Effect of Welding Residual Stresses on Behavior of Tubular T Joints

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Abstract:
Welded tubular joints are widely used in structural engineering due to their excellent resistance and stiffness, as well as simple connection. However, the welding process induces residual stresses in the welding area that can affect the structural behavior of joints. Currently very few papers investigate welding residual stresses in relation to tubular joints. This paper develops a finite element model of rectangular hollow section T joints considering welding residual stresses. Attention is paid particularly to welding sequences. The developed model is used to evaluate the effect of welding residual stresses on the resistance and initial stiffness of tubular joints. The results show that welding residual stresses increase the plastic resistance of rectangular hollow section joints under in-plane bending and axial brace loading.

Keywords: Welding simulation; residual stress; hollow section joint; resistance; initial stiffness.

1. INTRODUCTION
Welded hollow section joints are widely used in the building industry due to their excellent structural behavior. Although welding enables fast and simple connection of sections, it represents a complex thermomechanical process, which takes place at very high temperatures. When the welded joint is cooled to room temperature, the occurring shrinkage of the material leads to high residual stresses in the welded zone. To ensure that these residual stresses have no negative effect on the structural behavior of tubular joints, these stresses should be taken into account in the analysis.

\[ M(N) \]
\[ \text{elastic phase} \]
\[ \text{start of yielding} \]
\[ \text{hardening phase} \]

\[ S_{ji} (C_{ji}) \]
\[ \varphi_{\text{in}} (\theta_{\text{in}}) \]
\[ \varphi_{\text{in}} (\theta_{\text{in}}) \]

Figure 1. RHS T joint: a) notations; b) action-deformation curve when \( \beta \leq 0.85 \)

Many papers evaluate experimentally residual stresses in welded connections. In (Chen et al., 2017) it is shown that residual stresses can lead to the reduction of tensile strength for butt-welded plates by 10%. Some authors came to the conclusion that the reduction of tensile strength of high strength steel joints can reach 3-8% (Hochhauser et al., 2012) and even 15% (Khurshid et al., 2015). Similar results are obtained in (Günther et al., 2012; Knoedel et al., 2017; Rodrigues et al., 2004; Teng et al., 2001). A comprehensive analysis on simulated welding residual stresses in component-type welded I-girders is provided in (Pasternak et al., 2015). However, very few publications evaluate welding residual stresses in relation to hollow section joints. Brar & Singh (2014)
have proved that it is possible to increase the tensile strength of tubular X joints by 24% by changing welding input parameters. Moradi (2017) has shown that the load-bearing capacity of tubular T joints can vary by 10% depending on the welding sequence. At the same time, these papers do not provide the direct comparison of the structural behavior of joints taking into account and neglecting welding residual stresses.

This paper numerically investigates the behavior of rectangular hollow section (RHS) T joints taking into account welding residual stresses. A T joint represents the simplest joint configuration, when a brace is connected to a chord at an angle of 90°, as shown in Figure 1a. Section 2 provides a brief overview on the structural behavior of RHS T joints. Section 3 develops and verifies the finite element model of the joint taking into account welding residual stresses. Various welding sequences are analyzed in Section 4. Finally, the developed model is used for parametric studies to investigate the effect of welding residual stresses on the resistance and initial stiffness of joints. The considered joints are subjected separately to in-plane bending and axial brace loading.

2. STRUCTURAL BEHAVIOR OF RHS T JOINTS

The structural behavior of tubular joints demonstrates certain similarities in the case of in-plane bending and axial brace loading and is best described by the corresponding action-deformation curves. To construct the action-deformation curve of the joint, the applied forces and moments as well as the corresponding displacements and rotations are measured during FEA. The initial stiffness and resistance of the joint are found graphically, using a manual curve-fitting approach. Initial stiffness $S_{j,ini}$ ($C_{j,ini}$) is determined as the tangent line in the elastic phase of the curve. For the joints with $\beta \leq 0.85$ (see Figure 1a), bending of the chord top face governs the deformation of the whole joint, and the action-deformation curve has a clearly observed hardening phase, as shown in Figure 1b. In this case, plastic resistance $M_{pl}$ ($N_{pl}$) is determined as the intersection of two tangent lines corresponding to initial stiffness $S_{j,ini}$ ($C_{j,ini}$) and hardening stiffness $S_{j,h}$ ($C_{j,h}$). Ultimate resistance $M_u$ ($N_u$) in this case corresponds to very large deformations and, therefore, is of less interest for such joints. The deformation capacity of the joint is calculated in accordance with the 3% deformation limit of Lu (1997). Equation (1) presents the deformation limits $\phi_{lim}$ ($\delta_{lim}$) for a joint loaded by an in-plane bending moment and an axial force correspondingly.

