Numerical Study on the Deformation Behavior of Longitudinal Plate-to-High-Strength Circular Hollow-Section X-Joints under Axial Load

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Abstract: This study aims to investigate the joint strength of longitudinal plate-to-high-strength steel circular hollow-section X-type joints under plate axial load. The material properties of high-strength steel with nominal yield strengths of 460, 650, 900, and 1100 MPa were used for parametric analysis. The variables for analysis were ratios of chord diameter to thickness, plate width to chord diameter, and utilization. To determine the capacity of connections, the joint strengths using a deformation limit and a strength limit were considered and compared with American Institute of Steel Construction (AISC), Eurocode 3, and ISO 14346. The joint strength determined by the ultimate deformation limit is approximately equal to the joint strength determined by the strength limit state at the yield strength of 460 MPa. The difference between both the joint strengths, however, becomes higher with increasing yield strength. The design equations estimate the joint strength based on the ultimate deformation limit approximately until the limitation of the nominal yield strength in each design code. As the nominal yield strength increases, the joint strengths are overestimated. In using high-strength steel in circular hollow-section X-type joints, the reduction factors of 0.75 and 0.62 for AISC and ISO 14346 are suggested for the nominal yield strengths of 900 and 1100 MPa, respectively. In Eurocode 3, the reduction factor of 0.67 is also suggested for a yield strength of 1100 MPa.

Keywords: high-strength steel; circular hollow section (CHS); plate axial load; deformation limit state; strength limit state

1. Introduction

Hollow-section members are used in structural and composite members, for instance, concrete-filled steel tubes (CFTs). In the case of CFTs, the steel tube is used as a base pile or a column, because the steel tube can improve the workability and show its proof strength with the structural member. In contrast, a hollow structural section, non-filled concrete, is lightweight and used in various structural members such as columns, beams, and trusses. In particular, a circular hollow section (CHS) is often used because of its aesthetic and geometrical advantages [1]. The application of high-strength materials could secure the greater usability of CHS members, but most of the current standards [2–4] restrict the use of high-strength steel in hollow-section members. High-strength steels almost have higher yield ratios than the mild steels which were applied in the construction field until now. These standards are limited for the purpose of preventing the brittle fracture of steel members, however, conservatively evaluated parts should be improved.

The shape of hollow-section steel joints can be expressed in a wide variety of ways. In particular, the plate-to-CHS X-joint (XP-joint) can be easily assembled through welding, and the plate and H-steel...
or branch CHS are joined to form various shapes of joints. To determine the strength of the CHS XP-joint, the ring model [5], which was theoretically analyzed by two-dimensionally idealizing the cross-section of the chord and branch joints, was modified [6]. A number of experimental studies were carried out on the CHS XP-joint in the 1960s in Japan [7–10]. A design equation based on experimental data and finite element analysis was, thus, proposed [11].

The CHS XP-joint strength formula using the modified ring model by considering the branch chord to longitudinal plate joint was proposed [12]. Ariyoshi et al. [13] introduced a total of 220 CHS joints generated in Japan. Based on the results of these studies, the joint strength equation was developed by the International Institute of Welding (IIW) and the Comité International pour le Développement et l'Étude de la Construction Tubulaire (CIDECT) design guide [14]. The design equation of the American Petroleum Institute [15] was determined based on the nonlinear finite element analysis performed by Pecknold et al. [16,17]. The IIW sub-commission XV-E on tubular structures critically affected the design equations [2,4].

For cold-formed CHS, columns with yield strengths of 700, 900, and 1100 MPa were developed and compared with the design strength [18,19]. The comparison showed the applicability of high-strength steel. Puthli et al. [20] studied the design of steel tube X-joints made of S690 grade high-strength steel which has the yield strength of 690 MPa and showed that some reduction factors were necessary to predict the joint strength using high-strength steels. Lee et al. [21,22] conducted a study into CHS X-joints using the high-strength steel HSA 800, which has a yield strength of 650 MPa, and showed that the reduction factor of 0.8 used in Eurocode 3 may be conservative for high-strength steels. Pandey and Young [23] verified the applicability of Eurocode and CIDECT for high-strength steels of 960 MPa. Lan et al. [24] suggested that the existing design formula could be applied by performing a variable analysis of CHS X-joints using high-strength steel of S700, S900, and S1100 grades. Studies on CHS XP-joints using the high-strength steel HSB 600, which has a yield strength of 460 MPa [25–27], were conducted, and a formula for high-strength steels was suggested. Becque and Wilkinson [28] also studied the effect of the increased yield stress and reduced ductility up to the steel grade C450.

Although experimental and associated analytical studies on high-strength steel joints were conducted, these were insufficient due to the complexity and the diversity of the joint types. In this paper, finite element analysis was performed based on the existing experiment of the longitudinal plate-to-CHS X-joint (XP-joint) [26]. An analytical model was established, and parametric analysis was performed for high yield strength, the slenderness ratio of the CHS, plate width-to-CHS diameter, and utilization ratio. The results of this analysis were compared with the current design equations [2–4] to evaluate applicability.

2. Design Equations and Limitations

The joint design equations for hollow structural steel (HSS) members commonly limit the material properties such as the nominal yield strength ($F_y$) and yield ratio ($F_y/F_u$). In Eurocode 3 [3], the nominal yield strength is limited up to 460 MPa, and a reduction factor of 0.9 should be used when the nominal yield strength exceeds 355 MPa. In addition, the yield ratio should be less than 0.91 and the elongation should be at least 15%. In order to extend the application of high-strength steels, the limitation of the nominal yield strength is increased up to 700 MPa ($S700$) in Eurocode 3 [29]. For the nominal yield strength of 460 to 700 MPa, the reduction factor of 0.8 should be used instead of 0.9. The yield ratio and the elongation should be less than 0.95 and more than 10%, respectively. Therefore, the nominal yield strength can be used up to 700 MPa by applying the reduction factors to the nominal yield strength.

In ISO 14346 [4], the nominal yield strength is limited up to 460 MPa, and the reduction factor of 0.9 is given when it is more than 355 MPa, in the same way as Eurocode 3 [3]. In addition, when the yield ratio exceeds 0.8, the nominal yield strength should be $0.8F_u$. This limitation is to ensure the ductility and rotation capability of HSS joints with a high yield ratio. According to the American Institute of Steel Construction (AISC) [2], the nominal yield strength and yield ratio are limited up
to 360 MPa and 0.8, respectively. These are no longer applied to high-strength steel; therefore, the application of high-strength steels to HSS is actually limited.

