method. Figure 1 shows RHS-to-RHS X joints, along with relevant notations, examined herein.

This study compares the modified IIW method and the Lan-Kuhn method with a design method subsequently proposed by Kim and Lee (2021). Using additional finite element (FE) results obtained by Lee et al. (2022, 2023), the effects of chord sidewall convexity and misalignment between brace and chord sidewalls in full-width joints are evaluated. The chord sidewall bearing length is re-analysed for thick-walled X joints. Furthermore, design methods for the interactive chord sidewall and chord face failure are examined, and design rules for brace failure and chord punching shear failure are also discussed.

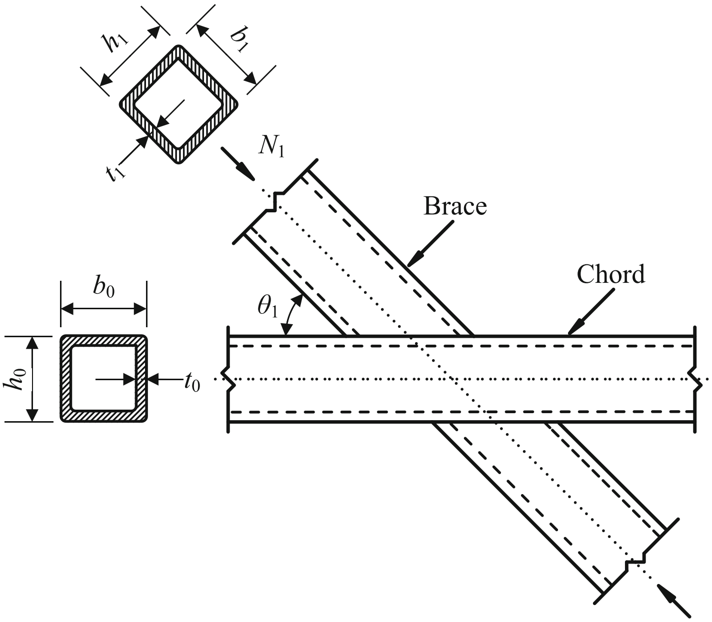

Fig. 1. RHS-to-RHS X joints with notations.

2 Reliability Analysis

For the three design approaches mentioned above for chord sidewall failure, resistance factors (ϕ) are computed using the simplified separation factor method proposed by Ravindra and Galambos (1978) and Fisher et al. (1978), as follows:

$$\phi = (\text{Mean})e^{(-0.55)(\beta_0)(\text{COV})} \tag{1}$$

where the mean refers to the average of the actual-to-predicted joint strength ratios, and the COV represents the associated coefficient of variation. Target reliability indexes (β_0) of 3.0 and 4.0 (AISC 2022) for respective ductile and non-ductile failure modes of RHS

X joints are adopted herein. The overall beneficial statistical effects of geometrical and material property variations are neglected, and the probability distributions associated with the loading are also not considered. The determined ϕ factor is the adjustment factor for converting a considered nominal strength equation into a design resistance equation. The ϕ value shall be capped at 1.0, and that exceeding unity indicates the conservative nature of the examined design methods. In the case of calculated $\phi > 1.0$, $\phi = 1.0$ can be used for the conversion of a nominal strength equation.

3 Design Methods for Chord Sidewall Compression Failure

3.1 Design Methods

The chord sidewall compression capacity at $\beta = 1.0$ is, for the modified IIW method proposed by Wardenier et al. (2020) and Lan et al. (2021), as follows:

$$N_{\mathrm{CSF}} = C_{\mathrm{f}} f_{\mathrm{k}} t_0 \cdot 2(h_1 + 5t_0)\sqrt{\frac{1}{\sin\theta_1}} \cdot Q_{\mathrm{f}} \tag{2}$$

$$C_{\mathrm{f}} = 1.1 - 0.1 f_{\mathrm{y0}} \big/ 355 \le 1.0 \tag{3}$$

$$f_{\mathrm{k}} = \chi_{0.5}\left(h_0 \big/ h_1\right)^{0.15} f_{\mathrm{y0}} \le f_{\mathrm{y0}} \tag{4}$$

$$\lambda_{0.5} = 1.73\left(\frac{h_0}{t_0} - 2\right) \cdot \frac{1}{\pi}\sqrt{\frac{f_{\mathrm{y0}}}{E}} \tag{5}$$

