INFLUENCE OF FILLET WELDS ON STRUCTURAL BEHAVIOR OF RHS T JOINTS

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Welding is the most commonly used technology for connecting tubular members. Currently, most tubular joints are connected using two weld types: butt welds and fillet welds.Butt welds are comparatively compact; however, fillet welds enlarge the cross-section of the brace in the area of connection and may influence the behavior of joints. Current design standards ignore the influence of welds on the behavior of tubular joints. This paper investigates the effect of fillet welds on the behavior of moment-loaded rectangular hollow section Tjoints. A numerical study is conducted for joints with varying geometry and weld sizes. Joints with butt welds and fillet welds with varying throat thicknesses are considered. The results show that the existing standards underestimate the resistance and initial stiffness of joints with fillet welds. To avoid this underestimation, the paper proposes a simple solution, which enlarges the cross-section of the brace, increasing the structural properties the joint. A conducted validation against experimental results shows that the proposed approach leads to more accurate prediction of structural properties of T joints.

Keywords: tubular joints, fillet welds, butt welds, resistance, initial stiffness.

1 Introduction

Welding is applied as a general way for connecting tubular members. Currently, most tubular joints are welded using two weld types: butt welds and fillet welds. A tubular joint with idealized full-penetration butt welds is presented in Figure 1a. Butt welds are comparatively compact and can be considered as a part of the brace. Based on this, it can be assumed that butt welds do not influence the structural behaviour of tubular joints.In contrast, fillet welds introduce additional material in the connection (Figure 1b) that interacts with the parent material of the brace and the chord. This interaction may lead to higher resistance and stiffness compared to the joint with the same geometry and butt welds. Such improvement of structural properties can be particularly noticeable for joints with full-strength fillet welds, which have very large throat thickness.

The beneficial influence of fillet welds on the structural properties of rectangular hollow section (RHS) T joints can be clearly seen in the results of Havula et al.(2018). The paper compares the behaviour of joints with matching geometry and steel grades but varying welds. The paper shows that the joints with large fillet welds have in average 60% higher experimental

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resistance and initial stiffness than the joints with butt welds. It should be noted that in the tests, the largest fillet welds accounted only 0.85 from full-strength fillet welds.

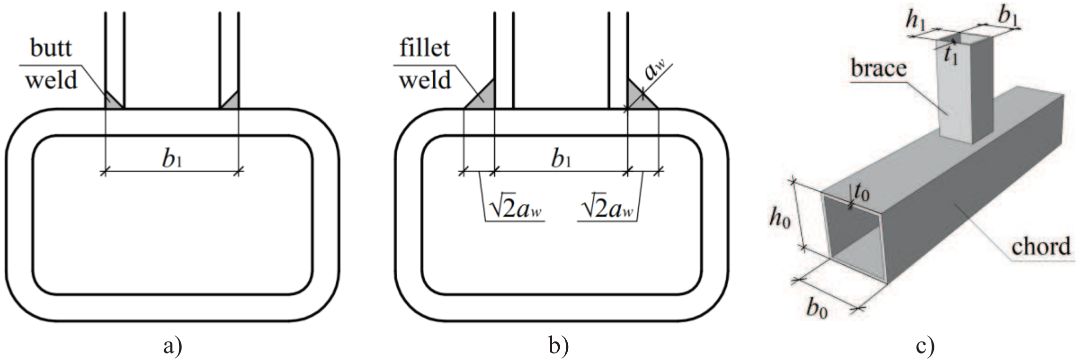


Figure 1. a) Idealized butt-welded joint; b) idealized fillet-welded joint; c) notations of RHS T joint.