Figure 1 shows the geometrical configuration and symbols of the CHS XP-joint studied in this paper. It is designed so that an axial load ($R_n$) is applied to the X-type longitudinal plate joined to the CHS. The HSS joint strength is commonly determined by the chord plastification and punching shear states. Equation (1) is the joint strength based on the chord punching shear of ISO 14346 [4].

$$F_1 = 0.58\sigma_{y0}d_0l_1.$$  

(1)

The joint strength based on the chord punching shear is calculated by the chord nominal yield strength ($0.58\sigma_{y0}$), the thickness of the chord ($t_0$), and the longitudinal plate width ($h_1$). The design strength of the CHS XP-joint is mainly determined by the chord plastification not punching shear, and AISC [2] also suggests that the limit state of the joint strength is HSS plastification. Table 1 shows the design strengths [2–4] for the CHS XP-joints, the limitations, and the range of validity of configurations such as the longitudinal plate width-to-chord diameter ratio ($\eta$) and chord diameter-to-thickness ratio ($2\gamma$).

**Table 1.** Design equations and limitations of plate-to-circular hollow-section X-joint (CHS XP).

| Factors | AISC (2016) [2] | Eurocode 3 (2005) [3] | ISO 14346 (2013) [4] |
|---------|----------------|------------------------|----------------------|
| $R_n$ ($N_{1,rd}$ and $F_1$) | $5.5F_{yt}t_1^2(1 + 0.25\eta)Q_f$ | $5\sigma_{y0}h_1^2(1 + 0.25\eta)k_p$ | $5\sigma_{y0}l_0^2(1 + 0.4\eta)Q_f$ |
| $Q_f (k_p)$ | Chord in tension: 1.0 | Chord in compression: 1.0 | Chord in tension: $(1 - [n])0.25$ |
| $U = \frac{h_1 - h_t}{D}$ | $1.0 - 0.3U(1 + L)$ | $1.0 - 0.3n_p(1 + n_p) \leq 1.0$ | $n = \frac{t_0}{t_{pl,0}} + \frac{M_{pl}}{k_p}$ |
| $F_y (f_{y0}$ and $\sigma_{y0})$ | $F_y \leq 360$ MPa | $f_{y0} \leq 355$ MPa: $f_{y0}$ | $\sigma_{y0} \leq 355$ MPa: $\sigma_{y0}$ |
| $f_{y0} < f_{y0} \leq 460$ MPa: $0.9f_{y0}$ | $460 < f_{y0} \leq 700$ MPa: $0.8f_{y0}$ | $355 < \sigma_{y0} \leq 460$ MPa: $0.9\sigma_{y0}$ |
| Yield ratio ($F_y/F_u$) | 0.80 | 0.95 for $f_{y0}$ of 460 to 700 MPa | 0.80 |
| $\eta$ | $\eta$ | $\eta \leq 4$ | $1 \leq \eta \leq 4$ |
| $2\gamma$ | $2\gamma \leq 50$ | $10 \leq 2\gamma \leq 50$ | $2\gamma \leq 40$ |
3. Finite Element Analysis

3.1. Finite Element Model

The finite element (FE) analysis was performed using ABAQUS software [30], and the FE model was verified based on the experiments [26]. Table 2 shows the specimens of the FE model for verification. The CHS XP-joints with SS400 and HSB600 steel, which have yield strengths of 235 and 460 MPa, were carried out. The chord outer diameter (D) and chord wall thickness (t) were 350 and 12 mm, respectively. The longitudinal plate widths (l_b) and thickness (t_b) were 350 mm, 700 mm, and 12 mm. The CHS XP-joints were planned to have a 2γ (D/t) of 29.17 and η (l_b/D) of 1 and 2. The compression stress in CHS (P_ro) was applied to evaluate the effect of the utilization ratio (U) in the design equation, as shown in Table 1. Figure 2 shows the test installation and LH-N350-0.6 specimen.

Table 2. Specimens for validating the finite element (FE) model.

| Specimen  | Steel Grade | D (mm) | t (mm) | l_b (mm) | t_b (mm) | P_ro (kN) |
|-----------|-------------|--------|--------|----------|----------|-----------|
| LH-N700-0.0 | SS400      | 700    |        |          |          | 0         |
| LH-N700-0.6 |            |        |        |          |          | 1797      |
| LH-N350-0.0 | HSB600     | 350    | 12     | 350      | 12       | 3364      |
| LH-N350-0.6 | HSB600     | 700    |        |          |          | 3364      |

1 LH is the longitudinal horizontal plate, N700 is the plate width, and 0.0 is the utilization ratio.

Figure 2. LH-N350-0.6 specimen (LH is the longitudinal horizontal plate, N350 is the plate width, and 0.6 is the utilization ratio).

3.2. Material Properties

The SS400 and HSB600 steel grades used in the test are materials with the yield and tensile strength shown in Table 3. The tensile strengths of SS400 in the tensile and sub-column tests are almost the same, but the yield strength shows a significant difference. This is because permanent deformation occurs in the curved section when the CHS is manufactured. However, the yield and tensile strength of HSB600, which is a high-strength steel, are almost the same. The yield strength was determined by the 0.2% offset method. In the FE analysis, a bi-linear material curve using the yield and tensile strength of the stub-column test was applied. The elastic modulus and strain at tensile strength were determined to be 205 GPa and 10%, respectively. This strain of 10% is also in good agreement with the tensile test, and the Poisson’s ratio is defined by 0.3.
Table 3. Results of material properties.

| Test         | $F_y$ (MPa) | $F_u$ (MPa) | Yield Ratio | Elongation (%) |
|--------------|-------------|-------------|-------------|----------------|
| Tensile SS400| 356         | 497         | 0.72        | 38.2           |
| HSB600       | 478         | 630         | 0.76        | 34.8           |
| Stub-column  | 440         | 487         | 0.90        | -              |
| HSB600       | 485         | 606         | 0.80        | -              |

The true stress–strain curve used in the FE analysis is converted from the nominal stress–strain by using Cauchy’s law, as shown in Equations (2) and (3).

\[ \sigma_{\text{true}} = \sigma_{\text{nom}}(1 + \varepsilon_{\text{nom}}), \quad (2) \]
\[ \varepsilon_{\text{plln}} = \ln(1 + \varepsilon_{\text{nom}}) - \frac{\sigma_{\text{true}}}{E}, \quad (3) \]

where $\sigma_{\text{true}}$ is the true stress, $\varepsilon_{\text{plln}}$ is the log strain, $\sigma_{\text{nom}}$ and $\varepsilon_{\text{nom}}$ are the nominal stress and nominal strain, respectively, and $E$ is the Young’s modulus. The plates and the welds were assumed to have the same material properties as CHS [31].

3.3. Mesh Size

In the FE model, shell and solid elements were used in the case of CHS XP-joints to select the appropriate element. Table 4 shows the mesh size of both elements, and the FE model was divided into two parts: the outside part of the joint and the joint part.

