EFFECT OF CHORD PRELOADING AND BRACE INCLINATION ON AXIAL RESISTANCE OF FULL-WIDTH RHS X-JOINT

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According to current representative design standards, the influence of brace angle on the axial resistance of rectangular hollow section (RHS) X-joints is assumed to be independent of the chord preloading state. To investigate the appropriateness of this assumption, extensive test-validated finite element (FE) analyses are performed on full-width RHS X-joints with varying brace angles and chord preloads. The analyses showed that an appreciable coupling effect between the brace angle and chord preload exists on the joint resistances. The most adverse coupling effect occurs under the condition of high brace inclination and large compressive chord preload, leading to the concern that the current design resistance formula may overestimate the ultimate joint strength. Consequently, a revised chord stress function is sought for inclined full-width RHS X-joints that accounts for the coupling effect between chord preload and brace angle. In the FE analyses, high strength steel joints are included as well as conventional mild steel joints. The chord stress effect in high strength steel joints is found to be more detrimental compared to geometrically identical mild steel joints, implying that the chord stress effect may be influenced by the class (slenderness) of the chord cross-section. Therefore, a proper limitation on the chord section slenderness, such as the Class 2 requirement in design codes, appears essential.

Keywords: Rectangular hollow section, Finite element (FE), Brace angle, Chord stress effect.

1 INTRODUCTION

This paper examines the influence of brace angle and chord preload on the axial resistance of full-width rectangular hollow section (RHS) X joints. Figure 1 shows the typical geometric configuration and important parameters of RHS X-joints, where the subscripts 0 and 1 correspond to the chord and brace, respectively. The scope of this investigation is limited to full-width joints, which have a brace-to-chord width ratio (β) of 1.0. Current design recommendations, such as CIDECT Design Guide No. 3 (Packer et al. 2009), assume that the chord stress effect and brace angle effect on the ultimate joint strength of RHS X-joints are independent of each other. However, this assumption has not been verified with relevant experimental evidence due to the lack of experimental data on RHS X-joints with inclined braces or chord preload. Therefore, there is a research need to perform supplemental numerical analyses to verify the uncoupled effect assumption.

In this study, extensive test-validated finite element (FE) analyses were conducted on full-width RHS X-joints with varying brace angles and chord preloads. The FE analyses included high
strength steel joints as well as conventional mild steel joints. The inclusion of high strength steel was motivated by the fact that the chord stress function in CIDECT Design Guide No. 3 was developed using numerical data that featured solely one mild steel grade with $f_y = 355$ MPa (Wardenier et al. 2007). Moreover, the chord stress effect in high strength steel joints has not been thoroughly studied (Kim et al. 2019).

**Figure 1.** Geometric configuration and important parameters of RHS X-joints.

### 2 RELAVANT PROVISIONS IN CIDECT DESIGN GUIDE NO. 3

The chord stress function is commonly used in the design resistance equation of a tubular joint configuration to account for the chord stress effect. This function therefore denotes the ratio of joint strength between the scenarios with chord preload and without chord preload. According to CIDECT Design Guide No. 3, the chord stress function for RHS X-joints is given by Eqs. (1)-(3) presented below:

$$Q_{f,\text{CIDECT}} = (1-|\eta|)^{0.6-0.5\beta} \quad (n < 0)$$

$$Q_{f,\text{CIDECT}} = (1-|\eta|)^{0.1} \quad (n \geq 0)$$

$$n = \frac{N_0}{N_{pl,0}} + \frac{M_0}{M_{pl,0}}$$

The primary factor in the chord stress function is the chord stress ratio ($n$) in Eq. (3), where $N_0$ and $M_0$ are the axial and moment preloads on the chord, respectively. $N_{pl,0}$ and $M_{pl,0}$ denote the axial yield load and plastic moment capacity of the chord cross-section. If $n < 0$, it indicates that compressive chord load is applied, while $n > 0$ means that tensile chord load is applied. This study only considers axial loads for chord preload, which means that $M_0 = 0$ and $n$ becomes the axial load-to-capacity ratio. The chord stress function takes into account the interaction between the width ratio ($\beta$) and the chord preload ratio ($n$). However, it does not consider the impact of other geometric parameters, such as the brace angle, on the chord stress effect.