The effect of fillet welds has been considered in some publications.One solution was proposed by Heinisuo et al. (2016)for the initial rotational stiffness of RHS Y joints. The authors assumed that a joint with fillet welds can be considered as a butt-welded joint with the equivalent width $b_{eq} > b_1$ so that both joints have the same initial stiffness. The equivalent width b_{eq} was presented in the way:

$$b_{eq} = b_1 + 2\sqrt{2}a_w k_{fw} \quad (1)$$

wherea_w is the throat thickness of fillet welds andk_{fw} is a correlation coefficient, determined as 0.6 for S355 grade, 0.7 for S700 grade, with a linear interpolation between. A validation of this approach was conducted by Garifullin(2019), who proved the solution to be more accurate rather than the conventional approach, which neglects the influence of the fillet welds.However, the proposed method is limited only for initial in-plane stiffness, while its applicability for resistance and other loading cases, such as axial loading and out-of-plane loading, has not been evaluated.

A similar equation for axially loaded RHS T joints was proposed by de Matos et al.(2015), as shown in Eq. (2).However, the authors provide no validation of the proposed equation and do not specify its applicability for other loading types.

$$b_{eq} = b_1 + 1.6a_w \quad (2)$$

Despite the presented solutions, there is still no consistent and common approach that can be applied for both resistance and initial stiffness of joints under all three loading cases, including axial loading, in-plane bending and out-of-plane bending. This paper numericallyinvestigates the influence of fillet welds on the behavior of RHS T joints under in-plane moment loading. The joints are considered made of the S355 steel grade with varying geometry, with butt and fillet welds. The obtained results are used to develop an approach to take into account the beneficial influence of fillet welds on the resistance and initial stiffness of joints. The proposed solution is validated with existing experimental results.

A typical RHS T joint consists of two RHS members, the chord and the brace, connected with a butt or fillet weld. The notations of an RHS T joints are presented in Figure 1c. Among them, b_0, h_0 and t_0 are the dimensions of the chord cross-section; b_1, h_1 and t_1 are the dimensions of the brace cross-section. In addition, two ratios are usually considered in the design: the brace-to-chord width ratio $\beta = b_1/b_0$ and the chord width-to-thickness ratio $2\gamma = b_0/t_0$.

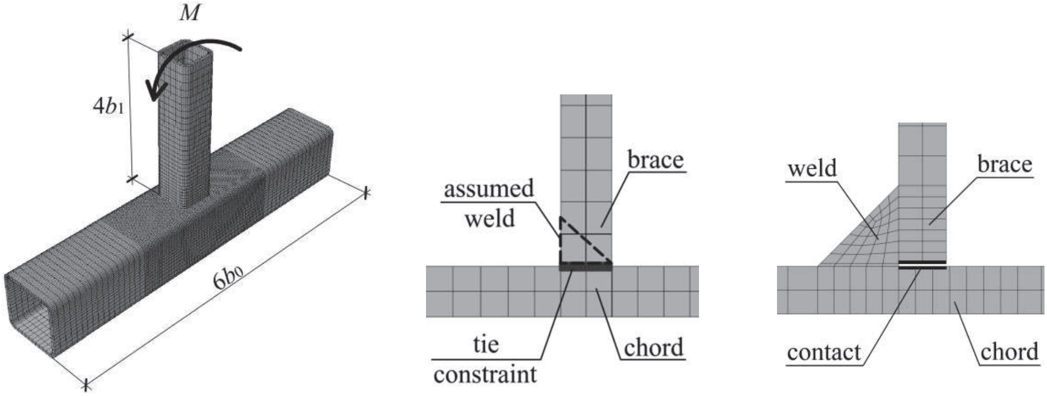
2 Numerical study

The numerical study considered RHS T joints with varying parameters, as shown in Table 1. All the joints were analyzed under in-plane bending and made of S355 steel grade.The joints had a chord of a single size 150×150 mm with three wall thicknesses of 5, 8 and 10 mm, corresponding to 2γ values of 30, 18.8 and 15, respectively. Three brace sizes wereconsidered: 40×40, 80×80 and 100×100 mm, corresponding toβvalues of 0.27, 0.53 and 0.67, respectively. The joints wereanalyzed with butt welds and fillet welds with three throat thicknesses a_w: $0.5a_{fs}$, $0.75a_{fs}$and $1.0a_{fs}$.Here, a_{fs}denotes the throat thickness of full-strength fillet welds calculated as $1.2t_1$ for the S355MH steel grade according to Table 3.9 of (Ongelin & Valkonen 2016).