$$\phi_{lim} = 0.03b_0 / (h / 2) = 0.06b_1 / h_1; \quad \delta_{lim} = 0.03b_0;$$

(1)

The behavior of the joints with 0.85 < $\beta$ ≤ 1.0 is generally governed by the buckling of their chord side walls; the resistance of such joints is determined differently (Zhao, 2000). In such case, the effect of residual stress might be also different. In addition, when 0.85 < $\beta$ ≤ 1.0, the finite element modeling of the joint becomes complicated, since the fillet weld reaches the rounded corner of the chord section. When $\beta = 1.0$ (the chord and the brace are of equal width), the fillet weld is replaced by a partial/full penetration butt weld. As the focus of this study is on T joints with fillet welds, only the joints with $\beta \leq 0.85$ are considered in this paper.

3. FE MODEL FOR RHS T JOINTS WITH RESIDUAL WELDING STRESSES

In this study, the welding process is simulated in Abaqus Welding Interface (AWI); the subsequent structural analyses of the joints are performed in Abaqus (Abaqus/Standard, 2003). AWI represents a free Abaqus plug-in for the simulation of welding processes, employing a sequentially coupled approach for the thermal stress analysis associated with the welding simulation (Shubert & Pandheeradi, 2013). The RHS profiles were modelled as cold-formed sections with rounded corners according to EN 10219-2:2006. Residual stresses due to cold-forming were not considered. To exclude possible effects of the chord boundary conditions, its length was selected as $6b_0$, while the brace length was chosen as $4b_1$, as shown in Figure 2a. A small gap of 0.5 mm was introduced between the chord and the brace to connect them only through the fillet weld (Figure 2b).

Figure 2. FE model: a) meshing; b) gap between connected members; c) weld chunking
According to (Zhao et al., 2010), tubular joints are best simulated with quadratic solid finite elements (C3D20 or C3D20R in Abaqus). This study employed linear full-integration hexahedral elements (C3D8 in Abaqus) to reduce calculation time, which tends to be particularly large in welding simulations. Provided that both connected members had three elements in thickness direction, the conducted trial analyses showed that the difference using linear and quadratic elements is negligible. To capture large temperature and stress gradients due to welding, the mesh was refined near the connection area, as shown in Figure 2a. A conducted mesh convergence study demonstrated that the 3 mm mesh was too coarse to capture the local changes of stresses close to the weld area. The 1 mm mesh provided accurate results but required considerable calculation time. For the described reasons, the 2 mm mesh was found as the optimal solution by the criteria of accuracy and reasonable calculation time.

Only fillet welds are considered in this paper, with a throat angle of 45°. AWI considers welds consisting of multiple beads (layers). Each bead is assumed divided into chunks, which generally correspond to weld pools, as shown in Figure 2c. The welds with throat thickness of \( a \leq 5 \) mm are assumed to consist of a single bead, while the welds with \( a > 5 \) mm consist of three beads. This paper considers only the joints in which the material properties of welds match those for the connected members. The following properties were introduced in the material model: thermal conductivity, specific heat, density and latent heat for thermal analyses; as well as expansion coefficient, Young’s modulus and plastic stress-strain curve for mechanical analyses. The properties were considered as temperature-dependent and were extracted from the library of Simufact Welding (Simufact-Engineering, 2009).

Particular attention was paid to the calibration of weld heat input. The welding speed was selected in accordance with available welding procedure specifications, depending on the weld throat thickness. The target torch heat-up temperature was determined so that both welded parts in the welding area were heated up to the melting temperature at the required depth. This criterion was evaluated visually by the expansion of the 1500°C isotherm during the welding process (Figure 3). The trial analyses showed that the torch heat-up temperature of 1500°C did not provide the required depth of the molten zone. For the temperature of 2500°C the welded zone expanded severely through the thickness of the brace, partly reaching its inner surface, which is not the case in practice. From the above observations, the torch heat-up temperature of 2000°C was adopted for further analyses.

