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Mechanical behaviour of welded high strength steel rectangular hollow section joints

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\textbf{ABSTRACT}

The material reduction factor of rectangular hollow section (RHS) joints in a new version of Eurocode 3 part 1–8 is validate for steel with the nominal yield strength up to 700 MPa. In this paper, finite element simulations of gap K-joints are conducted to investigate effects of material properties, gap size of the joint, the brace to chord width ratio and welds type on the secondary bending stresses and the resistance. The governing failure mode considered for all the FE models is the chord face failure followed by brace sidewall failure. The ratio of axial stresses to the nominal stress was lower in the compressive brace made of higher strength steel grades compared to the mild strength grades. The maximum secondary bending stresses is 0.12–0.32 yield strength. The secondary bending stresses are increasing with the increase of the steel grade and the brace to chord width ratio and with reducing the gap size. The level of secondary bending stresses varied between 38% and 56% of the average normal axial stress. The secondary bending stresses of fillet-welded joints are larger than the butt-welded joints. The yield line model is used to predict the ultimate load and good agreement is obtained compared with FE results.

1. Introduction

The high strength steel (HSS) benefits long-span and high-rise structures in civil engineering sector, such as sports arenas and bridges [1–5]. Tubular structures are generally recommended for such high-rise and long-span structures [6]. The safety and reliability of HSS welded hollow section joints are very important to tubular structures [7]. The hollow section joints could be divided into circular hollow section (CHS) joints [8–10] and rectangular hollow section (RHS) joints [13,14].

One obstacle for competitive use in engineering practice is due to uncertainties in whether current design standards of rectangular hollow section (RHS) joints validated for mild strength steels can be used to HSSs [15]. Because of non-uniform stiffness, eccentric forces and the large deformations in a truss girder, secondary bending stresses generally occurred in the tubular joints. In the design of truss structures, the joints are generally simplified as pinned jointed braces and continuous chords [7]. Bjork et al. [16] showed that the secondary bending moment is highly dependent on the joint geometry and material properties. Their results showed that the secondary bending stresses requires additional attention if high strength steels are used. The secondary bending moment is dependent on the plastic moment capacity of the brace member or the joints. The trilinear stress-strain relationship without softening or damage in their

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\textsuperscript{1} Present.

\textsuperscript{2} Previous.

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finite element simulation may lead to an unreal increase of secondary bending moment especially when the local material is in the stage of the post necking or fracture. The European design code [15] neglects the secondary bending stresses, and is validate for the RHS joints made of the steel with the nominal yield strength up to 460 MPa. A new draft version of European standard part 1–8 chapter 9 [17] proposes design rules for RHS joints with a yield strength up to 700 MPa. The design rules, which were originally developed by CIDECT [18], are based on experimental, numerical and analytical analysis and validated for a range of parameters for steel grades up to S460. The validity range gives various limitations on geometrical parameters of joints to ensure that the members and the joints have sufficient resistance validated by the design resistance formula. An open question on what would be justified level of material factors necessary to accept.

The behavior of hollow section joint may be different with increasing steel nominal yield strength and must be therefore checked. In this paper an attempt is made to investigate the effect of the secondary bending stresses of RHS joints with four steel grades, two gap size, three braces width to chord width ratios ($\beta$) and two types of welds. A parametric study is performed on the gap K-joint made of square hollow sections using finite element analysis.

Table 1
Joint geometry for the parametric study.