Table 1. Parameters of the calculated joints.

Joint	Chord cross-section (mm)	2γ	Brace cross-section (mm)	β
150×5-40	150×150×5	30.0	40×40×4	0.27
150×8-40	150×150×8	18.8	40×40×4	0.27
150×5-80	150×150×5	30.0	80×80×5	0.53
150×8-80	150×150×8	18.8	80×80×8	0.53
150×10-80	150×150×10	15.0	80×80×8	0.53
150×5-100	150×150×5	30.0	100×100×5	0.67
150×8-100	150×150×8	18.8	100×100×8	0.67
150×10-100	150×150×10	15.0	100×100×10	0.67

Afinite element (FE) model of the joint was developed in Abaqus/Standardaccording to (Garifullin et al. 2018). The lengths of the chord and the brace were selected as $6b_0$and $4b_1$, respectively, as shown in Figure 2a. The model was meshed using quadratic solid finite elements with reduced integration (C3D20R), with two elements in the thickness direction. To capture large stress gradients, the mesh was refined in the connection area. For the butt-welded joints, the chord and brace were modelled separately and connected by the tie constraint, as shown in Figure 2b. For the fillet-welded joints, the chord, the brace and the weld were modelled as a single part with common mesh,as shown in Figure 2c. To avoid merging the nodes of the brace and the chord, a 0.5 mm gap was introduced between them. To prevent the nodes of the brace penetrating into the chord, a contact interaction was defined between the chord and the brace.



a) b) c)

Figure 2. FE model: a) meshing; b) butt welds modelling, c) fillet welds modelling.

Material properties were introduced employing an elastic-plastic model with linear strain hardening (E/100),with theYoung's modulus of 210 GPa, the Poisson's ratio of 0.3 and the yield stress of 355 MPa. Loading was performed in a force-controlled nonlinear static analysis by a concentrated in-plane moment M applied to the end of the brace. To determine the local deformation of the joint, the analysis measured the applied moment$M$and the corresponding rotation φ of the joint according to (Garifullin et al. 2018).

The load-displacement curves were used to determine the resistance and initial stiffness of joints. Initial stiffness was calculated as the tangent line in the beginning of the load-displacement curves. Resistance was calculated according to Zhao (2000), who determines the resistance based onthe deformation limit of (Lu et al. 1994) and the serviceability limit. The deformation limit φ_{lim} and serviceability limitφ_{serv} restrict the deformation of tubular joints to 3% and 1% of b_0, respectively, and for moment-loaded joints are calculated as $0.06/\eta$ and $0.02/\eta$, respectively. The resistancedepends on the ratio of the moment at the deformation limitM_{lim} to the moment at the serviceability limitM_{serv},as shown in Figure 3.For$M_{lim}/ M_{serv} \leq 1.5$, the ultimate resistance is determined as M_{lim};for$M_{lim} / M_{serv} > 1.5$, the ultimate resistance is taken as $1.5M_{serv}$.