Table 4. Plan of mesh convergence study.

| Element Type                              | Outside Part of Joint (O.J.) | Joint and Weld Part (J.W.) |
|-------------------------------------------|------------------------------|----------------------------|
| Shell (S4R) and Solid (C3D8R) element     | 30 mm                        | 15 mm                      |
|                                           | 20 mm                        | 10 mm                      |
|                                           | 10 mm                        | 5 mm                       |

The solid element could accurately represent the weld, but the numbers of FE elements are much greater than those of the shell element, and the analysis time becomes excessive. On the other hand, the shell element has fewer elements than the solid, but there is an assumption that the welds become the shell elements, which could lead to inaccurate results. Both the shell and solid elements are modeled as shown in Figure 3. Because the modeling of the weld affects the joint strength, Lee and Wilmshurst [32] proposed the size and composition of the weld modeling. The welds were modeled as shell elements, and a weld size of 6 mm was input.

![Figure 3. Mesh composition of the shell and solid element (LH-N700-0.0): (a) shell; (b) solid element.](image-url)
All the mesh sizes (30/15, 20/10, and 10/5 mm) and the element types (shell and solid) were analyzed. Table 5 and Figure 4 show the FE results that best agree with test results based on mesh size and element type and the comparison with the results. The joint strength is determined when an indentation of the chord wall at the connection face reaches 3% of the chord diameter (3%D) as suggested by Lu et al. [33]. As shown in Table 5, the shell and solid elements show almost the same joint strength, which are determined by 3%D, compared to the test. The joint strengths of shell and solid elements show a 1.01 ratio compared to the test result. The comparison shows that the effect of element type on the CHS XP-joint is insignificant. Thus, the shell element (S4R), with 20 mm and 10 mm of the outside and the joint part, was used as the model for FE analysis.

Table 5. Comparison of joint strength. CoV—coefficient of variation.

| Specimen       | $R_{test}$ (kN) | Shell Element | Solid Element |
|----------------|-----------------|---------------|---------------|
| LH-N700-0.0    | 791.3           | 20/10         | 788.7         | 1.00          | 20/10         | 780.6         | 0.99          |
| SS400          |                 |               |               |
| LH-N700-0.6    | 784.0           | 30/15         | 767.0         | 0.98          | 30/15         | 781.2         | 1.00          |
| LH-N350-0.0    | 569.6           | 10/5          | 611.5         | 1.07          | 10/5          | 600.3         | 1.05          |
| HSB600         | 524.5           | 10/5          | 547.7         | 1.04          | 10/5          | 537.8         | 1.03          |
| LH-N700-0.0    | 872.5           | 20/10         | 870.6         | 1.00          | 20/10         | 861.0         | 0.99          |
| LH-N700-0.6    | 784.3           | 20/10         | 781.3         | 1.00          | 20/10         | 772.5         | 0.98          |
| Mean           | 1.01            |               | 1.01          |
| CoV            | 0.033           |               | 0.026         |

Figure 4. Load–indentation curves of test and finite element (FE) models: (a) HSB600; (b) HSB600 and SS400.

3.4. Chord Length Effect

It is known that the joint strength is affected by the boundary condition of the chord end and the chord length. Van der Vegte and Makino [34,35] proposed a length of CHS equal to 10D to reduce the end effect for analysis. Voth and Packer [36] performed the FE analysis with the chord length, excluding the longitudinal plate width, which is equal to 10D.

In this paper, to check the effect of joint strength according to the chord length, the chord length ($l_o$) excluding the longitudinal plate width ($l_p$), was changed from 1.5D to 10D. The chord length-to-diameter ratio ($\alpha = l_o/D$) of the test specimen was 1.5, and the chord length of the test affected the joint strength, as shown in Figure 5. As $\alpha$ increased, the joint strength decreased until $\alpha$ became 6. The length of CHS for the FE analysis was, therefore, determined by selecting an $\alpha$ of 6.
were adopted, and true stress–strain curves were used as shown in Figure 6. Lee et al. [21] reported the yield stress of 460 (HSB600) and 650 MPa (HSA800) steel. The yield stress of steel grades S900 and S1100 was studied by Ma et al. [18]. The simplified bi-linear stress–strain curves were adopted, and true stress–strain curves were used as shown in Figure 6.

4. Parametric Analysis

The material properties used for parametric analysis are shown in Table 6. Lee et al. [25] and Lee et al. [21] reported the yield stress of 460 (HSB600) and 650 MPa (HSA800) steel. The yield stress of steel grades S900 and S1100 was studied by Ma et al. [18]. The simplified bi-linear stress–strain curves were adopted, and true stress–strain curves were used as shown in Figure 6.

Table 6. Material properties for parametric study.

| Steel   | $F_y$ (MPa) | $E$ (MPa) | $\sigma_{0.2}$ (MPa) | $\sigma_y$ (MPa) | $\epsilon_u$ (%) |
|---------|-------------|-----------|---------------------|------------------|-----------------|
| HSB600  | 460         | 205,000   | 486                 | 606              | 10              |
| HSA800  | 650         | 205,000   | 798                 | 914              | 4.2             |
| S900    | 900         | 210,000   | 1054                | 1116             | 2.26            |
| S1100   | 1100        | 207,000   | 1152                | 1317             | 2.20            |

1 Assuming a Young’s modulus and strain at ultimate strength based on the stress–strain curve [22].

The CHS XP-joint for parametric analysis was selected as the shape currently used for the HSS type of AISC [37]. HSS14 × 0.625, 14 × 0.5, 14 × 0.375, and 14 × 0.25 have a diameter of 14 inches (355.6 mm) and nominal thicknesses of 0.625 (15.875 mm), 0.5 (12.7 mm), 0.375 (9.525 mm), and 0.25 inches (6.35 mm), respectively. As shown in Table 7, the parameters are as follows: a nominal yield strength ($F_y$) of 460, 650, 900, and 1100 MPa, the chord diameter-to-thickness ratio (2$\gamma$), the longitudinal plate width-to-chord diameter ratio ($\eta$), and the utilization ratio ($U$).
was assumed to be 1.5 or 1.67 [2]. The ultimate joint strength could be determined by selecting the American Welding Society (AWS) [38]. The configuration and plan of the parametric analysis model parametric analysis. The 2
2019 joint deformation at a service load less than 1% generally used as the ultimate deformation limit [33]. This ultimate deformation limit restricts the thickness is adopted. The out-of-plane deformation of the connecting CHS of 3% diameter (3% ultimate deformation limit states and ultimate joint strength. In order to show the joint strength in the capacity is defined by the lower end of the ultimate joint strength and the load corresponding to an
limit state corresponding to the maximum load carrying capacity. This maximum load-carrying capacity is defined by the lower end of the ultimate joint strength and the load corresponding to an
 utilization ratio is the chord preload ratio, and axial force is applied to the chord in the
diameter-to-thickness ratio; \( \eta \) is the longitudinal plate width-to-chord diameter ratio; \( U \) is the utilization ratio and
parameter range of the current design equations. This shape was, however, included for parametric analysis because it is currently manufactured and used in the field. The thickness of the longitudinal plate \((t_0)\) was equal to the thickness of CHS \((t)\). The weld size \((s)\) was determined considering the minimum fillet weld size of American Welding Society (AWS) [38]. The configuration and plan of the parametric analysis model are shown in Figure 7.