<table>
<thead>
<tr>
<th>Joint layout</th>
<th>$b_0$ (mm)</th>
<th>$t_{o}$ (mm)</th>
<th>$b_i$ (mm)</th>
<th>$t_i$ (mm)</th>
<th>$g$ (mm)</th>
<th>$\theta_i$ (°)</th>
<th>$e$ (mm)</th>
<th>$\beta$ (%)</th>
<th>Weld Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>120</td>
<td>5</td>
<td>80</td>
<td>5</td>
<td>40</td>
<td>30</td>
<td>-2.3</td>
<td>0.67</td>
<td>Fillet</td>
</tr>
<tr>
<td>K2</td>
<td>120</td>
<td>5</td>
<td>80</td>
<td>5</td>
<td>25</td>
<td>30</td>
<td>-6.6</td>
<td>0.67</td>
<td>Fillet</td>
</tr>
<tr>
<td>K3</td>
<td>140</td>
<td>6.3</td>
<td>70</td>
<td>5</td>
<td>40</td>
<td>30</td>
<td>-18</td>
<td>0.50</td>
<td>Fillet</td>
</tr>
<tr>
<td>K4</td>
<td>140</td>
<td>6.3</td>
<td>80</td>
<td>5</td>
<td>40</td>
<td>30</td>
<td>-12.3</td>
<td>0.57</td>
<td>Fillet</td>
</tr>
<tr>
<td>K5</td>
<td>140</td>
<td>6.3</td>
<td>90</td>
<td>5</td>
<td>40</td>
<td>30</td>
<td>-5.5</td>
<td>0.67</td>
<td>Fillet</td>
</tr>
<tr>
<td>K6</td>
<td>140</td>
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<td>70</td>
<td>5</td>
<td>40</td>
<td>30</td>
<td>-18</td>
<td>0.50</td>
<td>Butt</td>
</tr>
<tr>
<td>K7</td>
<td>140</td>
<td>6.3</td>
<td>80</td>
<td>5</td>
<td>40</td>
<td>30</td>
<td>-12.3</td>
<td>0.57</td>
<td>Butt</td>
</tr>
<tr>
<td>K8</td>
<td>140</td>
<td>6.3</td>
<td>90</td>
<td>5</td>
<td>40</td>
<td>30</td>
<td>-6.5</td>
<td>0.53</td>
<td>Butt</td>
</tr>
</tbody>
</table>

Table 2
The weld width, $t_{wx}$, used in FEA.

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Weld size</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_y \leq 500$ MPa</td>
<td>$t_w \geq 1.4t_i$</td>
</tr>
<tr>
<td>$500$ MPa $&lt; F_y &lt; 700$ MPa</td>
<td>$t_w \geq 1.69t_i$</td>
</tr>
<tr>
<td>$700$ MPa $&lt; F_y \leq 960$ MPa</td>
<td>$t_w \geq 1.98t_i$</td>
</tr>
</tbody>
</table>

finite element simulation may lead to an unreal increase of secondary bending moment especially when the local material is in the stage of the post necking or fracture. The European design code [15] neglects the secondary bending stresses, and is validate for the RHS joints made of the steel with the nominal yield strength up to 460 MPa. A new draft version of European standard part 1–8 chapter 9 [17] proposes design rules for RHS joints with a yield strength up to 700 MPa. The design rules, which were originally developed by CIDECT [18], are based on experimental, numerical and analytical analysis and validated for a range of parameters for steel grades up to S460. The validity range gives various limitations on geometrical parameters of joints to ensure that the members and the joints have sufficient resistance validated by the design resistance formula. An open question on what would be justified level of material factors necessary to accept.

The behavior of hollow section joint may be different with increasing steel nominal yield strength and must be therefore checked. In this paper an attempt is made to investigate the effect of the secondary bending stresses of RHS joints with four steel grades, two gap size, three braces width to chord width ratios ($\beta$) and two types of welds. A parametric study is performed on the gap K-joint made of square hollow sections using finite element analysis.
2. Finite element model

2.1. Geometry

Fig. 1 presented the symbols of the gap K-joint and Table 1 listed the values of each symbol. The angles between the brace and chord are same, $\theta = 30^\circ$. $\beta$ denoted the brace width to chord width ratio. Two gap size of $G_0 = 25$ mm and $G_1 = 40$ mm, three braces to chord width ratios of $\beta_1 = 0.50$, $\beta_2 = 0.57$ and $\beta_3 = 0.67$, fillet and butt welds are varied to investigate their effects on the secondary bending stresses and the failure modes. The weld width $t_w$ of fillet welds is related to the brace thickness and the yield strength of the material, as listed in Table 2.