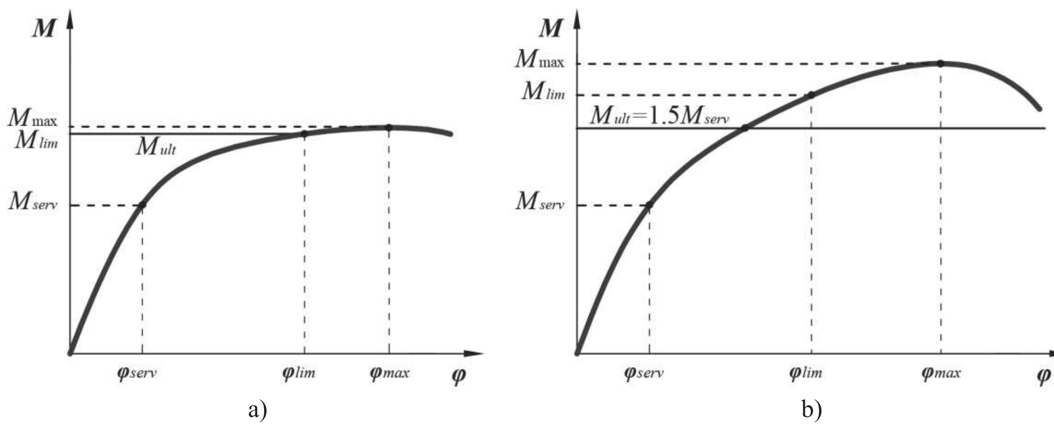


Figure 3. Resistance of RHS T joint: a) $M_{lim}/M_{serv} \leq 1.5$; b) $M_{lim}/M_{serv} > 1.5$.

3 Theoretical calculations

The resistance of RHS T joints is calculated theoretically according to EN 1993-1-8:2005(CEN 2005), as presented in Eq. (3).A similar equation is provided by CIDECT Design Guide No. 3 (Packer et al. 2009). Following EN 1993-1-8:2005, the resistance of high strength steel joints is calculated considering the reduction factor thattakes the following values: 0.9 for grades above S355and 0.8 for grades above S500 (CEN 2007). The initial rotational stiffness of RHS T joints is calculated according to Section 6 of EN 1993-1-8:2005(CEN 2005), as presented in Eq. (4), wherek_i denotes the stiffness for i-th joint component. The stiffnesses of all joint components arecalculated according to (Garifullin et al. 2017).

$$M_{ip,1,Rd} = f_{y0} t_0^{\,2} h_1 \left(\frac{1}{2\eta} + \frac{2}{\sqrt{1-\beta}} + \frac{\eta}{1-\beta} \right) \tag{3}$$

$$S_{j,ini} = Eh_1^2 \Big/ \sum_i \frac{1}{k_i} \tag{4}$$

4 Results

The obtained numerical results show that fillet welds have a considerable influence on the structural behavior of RHS T joints. Figure 4 presents the graphs for the joints with varying welds, i.e. butt welds and fillet welds with varying throat thickness. In the figure, $M_{ip,1,Rd}$denotes moment resistance calculated theoretically according to Eq. (3).The graphs show that fillet welds increase both initial stiffness and resistance of the joints, and the observed effect becomes more pronounced with the increase of the throat thickness a_w. The largest observed increase accounted 68% for resistance (joint 150×10-100) and 189% for initial stiffness (joint 150×10-80). The observed results highlight the necessity to consider the beneficial influence of fillet weld in the design of RHS T joints.

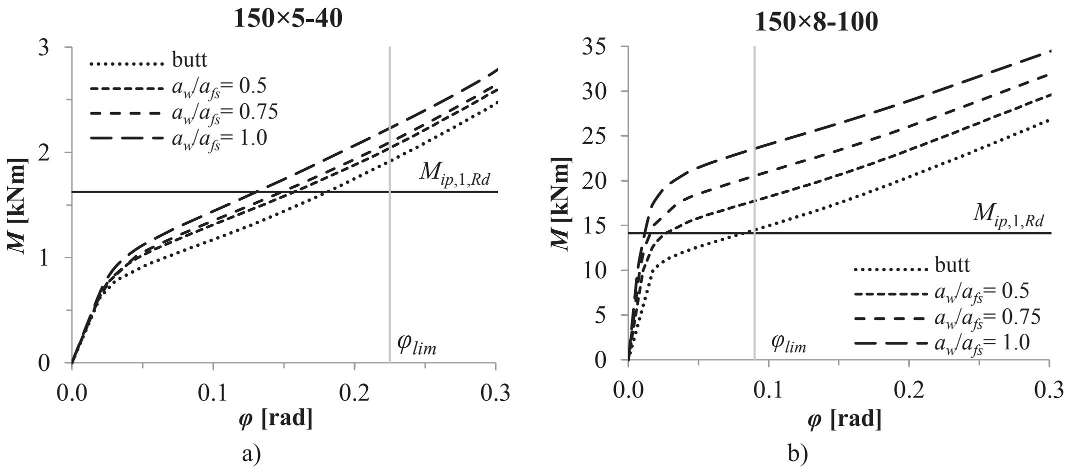


Figure 4. Load-displacement curves of T joints: a) 150×5-40-355 and b) 150x8-100-355.