The material factor (C_{f}) is introduced to consider the effect of the chord yield stress (f_{y0}). The chord sidewall buckling coefficient ($\chi_{0.5}$) for a reduced chord sidewall slenderness ($\lambda_{0.5}$), in conjunction with the buckling curve c for cold-formed hollow sections in EN 1993-1-1 (CEN 2005), and a correction function of $(h_0/h_1)^{0.15}$, which considers the effect of the h_0/h_1 ratio in joints with $h_0/h_1 \neq 1.0$, are adopted to obtain the buckling stress (f_{k}). The chord stress function (Q_{f}) is used to quantify the influence of chord longitudinal (normal) stresses. The adopted brace angle function of $(1/\sin\theta)^{0.5}$ is a simplified influence function, but is more accurate than the current codified equation.

The Lan-Kuhn method proposed by Wardenier et al. (2020) and Lan et al. (2021) also employs the basic resistance equations (Eqs. (2–3)). However, the $\chi_{0.5}$ value is, instead of using buckling curve c, determined using a linearised function against the h_0/t_0 ratio:

$$\chi_{0.5} = 1.12 - 0.012\frac{h_0}{t_0}\sqrt{\frac{f_{\mathrm{y0}}}{355}} \le 1.0 \tag{6}$$

The design equations proposed by Kim and Lee (2021) for chord sidewall failure are as follows:

$$N_{\mathrm{CSF}} = C_{\mathrm{f}} \chi_{\mathrm{K}} f_{\mathrm{y0}} t_0 \cdot 2h_1 \cdot Q_{\mathrm{f}} \big/ \gamma_{\mathrm{M}} \tag{7}$$

$$\lambda_K = 1.73\left(\frac{h_0}{t_0} - 2\right) \cdot \frac{1}{\pi}\sqrt{\frac{f_{y0}}{E}} \cdot \sqrt{\frac{h_1}{h_0}} \tag{8}$$

where the material strength effect is not included with $C_f = 1.0$, and the chord sidewall buckling coefficient (χ_K) is determined using a chord sidewall slenderness (λ_K) which covers the effect of the h_0/h_1 ratio and the Eurocode buckling curve c. However, considering cases of large corner radii of the chord, the load dispersion in the chord sidewall is assumed to be $2h_1$ instead of $2(h_1 + 5t_0)$. The partial factor γ_M is taken as 1.12 obtained using EN 1990 (2002) and a target reliability index of 3.8. Further, the Kim-Lee method does not include a brace angle function.

Table 1. Evaluation of design methods against results of 34 test specimens with 228 MPa $\leq f_{y0} \leq$ 1038 MPa and b_0/t_0 & $h_0/t_0 \leq 40$ under brace axial compression

Design method	Mean	COV	ϕ
Modified IIW method	1.15	0.090	0.99
Lan-Kuhn method	1.16	0.094	0.99
Kim-Lee method	1.53	0.104	1.29

Table 2. Evaluation of design methods against results of 85 FE models with $f_{y0} = 355$ & 398 MPa under brace axial compression

Design method	Mean	COV	ϕ
Modified IIW method	1.22	0.064	1.10
Lan-Kuhn method	1.23	0.058	1.12
Kim-Lee method	1.72	0.093	1.47

Table 3. Evaluation of design methods against results of 65 FE models for $0.21 \leq h_1/h_0 \leq 2.5$, excluding $h_1/h_0 = 1.0$

Design method	Mean	COV	ϕ
Modified IIW method	1.23	0.062	1.11
Lan-Kuhn method	1.25	0.056	1.14
Kim-Lee method	1.74	0.099	1.47

These three design approaches for chord sidewall failure were evaluated using the test database and the numerical results of Kuhn et al. (2019) and Yu (1997), which are detailed in Wardenier et al. (2023). It is noted that the FE models adopted by Yu (1997) and Kuhn et al. (2019) did not incorporate joint geometric imperfections. The statistical results for these analyses are shown in Tables 1–3, with the mean value corresponding to the average of the actual-to-predicted joint strength ratios according to one of the design approaches, COV being the associated coefficient of variation, and the ϕ value determined as per Eq. (1) in which $\beta_0 = 3.0$. Additionally, the h_1/h_0 terms in Eqs. (4) and (8) all equal 1.0 for $h_1/h_0 = 1.0$, thus the effects of the h_1/h_0 ratio are evaluated for the X joints with $h_1/h_0 \neq 1.0$ as shown in Table 3.