Figure 3. Temperature distribution [°C] for torch heat-up temperatures: a) 1500°C; b) 2000°C; c) 2500°C

The validation of the developed FE model was conducted with the results of Havula et al. (2015). Table 1 provides the details and the structural behavior of the two joints selected for the validation. The elastic properties and the plastic stress-strain response for S420 steel at room temperature were obtained from tensile coupon tests. The plastic stress-strain curves at elevated temperatures were extracted from the Simufact Welding library. The thermomechanical parameters were assumed equal to those for S355. The welding process was simulated in AWI, assuming double C-shaped welding sequence (see Sequence 1 in Section 4), as was used in the experiments. The welding simulation was followed by a nonlinear static analysis under in-plane bending.

<table>
<thead>
<tr>
<th>Joint</th>
<th>Chord</th>
<th>Brace</th>
<th>Material</th>
<th>( a ) [mm]</th>
<th>( S_{\text{lim}} ) [kN/m/( \text{rad} )]</th>
<th>( M_{\text{pl}} ) [kNm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1111</td>
<td>150x150x8</td>
<td>100x100x8</td>
<td>S420</td>
<td>6</td>
<td>1401</td>
<td>20.6</td>
</tr>
<tr>
<td>1121</td>
<td>150x150x8</td>
<td>100x100x8</td>
<td>S420</td>
<td>10</td>
<td>1778</td>
<td>31.0</td>
</tr>
</tbody>
</table>

Figure 4 presents the moment-rotation curves for the tested joints. As can be seen, the FE model provides good correlation in the elastic phase with accurate initial stiffness. Very close results are observed in the hardening phase for Joint 1111, almost repeating the experimental curve. Small difference in the hardening phase is noticed for Joint 1121, which can be caused by the difference in the material properties. The results show that the developed
FE model accurately predicts plastic moment resistance with the errors smaller than 5%. The model properly captures the local behavior of the joints and can be used for evaluation of the structural behavior of RHS T joints.

![Figure 4. Moment-rotation curves for joints used in validation](image)

### 4. INFLUENCE OF WELDING RESIDUAL STRESSES WITH VARIOUS WELDING SEQUENCES

This section investigates the effect of welding residual stresses on the structural behavior of RHS T joints with various welding sequences. The analyses were conducted on a single joint with a 100x100x6 chord and a 50x50x5 brace with $a = 5$ mm welds separately under in-plane bending and axial loading. Figure 5 presents three welding sequences considered in this study. Sequence 1 represents the sequence used by the steel manufacturer SSAB, when the weld bead consists of two C-shaped paths. Sequence 2 corresponds a single progressive path. Sequence 3 represents the most simplified variant, when the whole weld is inserted simultaneously to the model. This hypothetical case has no connection to reality, but was considered for comparison since it requires much less computational time. The sequence of welding in AWI is defined by introduction of passes, which determine the chunk (or a number of chunks) being activated at the particular time. Sequences 1 and 2 activated one chunk per pass; Sequence 3 activated all chunks in a single pass.

![Figure 5. Welding sequences](image)

All three sequences were simulated in AWI and the obtained residual stresses are presented in Figure 6. As can be seen, all cases have similar stress distribution patterns, with the stress-affected zones located in the chord top face and in the upper half of chord webs. Over a larger area the stresses reach the yield level, extreme values occur in the weld. As expected, Sequence 3 has a symmetrical stress distribution pattern.