2.2. Mesh and boundary conditions

C3D8 element of ABAQUS is used to model the K-joints and welds. The mesh and boundary conditions are shown in Fig. 2. As shown in Fig. 2b, one end of the chord is pinned, and the other end is left free. One brace member is pinned, and the other brace member is roller pinned to allow the translation in the axial direction. MPC constrain is used to transfer the load from the reference point to the
2.3. Material parameters

Material data obtained from a set of coupon specimens in RUOSTE project are used in the FEA [6]. The stress-strain curves for the steel grade varying from S355 to S960 are shown in Fig. 3 [19]. It should be noted that ratio of yield strength to tensile strength is 0.75 for S355, 0.80 for S460, 0.84 for S700, and 0.82 for S960.

2.4. Secondary bending moment

As shown in Fig. 4, the secondary bending moment is defined as the stress integration at the cross section 95 mm away from top chord surface at the compression brace. The secondary bending stress $\sigma_m$ is calculated based on FE secondary bending moment and moment inertia. The average stress or nominal stress $\sigma_n$ is determined using the obtained FE axial force and the cross-sectional area.

![Element set and node set](image1)

![Moment vector and force vector](image2)

Fig. 4. (a) Element set and node set and (b) moment and force vector K-joint.

![Load-displacement of K1 joints](image3)

Fig. 5. Load-displacement of K1 joints with different steel grades.

<table>
<thead>
<tr>
<th>Model</th>
<th>$N_{FEA}$ (kN)</th>
<th>$N_b$ (kN)</th>
<th>$N_b/N_{FEA}$ (-)</th>
<th>$N_{R,Cf}/N_{FEA}$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1-S355</td>
<td>421.49</td>
<td>420.69</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>K1-S460</td>
<td>503.99</td>
<td>522.17</td>
<td>1.04</td>
<td>0.93</td>
</tr>
<tr>
<td>K1-S700</td>
<td>773.35</td>
<td>792.41</td>
<td>1.02</td>
<td>0.82</td>
</tr>
<tr>
<td>K1-S960</td>
<td>1018.81</td>
<td>1162.36</td>
<td>1.14</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Table 3
Comparisons between FE results and design resistance with different steel grades.
3. Parametric analysis

3.1. Effects of steel grades

Fig. 5 shows the load-displacement relationship of K1 joints with different steel grades. Table 3 listed the comparisons between FE simulation results and design resistance [17] with different steel grades. The joints presented chord face failure (CFF). The design resistance is shown in Table 3.
resistance without considering reduction of material factor \( C_f \) and the partial safety factor denoted as \( N_{R,CF} \), and the design resistance only considering the material factor \( C_f \) \([17]\) denoted as \( N_{R,CF} \). The load corresponding to the 3\%\( b_0 \) (\( b_0 \) is the width of the chord) deformation limit is considered as the ultimate load of the joints. The ultimate load of RHS joints made of S460, S700, and S960 is 20\%, 83\% and 142\% larger than it of RHS joints made of S355. The ultimate load from FE is 14\%, 2\% and 4\% larger than the recommended design load of Eurocode \([17]\). Based on the FE results, the reduction factor is determined to be 1.0, 0.9, 0.8 and 0.8 for the RHS joints made of S355, S460, S690 and S960.

The stress distribution at 3\%\( b_0 \) deformation is shown in Fig. 6. The governing failure mode for all FE models is the chord face failure. In the zone of welds, the stresses are higher than the nominal yield strength of base materials. The ratio of maximum mises stress to nominal yield strength is 1.55, 1.43, 1.27 and 1.27 for the steel grades S355, S460, S690 and S960 respectively. That is the ratio of maximum mises stress to nominal yield strength is lower for the joints made of high steel grades.

In terms of K1 joints with different steel grades, the relationship between the ratio \( \sigma_m/\sigma_y \) and the ratio \( \sigma_n/\sigma_y \) is shown in Fig. 7a, and the relationship between the ratio \( \sigma_m/\sigma_n \) and the ratio \( \sigma_n/\sigma_y \) is presented in Fig. 7b. The secondary stress firstly increased and later decreased with the increasing applied load. The ratio \( \sigma_m/\sigma_n \) is larger with the nominal yield strength increasing. The ratio \( \sigma_m/\sigma_n \) decreased with the increasing applied load.