5 Proposed solution

Based on the obtained numerical results, this section develops a method to take into account the beneficial influence of fillet welds. A joint with fillet welds is considered as a butt-welded joint with the equivalent width $b_{eq} > b_1$and height $h_{eq} > h_1$, so that both joints have the same resistance and stiffness. The equivalent width $b_{eq}$and height h_{eq}can be presentedin the following way:

$$\begin{aligned} b_{eq} &= b_1 + 2\sqrt{2}a_w \cdot k_{fw} \\ h_{eq} &= h_1 + 2\sqrt{2}a_w \cdot k_{fw} \end{aligned} \tag{5}$$

where k_{fw} is a correlation coefficient. In the paper, it was determined based on the obtained numericalresults for every joint presented in Table 1. It was calculated so that the improved theoretical resistance and initial stiffness visually fitted as close as possible to the numerical data. For resistance, k_{fw} was searched in a way that the improved theoretical values did not exceed the numerical ones, as can be seen in Figure 5a, where *FEM* and *Theory* denote values computed numerically and theoretically, respectively. For stiffness, deviations in both directions (above and below the numerical values) were allowed, as shown in Figure 5b with the same notations.The conducted study shows that for resistance, the correlation coefficient k_{fw} varied from 0.4 to 0.9. To fit all the analyzed joints, a single value of 0.4 is proposed, leading to safe resistance for all the joints, but excessively conservative prediction for some joints. The value of 0.4 is found suitable also in terms of initial stiffness. Introducing $k_{fw} = 0.4$ into Eq. (5), the final solution can be presented in the way:

$$\begin{aligned} b_{eq} &= b_1 + 1.13a_w \\ h_{eq} &= h_1 + 1.13a_w \end{aligned} \quad (6)$$

The validity of the method is restricted by the range of the considered joints, i.e. $0.27 \leq \beta \leq 0.67$, $15 \leq 2\gamma \leq 30$withweldssmaller than a full-strength fillet weld ($a_w \leq a_{fs}$).

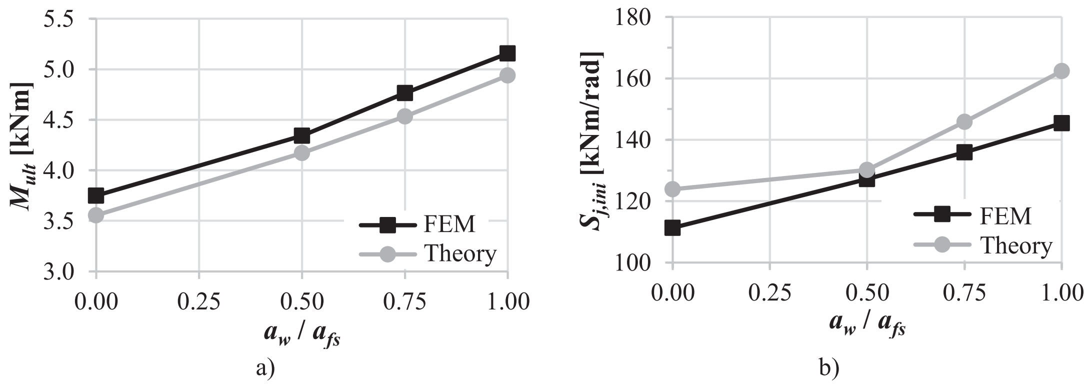


Figure 5. Determination of k_{fw} for joint 150×5-80: a) resistance ($k_{fw} = 0.9$), b) initial stiffness(k_{fw} = 0.4).$a_w/a_{fs} = 0$ corresponds to a butt-welded joint.