It is shown that, for the correlation against the test results in Table 1, the COV values are approximately the same for the modified IIW method and the Lan-Kuhn method, and are slightly lower than that of the Kim-Lee method. However, for the numerical data in Table 2, the COVs for the modified IIW method and the Lan-Kuhn method are considerably lower than that of the Kim-Lee method. It is concluded that, for the results of tests and FE simulations without modelling geometric imperfections, the modified IIW method and the Lan-Kuhn method can correlate better with the data.

3.2 Effect of Joint Geometric Imperfections

Current fabrication specifications do not stipulate clear tolerances for brace sidewall misalignment and chord sidewall convexity in RHS-to-RHS X joints. It is noted that EN 10219-2 (CEN 2006) prescribes a maximum misalignment of 2 mm (i.e. Class A fabrication tolerance quality class) for the unintentional eccentricity due to misalignment of the RHS walls, and specifies a RHS sidewall convexity tolerance of 0.8% h_0 for cold-formed hollow sections with 100 mm $\leq h_0$ & $b_0 \leq 200$ mm, which are also assumed as representative for the X joints herein.

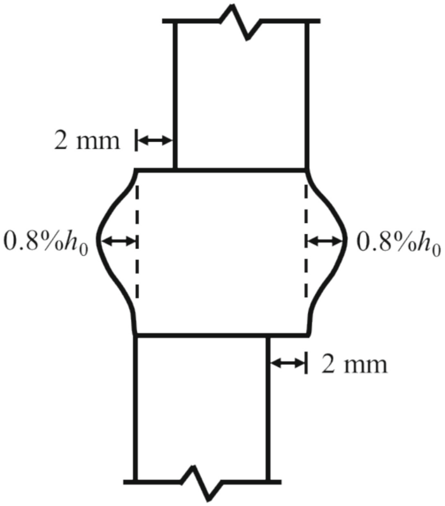

Fig. 2. Sidewall misalignment and convexity.

To study the effects of a brace sidewall misalignment of 2 mm and a chord sidewall convexity of 0.8%h_0, as shown in Fig. 2, Lee et al. (2022) performed additional numerical analyses for $\beta = 1.0$ and $2\gamma = 20, 30, 40$. The corresponding FE results are summarised in Table 4, which are detailed in Wardenier et al. (2023). Four cases of perfect geometry, convexity only, misalignment only and a combination of convexity and misalignment are covered, and six X joints are included for each case. It is shown that, for all 24 joints, the Kim-Lee method gives the lowest COV of 0.085 over the range of $2\gamma = 20 \sim 40$. Considering that in practice all types of imperfections may occur, the case for all 24 data is considered to be realistic with ϕ factors being close to unity for the modified IIW method and the Lan-Kuhn method, respectively, which are comparable to those for the tests in Table 1. Therefore, the modified IIW method and the Lan-Kuhn method generally provide equivalent resistance predictions, which agree well with the considered test and FE results, and are recommended for designing the chord sidewall under brace axial compression.

Table 4. Evaluation of design methods against results of 24 FE models with geometric imperfections and $f_{y0} = 715$ MPa

Design method	Mean	COV	ϕ
Modified IIW method	1.20	0.114	0.99
Lan-Kuhn method	1.19	0.096	1.01
Kim-Lee method	1.42	0.085	1.23

4 Thick-Walled Joints

Lee et al. (2023) conducted FE simulations on RHS X joints with large thicknesses up to 30 mm, large corner radii of $3t_0 = 90$ mm and $h_1/b_0 \neq 1.0$. The FE results show that the codified load dispersion $h_1 + 5t_0$ at each brace sidewall, i.e. a bearing length $b_w = 2(h_1 + 5t_0)$ for two chord sidewalls, could overestimate the actual bearing length in certain situations, and thus should be limited. Lee et al. (2023) and Wardenier et al. (2023) have evaluated the suitability of a bearing length of $b_w = 2(h_1 + 5t_0)$ but with limitations of $5t_0 \leq 5 \times 16$, $5t_0 \leq 5 \times 10$, $5t_0 \leq 0.2h_1$ and $5t_0 \leq 0.3h_1$, and an alternative bearing length of $b_w = 2h_1$, against the FE joint strengths obtained by Lee et al. (2023). Based on these studies it is proposed to include a limitation of $5t_0 \leq 0.3h_1$ in Eq. (2) to avoid overestimation of joint strengths for thick-walled joints.