The utilization ratio is the chord preload ratio, and axial force is applied to the chord in the parametric analysis. The \( 2\gamma \) of HSS14 \( \times 0.25 \) is 56.0, thus, it is out of the application range of the current design equations. This shape was, however, included for parametric analysis because it is currently manufactured and used in the field. The thickness of the longitudinal plate \((t_0)\) was equal to the thickness of CHS \((t)\). The weld size \((s)\) was determined considering the minimum fillet weld size of American Welding Society (AWS) [38]. The configuration and plan of the parametric analysis model are shown in Figure 7.

![Parametric analysis plan of CHS XP-joints.](image)

**Figure 7.** Parametric analysis plan of CHS XP-joints.

In order to determine the joint strength, design guides [3,4] are normally based on the ultimate limit state corresponding to the maximum load carrying capacity. This maximum load-carrying capacity is defined by the lower end of the ultimate joint strength and the load corresponding to an ultimate deformation limit. In contrast, AISC [2] adopts the strength limit state only, but suggests that designers should be aware of the potential for relatively large connection deformations in HSS joints. Figure 8 shows two methods for obtaining the joint strength in load-indentation curves: the ultimate deformation limit states and ultimate joint strength. In order to show the joint strength in the curves clearly, the normalization of the ordinate by dividing the yield strength and the square of the thickness is adopted. The out-of-plane deformation of the connecting CHS of 3% diameter (3%\( D \)) is generally used as the ultimate deformation limit [33]. This ultimate deformation limit restricts the joint deformation at a service load less than 1%\( D \). The ultimate deformation limit-to-service load ratio was assumed to be 1.5 or 1.67 [2]. The ultimate joint strength could be determined by selecting the

### Table 7. Parameters for CHS XP-joints made of HSB600, HSA800, S900, and S1100 steel.

| No. | Specimen (\(F_y\)-2\(\gamma\)-\(\eta\)-\(U\)) | \(2\gamma\) (\(D/t\)) | \(\eta\) | \(D\) (mm) | \(t_s\) (mm) | \(l_0\) (mm) |
|-----|---------------------------------|-----------------|-----|-----------|-----------|-----------|
| 1   | \(F_y\),2.2,2.1-U               | 2.2             | 0.949 | 460,900   | 355.6     | 355.6     |
| 2   | \(F_y\),2.2,2.1-U               | 2.2             | 0.949 | 460,900   | 355.6     | 355.6     |
| 3   | \(F_y\),2.2,2.1-U               | 2.2             | 0.949 | 460,900   | 355.6     | 355.6     |
| 4   | \(F_y\),2.2,2.1-U               | 2.2             | 0.949 | 460,900   | 355.6     | 355.6     |
| 5   | \(F_y\),2.2,2.1-U               | 2.2             | 0.949 | 460,900   | 355.6     | 355.6     |
| 6   | \(F_y\),2.2,2.1-U               | 2.2             | 0.949 | 460,900   | 355.6     | 355.6     |
| 7   | \(F_y\),2.2,2.1-U               | 2.2             | 0.949 | 460,900   | 355.6     | 355.6     |
| 8   | \(F_y\),2.2,2.1-U               | 2.2             | 0.949 | 460,900   | 355.6     | 355.6     |
| 9   | \(F_y\),2.2,2.1-U               | 2.2             | 0.949 | 460,900   | 355.6     | 355.6     |
| 10  | \(F_y\),2.2,2.1-U               | 2.2             | 0.949 | 460,900   | 355.6     | 355.6     |
| 11  | \(F_y\),2.2,2.1-U               | 2.2             | 0.949 | 460,900   | 355.6     | 355.6     |
| 12  | \(F_y\),2.2,2.1-U               | 2.2             | 0.949 | 460,900   | 355.6     | 355.6     |
| 13  | \(F_y\),2.2,2.1-U               | 2.2             | 0.949 | 460,900   | 355.6     | 355.6     |
| 14  | \(F_y\),2.2,2.1-U               | 2.2             | 0.949 | 460,900   | 355.6     | 355.6     |
| 15  | \(F_y\),2.2,2.1-U               | 2.2             | 0.949 | 460,900   | 355.6     | 355.6     |
| 16  | \(F_y\),2.2,2.1-U               | 2.2             | 0.949 | 460,900   | 355.6     | 355.6     |

1\(F_y\)-2\(\gamma\)-\(\eta\)-\(U\): \(F_y\) is the nominal yield strength for parametric analysis, (i.e., 460, 650, 900, and 1100); \(2\gamma\) is the chord diameter-to-thickness ratio; \(\eta\) is the longitudinal plate width-to-chord diameter ratio; \(U\) is the utilization ratio and
0.8 to +0.8 values with spacing 0.2 (−0.8, −0.6, −0.4, −0.2, 0.0, +0.2, +0.4, +0.6, +0.8).

### Table 7. Parameters for CHS XP-joints made of HSB600, HSA800, S900, and S1100 steel.
maximum load in the load-indentation curve. Ariyoshi and Makino [39], however, described three type of load-deformation relationships: (1) a curve in which the maximum load is clearly indicated by the decrease of the load after the maximum load; (2) a curve in which, after the first peak load, the load decreases and increases again; and (3) a curve in which the maximum load does not appear but continues to rise. The first and second types of the curves can determine the ultimate joint strength by selecting the maximum load or first peak load (F.P., see Figure 8), but the last type of curve does not facilitate determining the joint strength. Choo et al. [40] estimated the maximum strength of the CHS joints using the plastic-to-elastic work energy ratio when the maximum load did not appear in the curve. This plastic workload (P.W., see Figure 8) was defined by adopting the plastic-to-elastic work ratio of 3.0.