![Figure 6. Von Mises residual stresses [MPa] for Sequences 1-3](image)
After welding simulations, each joint was loaded separately by an in-plane bending moment and an axial brace force using nonlinear static FEA. The results are presented in Figure 7 and collected in Table 2, where “No welding” corresponds to the model, which was analyzed ignoring welding residual stresses. As can be seen, all three sequences provide practically the same responses. Compared to “No welding”, Sequences 1-3 show considerably smaller deformations in the transitional phase, for both loading cases. In the hardening phase, the difference is smaller, the curves with and without welding proceed more or less parallel to each other. This indicates that the plastification of the chord top face develops similarly, but welding residual stresses postpone its initiation. To evaluate the effect of welding-induced deformations, those were extracted from “Sequence 1” and were applied to “No welding” as initial geometric imperfections, this model is named as “No welding+U”. This case shows almost identical behavior as “No welding”, meaning that welding-induced imperfections have no influence on the behavior of the joint, and the observed difference for Sequences 1-3 is caused by welding residual stresses. Ultimate resistance is practically the same for the models with and without welding. In addition, all models demonstrate the required deformation capacity, clearly exceeding the introduced deformation limit.

Table 2 shows that welding stresses lead to higher resistance (4-5% for in-plane bending and 13-16% for axial loading) and lower initial stiffness (7-14% for in-plane bending and 4-6% for axial loading). Sequence 3 provides the same results as more sophisticated Sequences 1 and 2. For this reason, Sequence 3 was employed for further investigations, providing reasonable results with comparatively small computational time.

5. PARAMETRIC STUDIES FOR JOINTS WITH VARIOUS GEOMETRY AND STEEL GRADES

5.1 Influence of steel grade

The first parametric study investigates the effect of welding residual stresses on joints with various the steel grades. The analysis was conducted on the joint used in Section 4, considering three steel grades: S355, S500 and S690. The material properties for S690 were extracted from the Simufact Welding library. The properties for S500 were obtained from S355: the plastic stress-strain curves were scaled by $k = 500/355 \approx 1.41$, the remaining properties were kept the same. The behavior of each joint under an in-plane bending moment and an axial brace force is illustrated in Figure 8 and summarized in Table 3, where index $w$ corresponds to the models with welding residual stresses. The results show that the improving effect, observed initially for S355, remains also for higher steel grades. Residual stresses lead to 4-14% higher plastic resistance against bending moment and 11-12% higher resistance against axial loading. At the same time, ultimate resistance is not affected by the welding stresses. Initial stiffness is slightly lower for S355 and S500 but insignificantly higher for S690.
Table 3. Structural behavior of joints with various steel grades

<table>
<thead>
<tr>
<th>Material</th>
<th>$S355$</th>
<th>$S355w$</th>
<th>$S355w/S355$</th>
<th>$S500$</th>
<th>$S500w$</th>
<th>$S500w/S500$</th>
<th>$S690$</th>
<th>$S690w$</th>
<th>$S690w/S690$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{pl}$ [kNm]</td>
<td>4.40</td>
<td>4.62</td>
<td><strong>1.05</strong></td>
<td>6.18</td>
<td>6.39</td>
<td><strong>1.04</strong></td>
<td>7.56</td>
<td>8.60</td>
<td><strong>1.14</strong></td>
</tr>
<tr>
<td>$M_u$ [kNm]</td>
<td>6.61</td>
<td>6.67</td>
<td><strong>1.01</strong></td>
<td>9.25</td>
<td>9.34</td>
<td><strong>1.01</strong></td>
<td>12.63</td>
<td>12.77</td>
<td><strong>1.01</strong></td>
</tr>
<tr>
<td>$S_{j,ini}$ [kNm/rad]</td>
<td>226</td>
<td>195</td>
<td><strong>0.86</strong></td>
<td>226</td>
<td>211</td>
<td><strong>0.93</strong></td>
<td>227</td>
<td>244</td>
<td><strong>1.08</strong></td>
</tr>
<tr>
<td>$N_{pl}$ [kN]</td>
<td>131.8</td>
<td>145.8</td>
<td><strong>1.11</strong></td>
<td>182.4</td>
<td>203.7</td>
<td><strong>1.12</strong></td>
<td>256.9</td>
<td>283.9</td>
<td><strong>1.11</strong></td>
</tr>
<tr>
<td>$N_u$ [kN]</td>
<td>287.3</td>
<td>287.4</td>
<td><strong>1.00</strong></td>
<td>400.2</td>
<td>400.1</td>
<td><strong>1.00</strong></td>
<td>543.7</td>
<td>545.3</td>
<td><strong>1.00</strong></td>
</tr>
<tr>
<td>$C_{j,ini}$ [kN/mm]</td>
<td>240</td>
<td>227</td>
<td><strong>0.94</strong></td>
<td>240</td>
<td>234</td>
<td><strong>0.98</strong></td>
<td>240</td>
<td>251</td>
<td><strong>1.04</strong></td>
</tr>
</tbody>
</table>