As shown in Fig. 8, two cross-sections are selected to show the stress distribution along the brace. Figs. 9 and 10 the axial stress distribution at the design resistance in position 2–8 and 10–16 in the middle line of both the cross sections. The compressive axial stresses in the joint are larger than the nominal yield strength. The combination of secondary bending stress and the average stress at 3\%\( b_0 \) deformation is also plotted in the figures. The axial stress ratio between local stress and the average stress is largest for K-joints.

Fig. 7. Secondary bending stress and the level of secondary bending stress for K1 joints with different steel grades.

Fig. 8. Positions of cross-sections for K1 joints.
made of S355 materials and lowest for K-joints made of S960 materials.

3.2. Effects of the gap size

Fig. 11 presented the load displacement curve for the joints with different gap sizes. Table 4 shows the comparisons between FE simulation results and design resistance [17] with different steel grades. The gap size has larger effects on the ultimate load of K-joints made of mild steel. The joint made of S355 with lower gap size G0 has 6% larger ultimate load resistance compared with the joint with gap size G1. Similarly, above ratio is 6%, 9% and 12% respectively for the joint made of S460, S700 and S960 respectively. The ultimate load of K joints with larger gap size from FE is 2%-14% larger than the ultimate load $N_R$ based on Eurocode [17]. The ultimate load of K joints with smaller gap size is smaller or equal to the ultimate load $N_R$ based on Eurocode [17].

Fig. 12. Stress distribution of K1 joint in position 2–8 (a)cross-section 1 and (b) cross-section 2.

The secondary bending stresses $\sigma_m$ are higher for the K joints with smaller gap size with the same steel grade, as shown in Fig. 12. The $\sigma_m$ for the K joints with smaller gap size is 7–15% larger. Maximum $\sigma_m/\sigma_n$ ratio is around 53–56% for K-joint with larger gap size (G1) and 50–54% for K-joint with lower gap size (G0). The ratio $\sigma_m/\sigma_n$ for the joint with gap size G1 is 5% larger compared to the joint with gap size G0. In general, the ratio $\sigma_m/\sigma_n$ reached the top when the average stresses is up to $0.4f_y - 0.7f_y$.

3.3. Effects of the brace width to chord width ratio

To study the effect of the brace width to chord width ratio $\beta$ on the high-strength hollow section joints, K-joints with three different $\beta$ value are used. $\beta_1$ denoted K3 joint, $\beta_2$ denoted K4 joint, and $\beta_3$ denoted K5 joint in Table 1. As shown in Fig. 13 and Table 5, the ultimate load of K-joint with ratio $\beta_2$ and $\beta_3$ is 15–18% and 34–40% larger than it of K-joint with $\beta_1$. Generally, the ultimate load is larger with the larger $\beta$ value for the K-joint made of the same steel grade. However, the effect of the ultimate load of the $\beta$-value on high-strength joints are lower compared to it of the joints made of mild-strength steels.

As shown in Figs. 14 and 15, the $\beta$ value effect on secondary bending stresses $\sigma_m$ of K-joints made of high-strength steel is lower than it of K-joints made of mild strength steel. The $\sigma_m$ is around $0.09f_y - 0.19f_y$ for K-joints made of high-strength steel. In general, K joints made of high-strength steel and with larger $\beta$ value will lead to a larger $\sigma_m$ when the force reached to the ultimate load. The ratio $\sigma_m/\sigma_n$ of K joints with $\beta_2$ is 10%-13% larger than it with $\beta_1$, and the ratio $\sigma_m/\sigma_n$ of K joints with $\beta_3$ is 20–23% larger than it with $\beta_1$. For K-joints made of high-strength steel with same steel grade, larger $\beta$-value will lead to larger $\sigma_m/\sigma_n$ ratio.
Fig. 10. Stress distribution of K1 joint in cross-section 1 and 2 in the positions 10–16.