![Figure 8. Definition of the deformation limit and maximum load.](image)

Figure 9 and Table 8 show the results of HSB600 steel. The ultimate and serviceability deformation limits (3\%D and 1\%D) and the maximum strength determined by the first peak load or plastic workload are shown in Figure 9. In the deformation limit state, the ultimate deformation limit strengths (R_{3\%D}) are lower than 1.67 times the serviceability deformation limit strengths (R_{1\%D}) in models 2–4, but the other models are higher. As the 2\gamma increases, this ratio increases. The maximum strength (R_{max}) determined by strength limit state is entirely higher than R_{3\%D}, but this difference is not significant in models 1–4. In these cases, R_{3\%D} could represent the joint strength of CHS XP-joints.

![Figure 9. Load-indentation curves of HSB600 (F_y = 460 MPa): (a) 2\gamma of 22.4 and 37.3; (b) 2\gamma of 28.0 and 56.0.](image)
Table 8. Parametric analysis results of HSB600 ($F_y = 460$ MPa).

| No. | Specimen ($F_y$-$2\gamma$-$\eta$-$U$) | $R_{1\%D}$ (kN) | $R_{3\%D}$ (kN) | $R_{3\%D}/R_{1\%D}$ | $R_{max}$ (kN) | $R_{max}/R_{3\%D}$ | Det. |
|-----|-------------------------------------|-----------------|-----------------|----------------------|----------------|----------------------|------|
| 1   | 460-22.4-1-00                        | 577.2           | 987.3           | 1.71                 | 1076.0 (5.7)   | 1.09                 | F.P. |
| 2   | 460-22.4-2-00                        | 811.3           | 1290.7          | 1.59                 | 1402.8 (6.2)   | 1.09                 | F.P. |
| 3   | 460-22.4-3-00                        | 1047.3          | 1616.1          | 1.54                 | 1734.9 (6.8)   | 1.07                 | F.P. |
| 4   | 460-22.4-4-00                        | 1288.2          | 1956.3          | 1.52                 | 2076.0 (6.3)   | 1.06                 | F.P. |
| 5   | 460-28.0-1-00                        | 331.2           | 610.7           | 1.84                 | 695.8 (5.7)    | 1.14                 | F.P. |
| 6   | 460-28.0-2-00                        | 444.0           | 790.0           | 1.78                 | 896.8 (7.1)    | 1.14                 | F.P. |
| 7   | 460-28.0-3-00                        | 570.9           | 983.0           | 1.72                 | 1095.6 (6.7)   | 1.11                 | F.P. |
| 8   | 460-28.0-4-00                        | 694.5           | 1182.2          | 1.70                 | 1301.2 (6.8)   | 1.10                 | F.P. |
| 9   | 460-37.3-1-00                        | 162.8           | 325.5           | 2.00                 | 390.9 (6.4)    | 1.20                 | F.P. |
| 10  | 460-37.3-2-00                        | 207.5           | 415.3           | 2.00                 | 507.8 (7.7)    | 1.22                 | F.P. |
| 11  | 460-37.3-3-00                        | 258.3           | 511.1           | 1.98                 | 610.7 (8.5)    | 1.19                 | F.P. |
| 12  | 460-37.3-4-00                        | 309.6           | 613.4           | 1.98                 | 717.7 (8.5)    | 1.17                 | F.P. |
| 13  | 460-56.0-1-00                        | 63.4            | 138.0           | 2.18                 | 162.8 (5.8)    | 1.22                 | F.P. |
| 14  | 460-56.0-2-00                        | 74.8            | 172.2           | 2.30                 | 225.8 (7.8)    | 1.31                 | P.W. |
| 15  | 460-56.0-3-00                        | 88.6            | 204.8           | 2.31                 | 265.1 (7.5)    | 1.29                 | P.W. |
| 16  | 460-56.0-4-00                        | 103.6           | 241.8           | 2.33                 | 308.8 (7.8)    | 1.28                 | P.W. |

1 The indentation (%D) at $R_{max}$; 2 F.P. is the first peak load; P.W. is the plastic workload.

Figures 10–12 and Tables 9–11 show the results of HSA800, S900, and S1100 steel. In all parametric models, the ultimate-to-serviceability deformation limit ratio ($R_{3\%D}/R_{1\%D}$) continues to increase and shows a maximum ratio of 2.77. Lee et al. [21] explained that this ratio was increased by using the high-strength steel HSA800 and approaches 1.7. As the yield stress increases, the load at the ultimate deformation limit gradually moves to the elastic region of the load–indentation relationship and exhibits almost three times the load at the serviceability deformation limit. The difference between the maximum load ($R_{max}$) and the load ($R_{3\%D}$) at the ultimate deformation limit also increases simultaneously and exhibits more than two times the load in models 15 and 16 of S1100 steel.

Figure 10. Load–indentation curves of HSA800 ($F_y = 650$ MPa): (a) $2\gamma$ of 22.4 and 37.3; (b) $2\gamma$ of 28.0 and 56.0.
Table 9. Parametric analysis results of HSA800 ($F_y = 650$ MPa).

| No. | Specimen $F_y$-2γ-U & | $R_{1\%D}$ (kN) | $R_{3\%D}$ (kN) | $R_{3\%D}/R_{1\%D}$ | $R_{max}$ (kN) | $R_{max}/R_{3\%D}$ | Det. |
|-----|----------------------|-----------------|-----------------|---------------------|----------------|---------------------|------|
| 1   | 650-22.4-1-00        | 615.6           | 1312.4          | 2.13                | 1613.4         | 1.23                | F.P. |
| 2   | 650-22.4-2-00        | 859.2           | 1786.7          | 2.08                | 2141.0         | 1.20                | F.P. |
| 3   | 650-22.4-3-00        | 1110.9          | 2289.7          | 2.06                | 2681.4         | 1.17                | F.P. |
| 4   | 650-22.4-4-00        | 1366.1          | 2808.3          | 2.06                | 3238.1         | 1.15                | F.P. |
| 5   | 650-28.0-1-00        | 345.1           | 784.5           | 2.27                | 1018.8         | 1.30                | F.P. |
| 6   | 650-28.0-2-00        | 461.5           | 1051.8          | 2.28                | 1343.1         | 1.28                | F.P. |
| 7   | 650-28.0-3-00        | 587.7           | 1339.8          | 2.28                | 1665.2         | 1.24                | F.P. |
| 8   | 650-28.0-4-00        | 715.5           | 1626.1          | 2.27                | 1999.8         | 1.23                | F.P. |
| 9   | 650-37.3-1-00        | 165.5           | 404.5           | 2.44                | 552.7          | 1.37                | F.P. |
| 10  | 650-37.3-2-00        | 210.8           | 526.5           | 2.50                | 736.8          | 1.40                | F.P. |
| 11  | 650-37.3-3-00        | 261.4           | 657.1           | 2.51                | 904.8          | 1.38                | F.P. |
| 12  | 650-37.3-4-00        | 313.5           | 795.4           | 2.54                | 1073.4         | 1.35                | P.W. |
| 13  | 650-56.0-1-00        | 63.5            | 163.5           | 2.58                | 229.3          | 1.40                | P.W. |
| 14  | 650-56.0-2-00        | 75.0            | 199.8           | 2.66                | 315.9          | 1.58                | P.W. |
| 15  | 650-56.0-3-00        | 88.8            | 237.2           | 2.67                | 388.7          | 1.64                | P.W. |
| 16  | 650-56.0-4-00        | 104.0           | 279.2           | 2.69                | 458.0          | 1.64                | P.W. |
Table 10. Parametric analysis results of S900 ($F_y = 900$ MPa).