5.2 Influence of chord wall thickness

This part investigates the effect of welding residual stresses on the behavior of joints with various wall thickness of the chord. The wall thickness is characterized by the chord width-to-thickness ratio $\gamma = b_0/t_0$, which for simplicity is often considered as $2\gamma = b_0/t_0$. Chapter 7 of EN 1993-1-8:2005 limits this ratio in the range of $10 \leq 2\gamma \leq 35$. Three joints are considered in this study, with $2\gamma$ ratio of 16.6 (100x100x6 chord), 25 (100x100x4 chord) and 33.3 (100x100x3 chord). The behavior of each joint under an in-plane bending moment and an axial brace force is shown in Figure 9 and reported in Table 4, where index $w$ corresponds to the models with welding residual stresses. According to the results, the models with welds simulated with AWI show higher resistance than those without. The improving effect of welding residual stresses is more pronounced for the joints with thinner walls: for $2\gamma = 33.3$ moment resistance is increased by 19%, while axial resistance is increased by 17%. At the same time, initial stiffness is weakly affected by residual stresses for higher $2\gamma$. As before, no changes are observed for ultimate resistance.
Table 4. Structural behavior of joints with various wall thickness

<table>
<thead>
<tr>
<th>(\gamma)</th>
<th>16.6</th>
<th>16.6w</th>
<th>16.6w/16.6</th>
<th>25</th>
<th>25w</th>
<th>25w/25</th>
<th>33.3</th>
<th>33.3w</th>
<th>33w/33</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M_p) [kNm]</td>
<td>4.40</td>
<td>4.62</td>
<td>1.05</td>
<td>1.37</td>
<td>1.62</td>
<td>1.19</td>
<td>0.73</td>
<td>0.87</td>
<td>1.19</td>
</tr>
<tr>
<td>(M_u) [kNm]</td>
<td>6.61</td>
<td>6.67</td>
<td>1.01</td>
<td>5.33</td>
<td>5.38</td>
<td>1.01</td>
<td>3.94</td>
<td>3.96</td>
<td>1.00</td>
</tr>
<tr>
<td>(S_{j,ini}) [kNm/rad]</td>
<td>226</td>
<td>195</td>
<td>0.86</td>
<td>85</td>
<td>80</td>
<td>0.94</td>
<td>43</td>
<td>41</td>
<td>0.97</td>
</tr>
<tr>
<td>(N_p) [kN]</td>
<td>131.8</td>
<td>145.8</td>
<td>1.11</td>
<td>54.1</td>
<td>59.9</td>
<td>1.11</td>
<td>28.1</td>
<td>32.7</td>
<td>1.17</td>
</tr>
<tr>
<td>(N_u) [kN]</td>
<td>287.3</td>
<td>287.4</td>
<td>1.00</td>
<td>175.5</td>
<td>176.2</td>
<td>1.00</td>
<td>127.9</td>
<td>128.2</td>
<td>1.00</td>
</tr>
<tr>
<td>(C_{j,ini}) [kN/mm]</td>
<td>240</td>
<td>227</td>
<td>0.94</td>
<td>93</td>
<td>93</td>
<td>1.00</td>
<td>47</td>
<td>47</td>
<td>1.01</td>
</tr>
</tbody>
</table>

5.3 Influence of weld throat thickness

The last parametric study is conducted in relation to weld throat thickness. The analyses are based on the joint from Section 4 with three throat thicknesses: 3, 5 and 8 mm. Each joint was constructed with and without AWI and loaded separately by an in-plane moment and an axial brace force. The structural behavior of each joint is provided in Figure 10 and collected in Table 5, where index \(w\) corresponds to the models with welding residual stresses. As before, the presence of residual stresses positively affects the load-bearing capacity of the joints. For the moment-loaded joints, the improving effect declines from 19% for \(a = 3\) mm to 1% for \(a = 8\) mm. At the same time, for the axial-loaded joints, it has no correlation with the throat thickness and remains at the level of 8-11%. The stresses slightly reduce the initial stiffness of joints, almost not affecting their ultimate resistance.