5 Design Methods for Chord Sidewall Tension Failure

For the loading case of brace axial tension, the suitability of the modified IIW method, the Lan-Kuhn method and Kim-Lee method against the reported results of 19 tests was assessed in Lee et al. (2023) and in Wardenier et al. (2023). In the determination of predicted joint strengths, the buckling stress in Eqs. (2) and (4) was taken as $f_k = f_{y0}$, and the buckling coefficient in Eq. (7) was taken as $\chi_K = 1.0$. The limitation of

$5t_0 \le 0.3h_1$ and a target reliability index of 4.0 (to account for non-ductile behaviour) were adopted. Table 5 summarises the results of statistical analyses. It is shown that the modified IIW method and the Lan-Kuhn method provide more-consistent and reliable resistance predictions, and are suggested to be adopted for brace axial tension loading.

Table 5. Evaluation of design methods against results of 19 tests with 367 MPa $\le f_{y0} \le$ 609 MPa under brace axial tension

Design method	Mean	COV	ϕ
Modified IIW method	1.41	0.112	1.10
Lan-Kuhn method	1.41	0.112	1.10
Kim-Lee method	1.93	0.129	1.45

6 Chord Face Plastification

The three joint design approaches being considered herein all consider a limit state of chord plastification, which can be idealised as a yield line model and is adopted by ISO 14346 (ISO 2013). The corresponding basic resistance equation is expressed as follows:

$$N_{\mathrm{CFP}} = \frac{C_{\mathrm{f}} f_{\mathrm{y0}} t_0^2}{\sin\theta_1}\left(\frac{2\eta}{(1-\beta)\sin\theta_1} + \frac{4}{\sqrt{1-\beta}}\right) Q_{\mathrm{f}} \tag{9}$$

which consider the effects of the brace-to-chord width ratio ($\beta = b_1/b_0$) and the brace depth to chord width ratio ($\eta = h_1/b_0$). The modified IIW method and the Lan-Kuhn method adopt the unified Eq. (3) to consider the steel grade effect. In contrast, the C_{f} values in the Kim-Lee method are taken, according to EN 1993-1-12 (CEN 2007), as 1.0, 0.9 and 0.8 for $f_{y0} \le 355$ MPa, 355 MPa $< f_{y0} \le 460$ MPa, and 460 MPa $< f_{y0} \le$ 700 MPa, respectively.

7 Interactive Chord Sidewall and Chord Face Failure

Kim and Lee (2021) proposed a somewhat-complicated function (Eq. 10) of border width ratio (β_{bo}), above which interaction between chord sidewall failure and chord face plastification has to be considered as follows:

$$\beta_{\mathrm{bo}} = 1 - \frac{5 + 0.5\lambda^2}{b_0/t_0} \tag{10}$$

$$\lambda = 3.46\left(\frac{h_0}{t_0} - 2\right) \cdot \frac{1}{\pi}\sqrt{\frac{f_{y0}}{E}} \tag{11}$$

In order to further simplify Eqs. (10–11) to be more user-friendly, Wardenier et al. (2023) proposed the following alternative conservative β_{bo} function:

$$\beta_{\text{bo}} = 0.65 + 0.01\gamma \leq 0.85 \tag{12}$$

Using a linear interpolation approach, the resistance (N_{int}) of RHS X joints with $\beta_{\text{bo}} < \beta < 1.0$, failing by interactive chord sidewall and face failure, can be obtained from:

$$N_{\text{int}} = N_{\text{CSF}} - \frac{1-\beta}{1-\beta_{\text{bo}}}\left(N_{\text{CSF}} - N_{\text{CFP},\beta_{\text{bo}}}\right) \tag{13}$$

Lee et al. (2023) conducted additional FE simulations on X joints with $f_{y0} = 715$ MPa failing by the interactive failure. The 16 joint strength data obtained (i.e. four imperfection cases mentioned in Sect. 3.2 and four β values between β_{bo} and $\beta = 1.0$ for each case) for $b_0/t_0 = h_0/t_0 = 20$, and the corresponding 16 capacity data for $b_0/t_0 = h_0/t_0 = 40$, are compared with the joint resistances predicted by the modified IIW method, the Lan-Kuhn method and the Kim-Lee method. The comparison results are summarised in Table 6. It is shown that, for the 32 data, the Kim-Lee method produces the lowest COV of 0.066, while the modified IIW method and the Lan-Kuhn method give higher COVs of 0.093 and 0.077, respectively.