| No. | Specimen ($F_y$-2γ-η-U) | $R_{1\%}$ (kN) | $R_{3\%}$ (kN) | $R_{3\%}/R_{1\%}$ | $R_{\text{max}}$ (kN) | $R_{\text{max}}/R_{3\%}$ | Det. |
|-----|------------------------|-----------------|-----------------|---------------------|------------------------|--------------------------|------|
| 1   | 900-22.4-1-00          | 634.5           | 1508.9          | 2.38                | 1950.4 (7.9)           | 1.29                     | F.P. |
| 2   | 900-22.4-2-00          | 882.1           | 2092.1          | 2.37                | 2602.6 (8.0)           | 1.24                     | F.P. |
| 3   | 900-22.4-3-00          | 1141.5          | 2704.1          | 2.37                | 3271.5 (7.7)           | 1.21                     | F.P. |
| 4   | 900-22.4-4-00          | 1403.2          | 3327.5          | 2.37                | 3964.5 (7.3)           | 1.19                     | F.P. |
| 5   | 900-28.0-1-00          | 354.5           | 890.1           | 2.51                | 1213.4 (8.8)           | 1.36                     | F.P. |
| 6   | 900-28.0-2-00          | 474.1           | 1204.7          | 2.54                | 1618.4 (9.3)           | 1.34                     | F.P. |
| 7   | 900-28.0-3-00          | 602.5           | 1532.2          | 2.54                | 2018.8 (9.6)           | 1.32                     | F.P. |
| 8   | 900-28.0-4-00          | 733.8           | 1874.1          | 2.55                | 2436.6 (8.8)           | 1.30                     | F.P. |
| 9   | 900-37.3-1-00          | 169.7           | 446.1           | 2.63                | 643.4 (9.1)            | 1.44                     | F.P. |
| 10  | 900-37.3-2-00          | 216.1           | 575.3           | 2.66                | 871.4 (10.3)           | 1.51                     | P.W. |
| 11  | 900-37.3-3-00          | 267.8           | 717.4           | 2.68                | 1083.3 (10.5)          | 1.51                     | P.W. |
| 12  | 900-37.3-4-00          | 321.4           | 867.0           | 2.70                | 1321.4 (10.6)          | 1.50                     | P.W. |
| 13  | 900-56.0-1-00          | 65.0            | 174.9           | 2.75                | 446.4 (13.1)           | 1.86                     | P.W. |
| 14  | 900-56.0-2-00          | 76.8            | 210.3           | 2.74                | 371.1 (12.6)           | 1.76                     | P.W. |
| 15  | 900-56.0-3-00          | 91.0            | 247.9           | 2.75                | 462.5 (14.0)           | 1.92                     | P.W. |
| 16  | 900-56.0-4-00          | 106.5           | 293.4           | 2.76                | 562.5 (16.3)           | 2.20                     | P.W. |

Table 11. Parametric analysis results of S1100 ($F_y = 1100$ MPa).

| No. | Specimen ($F_y$-2γ-η-U) | $R_{1\%}$ (kN) | $R_{3\%}$ (kN) | $R_{3\%}/R_{1\%}$ | $R_{\text{max}}$ (kN) | $R_{\text{max}}/R_{3\%}$ | Det. |
|-----|------------------------|-----------------|-----------------|---------------------|------------------------|--------------------------|------|
| 1   | 1100-22.4-1-00         | 626.0           | 1569.5          | 2.51                | 2146.6 (8.5)           | 1.37                     | F.P. |
| 2   | 1100-22.4-2-00         | 870.1           | 2185.7          | 2.51                | 2901.0 (9.1)           | 1.33                     | F.P. |
| 3   | 1100-22.4-3-00         | 1125.1          | 2824.8          | 2.70                | 3676.7 (8.9)           | 1.50                     | P.W. |
| 4   | 1100-22.4-4-00         | 1383.0          | 3479.9          | 2.74                | 4477.4 (8.5)           | 1.29                     | F.P. |
| 5   | 1100-28.0-1-00         | 349.5           | 912.3           | 2.61                | 1324.8 (9.5)           | 1.45                     | F.P. |
| 6   | 1100-28.0-2-00         | 467.3           | 1228.2          | 2.63                | 1791.3 (10.8)          | 1.46                     | F.P. |
| 7   | 1100-28.0-3-00         | 594.2           | 1566.8          | 2.64                | 2256.0 (10.4)          | 1.44                     | F.P. |
| 8   | 1100-28.0-4-00         | 723.2           | 1911.1          | 2.64                | 2736.8 (9.8)           | 1.43                     | F.P. |
| 9   | 1100-37.3-1-00         | 167.3           | 449.5           | 2.69                | 697.5 (10.6)           | 1.55                     | F.P. |
| 10  | 1100-37.3-2-00         | 213.0           | 578.1           | 2.71                | 958.7 (11.8)           | 1.66                     | P.W. |
| 11  | 1100-37.3-3-00         | 264.0           | 720.4           | 2.73                | 1203.5 (11.8)          | 1.67                     | P.W. |
| 12  | 1100-37.3-4-00         | 316.8           | 869.7           | 2.75                | 1455.6 (12.2)          | 1.67                     | P.W. |
| 13  | 1100-56.0-1-00         | 64.1            | 174.0           | 2.72                | 286.5 (11.6)           | 1.65                     | P.W. |
| 14  | 1100-56.0-2-00         | 75.7            | 208.7           | 2.76                | 412.7 (14.7)           | 1.98                     | P.W. |
| 15  | 1100-56.0-3-00         | 89.7            | 247.7           | 2.76                | 527.1 (15.8)           | 2.13                     | P.W. |
| 16  | 1100-56.0-4-00         | 105.0           | 290.9           | 2.77                | 639.2 (16.3)           | 2.20                     | P.W. |

5. Comparison of Design Equations

The results of the parametric analysis were compared with the current design equations mentioned in Table 1. Each design equation is constructed as shown in Equation (4). By dividing the nominal yield stress ($F_y$) and the square of the chord thickness ($t^2$) and assuming that the CHS has no axial load and bending moment applied, the design equations are simply constructed as shown in Equation (5).