Fig. 11. Load displacement relation for two gap sizes, (G1 denoted K1 joint, G0 denoted K2 joint).
3.4. Effects of weld types

The load-displacement curves with different weld types are plotted in Figs. 16–18. In terms of joints with the ratio $\beta_1$ (K3 and K6 joints in Table 1 correspond to fillet and butt welds respectively), the K joint with fillet-welds result in 37%, 28%, 20% and 18% larger ultimate load when compared with K joint with butt-welds for S960, S700, S460 and S355 steel grades respectively. In terms of joints with the ratio $\beta_2$ (K4 and K7 joints in Table 1 correspond to fillet and butt welds respectively), the K joint with fillet-welds result in 33%, 26%, 17% and 17% larger ultimate load when compared with K joint with butt-welds for S960, S700, S460 and S355 steel grades respectively. In terms of joints with the ratio $\beta_2$ (K4 and K7 joints in Table 1 correspond to fillet and butt welds respectively), the K joint with fillet-welds result in 30%, 26%, 18% and 16% larger ultimate load when compared with K joint with butt-welds for S960, S700, S460 and S355 steel grades respectively.

As shown in Figs. 19–21, the secondary bending stresses of K-joint made of fillet-welds are larger than it of K-joint made of butt-welds in terms of same steel grade. In detail, 37%, 38%, 46% and 60% larger maximum secondary bending stress is observed for the K-joint made of S355, S460, S700 and S960 respectively. The maximum $\sigma_m/\sigma_n$ ratio in the fillet-welded joints is 5–8% larger when compared to the butt-welded joints.

4. Yield line model

In this section, an attempt is done to predict the joint resistance with the help of yield line mechanism analysis. This is done by equating the internal work and the external work. Deformation pattern of joint at ultimate load resistance are used to access the yield lines. The governing failure mode for the square hollow section joints is the chord face plastification, therefore the axial stress distribution in the chord are evaluated. It is observed that the stress at the chord face is non-uniformly distributed and along the brace perimeter the largest. Along the yield lines in the chord face, stresses are equal to the yield strength as shown in Fig. 22. As shown in Fig. 23, yield lines are assumed to be straight and generally appear at the brace toe and heel. The length of the yield lines is measured using the tool “path”. The external work is equal to the joint resistance multiplied by a small deflection of the chord face. The displaced, rotated yield lines and the plastic moment are used to determine the internal work. The joint resistance is determined by dividing the

<table>
<thead>
<tr>
<th>Model</th>
<th>$N_{\text{FEA}}$ (kN)</th>
<th>$N_R$ (kN)</th>
<th>$N_R/N_{\text{FEA}}$ (%)</th>
<th>$N_{R,Cf}/N_{\text{FEA}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G0-S355</td>
<td>445.11</td>
<td>414.48</td>
<td>0.93</td>
<td>0.93</td>
</tr>
<tr>
<td>G0-S460</td>
<td>534.74</td>
<td>520.92</td>
<td>0.97</td>
<td>0.88</td>
</tr>
<tr>
<td>G0-S700</td>
<td>845.17</td>
<td>790.14</td>
<td>0.93</td>
<td>0.75</td>
</tr>
<tr>
<td>G0-S960</td>
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<td>1144.66</td>
<td>1.00</td>
<td>0.80</td>
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<tr>
<td>G1-S355</td>
<td>421.49</td>
<td>420.69</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>G1-S460</td>
<td>503.99</td>
<td>522.17</td>
<td>1.04</td>
<td>0.93</td>
</tr>
<tr>
<td>G1-S700</td>
<td>773.35</td>
<td>792.41</td>
<td>1.02</td>
<td>0.82</td>
</tr>
<tr>
<td>G1-S960</td>
<td>1018.81</td>
<td>1162.36</td>
<td>1.14</td>
<td>0.91</td>
</tr>
</tbody>
</table>
Fig. 13. Load displacement curve with different $\beta$ for (a) S960, (b) S700, (c) S460 and (d) S355.

Table 5
Comparisons between FE results and design resistance with different $\beta$ parameter.