It is important to note that the CIDECT chord stress function is applicable only to joints with Class 1 or 2 chord cross-sections when compressive preload is applied or the chord preload ratio ($n$) is negative. The Class 2 requirement is a universal one that applies to general joint configurations and is also adopted in various international codes, including EN 1993-1-8 (CEN 2005b) and ISO 14346 (IIW 2013). Table 1 presents the class limits (CEN 2005a) for the two types
of steel considered in this study. For mild steel SM355 ($f_y = 338$ MPa), the Class 2 requirement has little impact on the design of RHS X-joints since it is mostly satisfied within the basic applicable range of $b/t \leq 40$ and $h/t \leq 40$, as per CIDECT Design Guide No. 3. However, for high strength steel HSA650, the Class 2 requirement becomes much more stringent than the basic requirement of $b/t \leq 40$ and $h/t \leq 40$. Due to this fact, there have been some concerns that the class requirement may hinder the use of many practically useful high strength steel tubular sections, which belong to Class 3 or 4 but still have popular $b/t$ or $h/t$ ratios. While the rationale behind the Class 2 requirement is unclear and appears to be undocumented, the behavior of high strength steel tubular joints with Class 3 or 4 cross sections needs be examined to determine whether the Class 2 requirement can be relaxed to allow for more high strength steel applications.

### Table 1. Class limits of mild and high strength steel RHSs.

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>SM355 ($f_y = 338$ MPa)</th>
<th>HSA650 ($f_y = 715$ MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class</td>
<td>Limiting $b/t$ or $h/t$ values</td>
<td>Limiting $b/t$ or $h/t$ values</td>
</tr>
<tr>
<td>1 (33x=24)</td>
<td>$b/t$ or $h/t \leq 33.5$</td>
<td>$b/t$ or $h/t \leq 24.9$</td>
</tr>
<tr>
<td>2 (38x=24)</td>
<td>$b/t$ or $h/t \leq 37.7$</td>
<td>$b/t$ or $h/t \leq 27.8$</td>
</tr>
<tr>
<td>3 (42x=24)</td>
<td>$b/t$ or $h/t \leq 41$</td>
<td>$b/t$ or $h/t \leq 30.1$</td>
</tr>
<tr>
<td>4</td>
<td>$b/t$ or $h/t &gt; 41$</td>
<td>$b/t$ or $h/t &gt; 30.1$</td>
</tr>
</tbody>
</table>

Note 1: $\varepsilon = 235f_y$

Note 2: $k =$ outer corner radius divided by thickness ($k = 3$ in this study)

### 3 Finite Element Analysis

#### 3.1 Modeling

FE analyses were performed using a general-purpose analysis code ABAQUS 6.14 (Simulia 2014). 20-node solid elements with reduced integration (C3D20R in ABAQUS) were chosen for the construction of FE models. The von Mises yield criterion with isotropic hardening was assumed for material properties. Modeling only a half of the entire connection was sufficient considering the symmetries in geometry and loading. Weld shape was determined in accordance with the prequalified detail in Fig. 10.9 of AWS D1.1 (AWS 2020). Examples of FE model and result are shown in Figure 2. The end of the lower brace was given a fully fixed condition, while the end of the upper brace was rotationally restrained but translationally free only in the brace axial direction. The chord preload and joint load (i.e., axial load on the brace) were applied in a sequential manner; application of chord preload preceded and was followed by the joint loading. For further details and experimental validation of the modeling approach, interested readers may refer to Kim and Lee (2021).

Material and geometric parameters considered in the analyses are summarized in Table 2. Only square cross-sections were included for the chord ($b_0 = h_0$), and the brace-to-chord width ratio was fixed to 1.0 ($\beta = 1.0$). Identical thicknesses were used for brace and chord members in a joint. Wide ranges of brace angle ($\theta_1$) and chord stress ratio ($n$) were covered as the study intended to investigate the coupled effects of brace angle and chord preload. Two steel grades, SM355 and HSA650, were included, representing typical mild and high-strength steels, respectively. Various section classes of the chord were accommodated by the two steel grades and the two width-to-thickness ratios ($2\gamma$). Although all possible combinations of the parameters in Table 2 were tested, convergence was not always achieved, particularly when the analysis was related to extreme geometry and loading conditions such as $\theta_1 = 30^\circ$ or $n = -0.8$. Possible reasons for the low convergence include: 1) formation of distorted elements due to highly curved weld geometry with $\theta_1 = 30^\circ$ and 2) local instability in the chord member outside the joint region due to the large
compressive stress with $n = -0.8$. Some non-convergence with $n = -0.8$ was resolved by marginally decreasing the preload ratio to $n = -0.75$ or -0.7. The data with $n = -0.75$ or -0.7 are distinguished by the red marks in Figures 3(a)-(b).

![Half joint model](image1)
![Weld geometry](image2)
![FE result](image3)

Figure 2. FE modeling.