$$R_u = Q_u Q_f F_y t^2,$$  \hspace{1cm} (4)

$$Q_u = A(1 + B\eta),$$  \hspace{1cm} (5)

where $Q_u$ is a partial design strength function that predicts the joint capacity without chord axial stress, and $Q_f$ is a chord stress function that reduces the joint resistance based on the chord normal stress influence. $Q_u$ is a value only affected by the longitudinal plate width-to-chord diameter ratio ($\eta$). The values of $A$ and $B$ are constants, which are 5.5 and 0.25 for AISC [2], 5.0 and 0.25 for Eurocode 3 [3], and 5.0 and 0.4 for ISO 14346 [4].
Table 12 shows the comparison of the design equations [2–4], with the ultimate deformation limit load divided by the yield strength and square of the chord thickness. The design equations show only the value related to $\eta$ independently of the yield strength, but the $R_{3\%D}$ gradually decreases as the yield strength increases. This is because the $R_{3\%D}$ determined by the ultimate deformation limit is moved to the elastic region as the yield strength increases and is determined to be lower than the $R_{max}$. This is remarkable in the results of S900 and S1100 steel. The $R_{3\%D}$ of those (see Tables 10 and 11) is almost the same, thus, the normalized $R_{3\%D}$ gradually decreases. The mean values of the design strength of the AISC [2] to $R_{3\%D}$ ratio and the coefficient of variation (CoV) are 0.79 and 0.101 at yield stresses of 460 MPa, 0.88 and 0.168 at 650 MPa, 1.10 and 0.206 at 900 MPa, and 1.32 and 0.223 at 1100 MPa, respectively.

Figure 13 shows the ratio of the design equations to the $R_{3\%D}$ and $R_{max}$ according to the nominal yield stress. In AISC [2], the nominal yield strength is limited to 360 MPa, which is the reason that the design joint strength is overestimated in high-strength steels. In Eurocode 3 [3] and ISO 14346 [4], the design equations would be estimated properly until nominal yield strength limitations of 700 MPa and 460 MPa, respectively. As the nominal yield strength and $2\gamma$ value increase, the design equations are overestimated. However, the ratio of the current design equations to $R_{max}$ is less than 1.0 and the CoV is not large, as shown in Figure 13.

Figure 14 shows the strength reduction effect according to the utilization ratio ($\delta$). As shown in Table 1, AISC [2] and Eurocode 3 [3] apply the same relational expression considering the reduction effect when compressive force is applied, and there is no reduction effect when tensile force is applied to CHS. ISO 14364 [4], on the other hand, considers the reduction effects in both compressive and tensile conditions. Figure 14a,b and Figure 14c,d show the chord stress function ($Q_f$) using $R_{3\%D}$ and $R_{max}$, respectively. Compared with the design equations in compressive force acting on the chord, the tendency of the design equation is slightly conservative. When the tensile force is applied, $Q_f$ is gradually lowered at the yield stress of 460 MPa, but AISC [2] and Eurocode 3 [3] do not consider the reduction effect. However, at a yield stress of 650 MPa or more, the reduction effect does not appear or is even higher, and this is different from ISO 14346 [4]. The $Q_f$ determined by $R_{max}$ is slightly lower than $R_{3\%D}$, but the tendency is similar.
Table 12. Comparison of design equations with the joint strength using the ultimate deformation limit.

| No. | Yield Stress of CHS | Normalized Joint Strength, $R_{3\%D}/F_{y}t^{2}$ | AISC (2016) [2] | Eurocode (2005) [3] | ISO 14346 (2013) [4] |
|-----|---------------------|-----------------------------------------------|-----------------|---------------------|---------------------|
|     |                     | $R_{u}/F_{y}t^{2}$ | $R_{u}/R_{3\%D}$ | $N_{L,Rd}/F_{y}t^{2}$ | $N_{L,Rd}/R_{3\%D}$ | $F_{1}/F_{y}t^{2}$ | $F_{1}/R_{3\%D}$ |
| 1   | 460                 | 6.9     | 0.8     | 1.0     | 1.2     | 5.0     | 0.6     | 0.6     | 0.8     | 0.9     | 6.3     | 0.7     | 0.8     | 0.9     | 1.1     |
| 2   | 650                 | 8.3     | 0.7     | 0.8     | 0.9     | 1.0     | 6.0     | 0.5     | 0.6     | 0.7     | 0.8     | 8.1     | 0.7     | 0.7     | 0.9     | 1.0     |
| 3   | 900                 | 9.6     | 0.7     | 0.7     | 0.8     | 0.9     | 7.0     | 0.5     | 0.5     | 0.6     | 0.7     | 9.9     | 0.7     | 0.7     | 0.8     | 1.0     |
| 4   | 1100                | 11.0    | 0.7     | 0.6     | 0.7     | 0.9     | 8.0     | 0.5     | 0.5     | 0.5     | 0.6     | 11.7    | 0.7     | 0.7     | 0.8     | 0.9     |
| 5   | 6.9                 | 0.8     | 0.9     | 1.1     | 1.3     | 5.0     | 0.6     | 0.7     | 0.8     | 1.0     | 6.3     | 0.8     | 0.8     | 1.0     | 1.2     |
| 6   | 8.3                 | 0.8     | 0.8     | 1.0     | 1.2     | 6.0     | 0.6     | 0.6     | 0.7     | 0.9     | 8.1     | 0.8     | 0.8     | 1.0     | 1.2     |
| 7   | 10.6                | 0.7     | 0.8     | 0.9     | 1.1     | 7.0     | 0.5     | 0.5     | 0.7     | 0.8     | 9.9     | 0.7     | 0.8     | 0.9     | 1.1     |
| 8   | 12.8                | 9.6     | 0.7     | 0.8     | 0.9     | 1.1     | 7.0     | 0.5     | 0.5     | 0.7     | 0.8     | 9.9     | 0.7     | 0.8     | 0.9     | 1.1     |
| 9   | 15.5                | 11.0    | 0.7     | 0.7     | 0.9     | 1.0     | 8.0     | 0.5     | 0.5     | 0.6     | 0.7     | 11.7    | 0.7     | 0.8     | 0.9     | 1.1     |
| 10  | 17.7                | 6.9     | 0.9     | 1.0     | 1.3     | 1.5     | 5.0     | 0.6     | 0.7     | 0.9     | 1.1     | 6.3     | 0.8     | 0.9     | 1.2     | 1.4     |
| 11  | 10.0                | 8.3     | 0.8     | 0.9     | 1.2     | 1.4     | 6.0     | 0.6     | 0.7     | 0.9     | 1.0     | 8.1     | 0.8     | 0.9     | 1.1     | 1.4     |
| 12  | 12.2                | 9.6     | 0.8     | 0.9     | 1.1     | 1.3     | 7.0     | 0.6     | 0.6     | 0.8     | 1.0     | 9.9     | 0.8     | 0.9     | 1.1     | 1.4     |
| 13  | 14.7                | 11.0    | 0.7     | 0.8     | 1.0     | 1.3     | 8.0     | 0.5     | 0.6     | 0.8     | 0.9     | 11.7    | 0.8     | 0.9     | 1.1     | 1.3     |
| 14  | 16.7                | 6.9     | 0.9     | 1.1     | 1.4     | 1.8     | 5.0     | 0.7     | 0.8     | 1.0     | 1.3     | 6.3     | 0.8     | 1.0     | 1.3     | 1.6     |
| 15  | 18.7                | 8.3     | 0.9     | 1.1     | 1.4     | 1.8     | 6.0     | 0.6     | 0.8     | 1.0     | 1.3     | 8.1     | 0.9     | 1.1     | 1.4     | 1.7     |
| 16  | 20.6                | 9.6     | 0.9     | 1.1     | 1.4     | 1.7     | 7.0     | 0.6     | 0.8     | 1.0     | 1.3     | 9.9     | 0.9     | 1.1     | 1.4     | 1.8     |
| Mean|                    |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |
| CoV |                    | 0.07    | 0.08    | 0.10    | 0.13    | 0.06    | 0.08    | 0.09    | 0.11    | 0.07    | 0.09    | 0.12    | 0.08    | 0.10    | 0.12    | 0.14    |