Table 6. Evaluation of design methods against results of 32 FE models with $f_{y0} = 715$ MPa, failing by the interactive failure

Design method	Mean	COV	ϕ
Modified IIW method	1.19	0.093	1.02
Lan-Kuhn method	1.19	0.077	1.05
Kim-Lee method	1.39	0.066	1.25

8 Conclusions and Outlook

An evaluation of design methods against reported test and numerical results of RHS-to-RHS X joints has been conducted aiming to update ISO 14346 (ISO 2013). Representative design approaches, including the modified IIW method, the Lan-Kuhn method and the Kim-Lee method, are examined. Chord sidewall failure and interactive chord sidewall and chord face failure are covered. Conclusions are summarised as follows:

(1) The resistance predictions produced by the Kim-Lee method agree best with the FE results of thick-walled X joints when considering geometric imperfections. However, the modified IIW method and the Lan-Kuhn method are more accurate, in general, when compared with all experimental and numerical results, and are suggested for codification in design standards.

(2) The suggested design resistance equations for chord sidewall failure and interactive chord sidewall and chord face failure are tabulated in Table 7, which have already included an implicit resistance factor of $\phi = 1.0$.

However, the proposed design rules need to be further verified to include Class 3 cross-sections for steel grades higher than S460 up to S700 because:

(1) The design rules of ISO 14346 (2013) are being updated and the cross-section classification may follow prEN 1993-1-1 (CEN 2023) in which the previous slenderness limit for Class 2 is downgraded to Class 3.
(2) The effects of secondary bending moments on high-strength steel tubular structures should be studied more in detail before limits can be given where the effects can be ignored.

Table 7. Suggested design rules for chord sidewall failure and interactive chord sidewall and chord face failure in RHS-to-RHS X joints under brace axial loading.

Chord sidewall failure	$N_{\text{CSF}} = C_{\text{f}} b_{\text{w}} t_0 f_{\text{k}} \sqrt{\frac{1}{\sin\theta_1}} Q_{\text{f}}$ with $f_{\text{k}} = \chi_{0.5} \left(\frac{h_0}{h_1}\right)^{0.15} f_{\text{y0}} \leq f_{\text{y0}}$ for brace axial compression $f_{\text{k}} = f_{\text{y0}}$ for brace axial tension
Chord face plastification at β_{bo}	N_{CFP}, $\beta_{\text{bo}} = C_{\text{f}} f_{\text{y0}} t_0^2 \left(\frac{2\eta}{(1-\beta_{\text{bo}})\sin\theta_1} + \frac{4}{\sqrt{1-\beta_{\text{bo}}}}\right) \frac{Q_{\text{f}}}{\sin\theta_1}$
Interactive chord sidewall and chord face failure	$N_{\text{int}} = N_{\text{CSF}} - \frac{1-\beta}{1-\beta_{\text{bo}}} \left(N_{\text{CSF}} - N_{\text{CFP},\beta_{\text{bo}}}\right)$
Parameters	$C_{\text{f}} = 1.1 \text{ -}0.1 f_{\text{y0}} / 355 \leq 1.0$ $b_{\text{w}} = 2(h_1 + 5t_0)$ but $5t_0 \leq 0.3h_1$ $\chi_{0.5} = 1.12 \text{ -}0.012 \frac{h_0}{t_0} \sqrt{\frac{f_{\text{y0}}}{355}}$ $\beta_{\text{bo}} = 0.65 + 0.01\gamma \leq 0.85$ $Q_{\text{f}} = (1 - \lvert n \rvert)^{C}$ with n referring to the chord longitudinal-to-yield stress ratio $C = (0.6 \text{ - } 0.5\beta)$ and 0.1, for chord compression stress (n negative) and chord tension stress (n positive), respectively

(*continued*)

Table 7. (*continued*)

Validity ranges	Steel grades with $f_{y0} \leq 460$ MPa: Class 1-3 cross-sections Steel grades with 460 MPa $< f_{y0} \leq 700$ MPa: Class 1-2 cross-sections (need more verifications to include Class 3 cross-sections) $b_0/t_0 \leq 40$, $h_0/t_0 \leq 40$; $\beta_{bo} < \beta \leq 1.0$; $0.25 \leq h_1/h_0 \leq 2.0$; $0.5 \leq h_0/b_0 \leq 2.0$; $\theta_1 \geq 30°$
Note: The cross-section slenderness limits of Class 1, 2 and 3 refer to those in prEN 1993-1-1 (CEN 2023); the effects of secondary bending moments are not included	

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