<table>
<thead>
<tr>
<th>Model</th>
<th>$N_{FEA}$ (kN)</th>
<th>$N_R$ (kN)</th>
<th>$N_R/N_{FEA}$ (-)</th>
<th>$N_{RF}/N_{FEA}$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K3-S355</td>
<td>413.03</td>
<td>402.25</td>
<td>0.97</td>
<td>0.97</td>
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<td>K3-S460</td>
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<td>514.92</td>
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<td>0.93</td>
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<tr>
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<td>759.20</td>
<td>0.96</td>
<td>0.77</td>
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<tr>
<td>K3-S960</td>
<td>1061.02</td>
<td>1067.22</td>
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<td>587.24</td>
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<tr>
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<td>0.76</td>
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<td>0.80</td>
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<td>0.73</td>
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<tr>
<td>K5-S960</td>
<td>1427.38</td>
<td>1407.28</td>
<td>0.99</td>
<td>0.79</td>
</tr>
</tbody>
</table>
Fig. 14. Secondary bending stress with different \( \beta \) parameter for (a) S355, (b) S460, (c) S700 and (d) S960.
Fig. 15. Level of secondary bending stress with different $\beta$ parameter for (a) S355, (b) S460, (c) S700 and (d) S960.
internal work by the displacement of the chord face. As listed in Table 6, the joint resistance obtained by the yield line mechanism is 2%-16% lower compared to the ultimate load resistance obtained by the FEA.

5. Comparisons between FE results and design proposals

Fig. 24 shows material reduction factor $C_f$ distribution for various steel grades. EN1993-1-8-DRAFT V4.2 recommended that $C_f = 1.0$ when $F_y \leq 355$ MPa, and $C_f = 0.9$ when $355 < F_y \leq 460$ MPa, and $C_f = 0.8$ when $460 < F_y \leq 700$ MPa. Based on the results presented in the paper, $C_f$ is proposed as $1.0$ when $F_y \leq 355$ MPa, $0.9$ when $355 < F_y \leq 700$ MPa, and $0.8$ when $700 < F_y \leq 960$ MPa. Note the assumption that material properties of welds and HAZ are same as the base material may affect the value of $C_f$. The values of reduction factor $C_f$ need to be further improved.

6. Conclusion

A parametric study on the gap K joints is performed using “traditional” assumptions such as the same material properties for weld and base material and J2 plasticity model. Investigation of the material characteristics, gap size, the brace to chord width ratio and
The secondary bending stress is larger for joints made of higher steel grades. The secondary bending stresses increases with increasing applied load but decreases later due to material softening. Note that the material models still need to be improved to better consider post necking behavior and multiaxial damage of the joints using HSS. These improvements may influence the ultimate resistance and failure mode. The material model used in this model underestimates the true stress magnitude after necking, and also did not consider the fracture effects. Joints with lower gap size, exhibit larger secondary bending stresses and lower ratio between secondary bending stress to average axial stress than joint with larger gap size.

For each steel grade, larger $\beta$-values result in larger secondary bending stresses. Influence of the larger $\beta$-values for higher strength hollow section joints are lower when compared to mild-strength hollow section joints. For each steel grade, the secondary bending stresses in the fillet-welded joints are larger than that of the butt-welded joints.

Based on the results presented in the paper, $C_f$ is proposed 1.0 when $F_y \leq 355$ MPa, 0.9 when 355 < $F_y$ ≤ 700 MPa, and 0.8 when 700 < $F_y$ ≤ 960 MPa. Note that the material properties assumptions may affect the value of $C_f$. The values of reduction factor $C_f$ affect
Fig. 20. Different weld type with $\beta_2$ (a) Secondary bending stress and (b) level of secondary bending stress.

Fig. 21. Different weld type with $\beta_3$ (a) Secondary bending stress and (b) level of secondary bending stress.

Fig. 22. Plastic moment at ultimate load resistance for K3 joints made of S355 materials.
Fig. 23. Typical yield line pattern of K-joints made of S355 materials.
will be further investigated by improved material models including distinction between HAZ, the filler material and base material.

Declarations of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References