Table 5. Structural behavior of joints with various weld throat thickness

<table>
<thead>
<tr>
<th>(a) [mm]</th>
<th>3</th>
<th>3w</th>
<th>3w/3</th>
<th>5</th>
<th>5w</th>
<th>5w/5</th>
<th>8</th>
<th>8w</th>
<th>8w/8</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M_p) [kNm]</td>
<td>2.76</td>
<td>3.27</td>
<td>1.19</td>
<td>4.40</td>
<td>4.62</td>
<td>1.05</td>
<td>4.70</td>
<td>4.77</td>
<td>1.01</td>
</tr>
<tr>
<td>(M_u) [kNm]</td>
<td>5.12</td>
<td>5.26</td>
<td>1.03</td>
<td>6.61</td>
<td>6.67</td>
<td>1.01</td>
<td>6.70</td>
<td>6.69</td>
<td>1.00</td>
</tr>
<tr>
<td>(S_{j,ini}) [kNm/rad]</td>
<td>180</td>
<td>171</td>
<td>0.95</td>
<td>226</td>
<td>195</td>
<td>0.86</td>
<td>326</td>
<td>284</td>
<td>0.87</td>
</tr>
<tr>
<td>(N_p) [kN]</td>
<td>107.6</td>
<td>116.5</td>
<td>1.08</td>
<td>131.8</td>
<td>145.8</td>
<td>1.11</td>
<td>179.5</td>
<td>197.5</td>
<td>1.10</td>
</tr>
<tr>
<td>(N_u) [kN]</td>
<td>285.9</td>
<td>286.0</td>
<td>1.00</td>
<td>287.3</td>
<td>287.4</td>
<td>1.00</td>
<td>289.2</td>
<td>289.2</td>
<td>1.00</td>
</tr>
<tr>
<td>(C_{j,ini}) [kN/mm]</td>
<td>186</td>
<td>176</td>
<td>0.95</td>
<td>240</td>
<td>227</td>
<td>0.94</td>
<td>355</td>
<td>336</td>
<td>0.95</td>
</tr>
</tbody>
</table>

6. CONCLUSIONS

This paper develops a FE model for RHS T joints taking into account welding residual stresses. The validation with the experimental results has shown that the model properly captures the local deformation of joints and effectively predicts their behavior. The conducted FE analyses demonstrate that AWI provides the same distribution pattern of welding residual stresses for all joints, with some deviations depending on steel grade, chord wall thickness and weld throat thickness.

All the joints studied in this paper demonstrate a positive effect of welding residual stresses on their plastic resistance. Figure 7 clearly shows that the improving effect is primarily connected with residual stresses and is not dependent on welding-induced deformations. The observed influence is found not to depend on the welding sequence used; therefore, an idealized sequence is recommended to reduce the calculation time of simulations.

The parametric studies have shown that welding residual stresses increase bending resistance in the range of 1-19%. The improving effect is more pronounced for higher steel grades, smaller chord wall thickness and smaller
weld throat thickness. Axial resistance is improved by 8-17%. For this case, the improving effect is more pronounced for smaller chord wall thickness but is weakly dependent on the other studied parameters. Residual stresses also affect the initial axial and rotational stiffness of joints, reducing it by 5-14%. Ultimate resistance is not influenced by residual stresses. These results mean that neglecting of welding residual stresses leads to the insignificant underestimation of plastic resistance, providing thus safe results.

This paper considers the joints with fillet welds from $a = 3$ mm to $a = 8$ mm, $\beta \leq 0.85$, $10 \leq 2\gamma \leq 35$ and steel grades from S355 to S690. The research can be further extended to explore additional cases and develop more generalized conclusions. Additional studies are also required to eliminate a possible scaling effect, considering different chord sizes. A further experimental validation of the obtained findings may be possible by comparing welded T joints with the joints that received a stress-relief heat treatment prior to loading. Such a comparison will allow to evaluate experimentally the influence of welding residual stress on the structural behavior of tubular joints. The presented results can serve as a starting point for studying the issue of welding residual stresses in relation to high strength steel tubular joints.

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