1 Use reduction factors of 0.8 for Eurocode 3 and 2 0.9 for ISO 14346. CoV: coefficient of variation.
Figure 14. Comparison of the chord stress functions with parametric analysis results: (a) HSB600 and HSA800 steel with \( R_{\text{ELD}} \); (b) S900 and S1100 steel with \( R_{\text{ELD}} \); (c) HSB600 and HSA800 steel with \( R_{\text{max}} \); (d) S900 and S1100 steel with \( R_{\text{max}} \).

Figure 15 shows a comparison of the design equations using additional reduction factors (\( \beta \)) with analysis results without the 2\( \gamma \) value of 56.0 (No. 13 to 16) because of the limitation of the slenderness of the chord in codes. The \( \beta \) values are shown in Table 13 and determined by adjusting the mean and CoV of the ratio between the joint strength and design strength without exceeding 1.0.

Figure 15. Comparison of design equations using reduction factors (\( \beta \)) with analysis results: (a) AISC (2016); (b) Eurocode (2005); (c) ISO 14346.
Table 13. Reduction factors for high-strength steel.

| Nominal Yield Strength | AISC (2016) [2] | Eurocode (2005) [3] | ISO 14346 (2013) [4] |
|------------------------|-----------------|---------------------|---------------------|
| 460                    | 1.0             | 0.8                 | 0.9                 |
| 650                    | 0.9             | 0.8                 | 0.9                 |
| 900                    | 0.75            | 0.8                 | 0.75                |
| 1100                   | 0.62            | 0.67                | 0.62                |

1 Design equations have reduction factors for high-strength steel in each code (See Table 1).

6. Conclusions

In this paper, a longitudinal plate-to-CHS XP-joint using high-strength steel with a yield strength of 460 to 1100 MPa was investigated. The following results were obtained by the results of the parametric analysis with the variables of the CHS shape, the application range of the plate joint, and the stress ratio acting on the chord, as well as a comparison with current design equations:

(1) The joint strength ($R_{3\%D}$) at the ultimate deformation limit is slightly lower than the maximum strength ($R_{max}$) at the yield strength of 460 MPa. The difference between $R_{3\%D}$ and $R_{max}$ gradually increases, because the $R_{3\%D}$ is moved in the elastic region of the load-indentation relationship. However, taking into account the deformation at the $R_{max}$, which has a relatively large connection deformation, the $R_{3\%D}$ could be represented as the joint capacity.

(2) The $R_{3\%D}$ at yield strengths of 900 and 1100 MPa is almost the same because it belongs to the elastic range. The deformation limit criterion controls the ultimate behavior of the CHS XP-joints, and the elasticity modulus of the material controls the deformation behavior of the joint. This aspect shows that the joint strength determined by the deformation limit converges to a specific level when using higher-strength steels.

(3) The design equations limit the nominal yield strength with different levels in each code. The strength reduction factor can be applied to secure the applicability to high-strength steels while maintaining the design formula. The reduction factors ($\beta$), therefore, are suggested for high-strength steel.

(4) The chord stress function ($Q_f$) tends to decrease in axial compression chord stress, and it shows a similar tendency to ISO 14346. When the axial tension chord stress is acting on, ISO 14346 is similar at the yield strength of 460 MPa, but AISC and Eurocode 3, which do not consider the strength reduction effect, are similar with increasing yield strength. Therefore, when using the high-strength steel under axial tension chord stress, the strength reduction effect can be neglected.

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Glossary

$A_g$: Gross cross-section area of chord;
$D$: Diameter of chord ($=d_0$);
$E$: Elastic modulus;
$F_c$: Available stress of chord;
$F_{pl,0}$: Chord axial capacity;
$F_u$: Nominal ultimate strength of chord ($=\sigma_u$);
$F_y$: Nominal yield strength of chord ($=f_{y0}$ and $\sigma_{y0}$);
Width of longitudinal plate (\(=h_1\));
Length of chord excluding plate width;
Chord plastic moment capacity;
Required flexural strength in chord (\(=M_0\));
Required axial strength in chord (\(=F_0\));
Chord stress interaction parameter (\(=k_p\));
Partial design strength function;
Joint strength in finite element analysis;
Joint strength determined by strength limit state;
Nominal strength of joint (\(=N_{1,Rd}\) and \(F_1\));
Joint strength in test;
Joint strength in serviceability deformation limit;
Joint strength in ultimate deformation limit;
Elastic section modulus about the bending axis;
Weld size;
Thickness of chord (\(=t_0\));
Thickness of longitudinal plate (\(=t_1\));
Utilization ratio (\(=\eta_p\) and \(\eta\));
Chord length-to-diameter ratio (\(=l_0/D\));
Reduction factor for high-strength steel;
Chord diameter-to-thickness ratio (\(=D/t\) or \(d_0/t_0\));
Log strain;
Nominal strain;
Plate width-to-chord diameter ratio (\(=l_b/D\) or \(h_1/d_0\));
Nominal stress;
Maximum compressive stress in the chord;
True stress;
Chord indentation of joint strength by deformation limit state.

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