### Table 2. Parameters considered in FE analyses.

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>$f_y = 338$ MPa</th>
<th>$f_y = 715$ MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_0 = h_0$</td>
<td>300 mm</td>
<td></td>
</tr>
<tr>
<td>$\beta$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$2\gamma$</td>
<td>20, 40</td>
<td></td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.5, 1, 1.5</td>
<td></td>
</tr>
<tr>
<td>$n$</td>
<td>-0.8, 0, 0.8</td>
<td></td>
</tr>
<tr>
<td>$\theta_1$, in degrees</td>
<td>90, 60, 45, 30</td>
<td></td>
</tr>
</tbody>
</table>

### 3.2 Results and Discussions

The results of the FE analyses are compared with the CIDECT chord stress function ($Q_{f,CIDECT}$) in Figure 3. $Q_f$ is the joint strength ratio between the cases of chord preload and no chord preload obtained from FE analyses. $Q_f/Q_{f,CIDECT}$ values higher than 1.0 indicate that the CIDECT chord stress function can conservatively evaluate the chord stress effect. Conversely, values lower than 1.0 indicate that the CIDECT chord stress function provides optimistic predictions of the actual chord stress effect, potentially leading to non-conservatism of the design resistance. However, slightly unconservative results of orthogonal joints (i.e., $\theta = 90^\circ$), observed for both compressive and tensile chord preload cases, may be compensated by conservatism in other parts of the joint strength design equation.

As shown in Figure 3, there is clear evidence of a coupled effect between brace angle and chord preload, with opposite trends observed in Figures 3(a)-(b) for $n = -0.8$ and Figures 3(c)-(d) for $n = 0.8$. When compressive chord preload is applied ($n = -0.8$), the chord stress effect intensifies as the brace angle $\theta_1$ decreases. For $\theta_1 = 30^\circ$, the CIDECT chord stress function is highly non-conservative, raising concerns that the design resistance equation may unduly overestimate the ultimate joint strength. Therefore, a revised chord stress function is needed for inclined full-width RHS X-joints subjected to large compressive chord preload. On the other hand, when tensile preload is applied ($n = +0.8$), the chord stress effect diminishes as the inclination of the brace increases.

The impact of chord section slenderness on the chord stress effect can also be observed in Figure 3. The FE models used two values of $2\gamma$, i.e., 20 and 40, as shown in Table 2. According
to Table 1, the chord cross-section with $2\gamma = 20$ corresponds to Class 1 for both SM355 and HSA650. With $2\gamma = 40$, the SM355 chord marginally violates the Class 2 requirement and belongs to Class 3, while the HSA650 chord with $2\gamma = 40$ is even slenderer and belongs to Class 4. When $2\gamma = 20$, the SM355 and HSA650 joints exhibit similar chord stress effects for both compression and tension preloads (Figures 3(a) and (c)). However, when $2\gamma = 40$, similar chord stress effects between the two steels are only observed for the tensile preload case (Figure 3(d)), whereas distinct trends are shown for the compressive preload case (Figure 3(b)).

This may be explained by the difference in the section classes of SM355 and HSA650 with $2\gamma = 40$ (Classes 3 and 4, respectively). Lower section class indicates higher vulnerability to compressive local buckling, and the degradation of joint strength due to compressive chord preload might have been intensified by the possible local instability in the slenderer chord cross-section. While the chord section class may have a significant impact in the presence of compressive chord preload, it may not be influential under tensile preload because local instability is not expected. This justifies the similar trends between the two steels shown in Figure 3(d) despite the lower section class for HSA650. Although the Class 2 requirement specified in current design codes may act as a technical barrier against the application of high-strength steel to tubular connections, considering the aforementioned aspects related to the section class, it still seems logical to retain a limitation on the section slenderness. It is worth mentioning that the necessity of imposing a section class limitation was also underscored by Kim et al. (2019) for RHS X-joints having $\beta < 1.0$ and $\theta_1 = 90^\circ$.

Figure 3. Evaluation of CIDECT chord stress function of RHS X-joints ($\beta = 1.0$).
4 CONCLUSIONS

In this study, test-validated finite element (FE) analyses were conducted on full-width RHS X-joints under brace axial compression. The effects of brace angle and chord preload on the ultimate joint strength were explored through a parametric study, including mild and high strength steels. The results were used to evaluate the chord stress function specified in CIDECT Design Guide No. 3. The following summarizes the conclusions drawn from this study.

(i) The FE analysis results showed that the coupled effect between chord preload and brace angle has a significant impact on the ultimate joint strength of full-width RHS X-joints.

(ii) The most adverse coupling effect occurred under the combination of high brace inclination and large compressive chord preload, raising the concern that the current design resistance formula may overestimate the ultimate joint strength in such cases.

(iii) The detrimental effect by the chord stress was more significant in high strength steel joints than in geometrically identical mild steel joints. This suggests that the class of the chord cross-section can influence the chord stress effect, and a proper limitation on the chord section slenderness, such as the Class 2 requirement in design codes, is necessary for the design of full width RHS X-joints in the presence of chord preload.

References