6 Validation of the proposed solution

The validation of the proposed solution for tubular joints is carried out based on the experimental results of Havula et al. (2018). In the research, 18RHS T joints with various geometry and material properties were tested under in-plane bending. All the joints had a single chord size of 150×150×8, while the brace sizes were either 100×100×8 or 120×120×8. The joints were made of three steel gradesS420, S500 and S700, and their combinations. The joints had three weld types: butt welds, 6 mm fillet welds and 10 mm fillet welds, denoted as 1/2v, a6 and a10, respectively.

The efficiency of the proposed method for resistance can be seen in Table 2, where the joints are named in the way [chord steel grade]_[brace steel grade]_[weld type], $M_{ip,1,Rd}$ is the resistance calculated according to EN 1993-1-8:2005, $M^*_{ip,1,Rd}$is the resistance calculated according to EN 1993-1-8:2005considering the proposed solution,$M_{exp}$is the experimental moment resistance.As can be seen, the proposed solution provides a better match to the experimental results, improving the average $M_{ip,1,Rd}$ / M_{exp} ratio from 0.70 to 0.84 for a6 joints and from 0.50 to 0.69 for a10 joints. For all the joints, the predicted resistance does not exceed the experimental value. However, for some joints the prediction is still conservative, which might be caused by the commonk_{fw} = 0.4 proposed for all joints and the high strength steel reduction factors 0.9 and 0.8 (see Section 3).

The reliability of the proposed method for initial stiffness can be seen in Table 3, where the joints are named similarly, $S_{j,ini}$ is the resistance calculated according to (Garifullin et al. 2017),

$S^*_{j,ini}$ is the resistance calculated according to according to (Garifullin et al. 2017) considering the proposed solution, $S_{j,exp}$is the experimental initial stiffness. Although for a6 joints the application of the proposed method is doubtful, for a10 joints it leads to more accurate values, improving the average $S_{j,ini}$ / $S_{j,exp}$ratio from 0.65 to 1.04.

Table 2. Validation of the proposed solution, resistance

Joint	β	a_w (mm)	a_w / a_{fs}	$M_{ip,1,Rd}$ (kNm)	$M^*_{ip,1,Rd}$ (kNm)	M_{exp} (kNm)	$M_{ip,1,Rd}$ / M_{exp}	$M^*_{ip,1,Rd}$/ M_{exp}
S420_S420_a6	0.67	6	0.51	15.0	17.8	21.2	0.71	0.84
S500_S420_a6	0.67	6	0.51	15.9	18.9	24.3	0.65	0.78
S500_S500_a6	0.67	6	0.47	15.9	18.9	25.0	0.64	0.75
S700_S420_a6	0.67	6	0.51	22.3	26.4	27.7	0.81	0.95
S700_S500_a6	0.67	6	0.47	22.3	26.4	29.4	0.76	0.90
S700_S700_a6	0.80	6	0.45	39.1	50.6	61.2	0.64	0.83
Average							**0.70**	**0.84**
S420_S420_a10	0.67	10	0.84	15.0	20.2	31.6	0.47	0.64
S500_S420_a10	0.67	10	0.84	15.9	21.3	35.1	0.45	0.61
S500_S500_a10	0.67	10	0.78	15.9	21.3	37.2	0.43	0.57
S700_S420_a10	0.67	10	0.84	22.3	29.9	38.5	0.58	0.78
S700_S500_a10	0.67	10	0.78	22.3	29.9	45.5	0.49	0.66
S700_S700_a10	0.80	10	0.76	39.1	62.4	70.1	0.56	0.89
Average							**0.50**	**0.69**
S420_S420_1/2v	0.67	butt	-	15.0	15.0	18.5	0.81	0.81
S500_S420_1/2v	0.67	butt	-	15.9	15.9	21.1	0.75	0.75
S500_S500_1/2v	0.67	butt	-	15.9	15.9	21.0	0.76	0.76
S700_S420_1/2v	0.67	butt	-	22.3	22.3	24.2	0.92	0.92
S700_S500_1/2v	0.67	butt	-	22.3	22.3	26.4	0.84	0.84
S700_S700_1/2v	0.80	butt	-	39.1	39.1	46.8	0.84	0.84
Average							**0.82**	**0.82**

Table 3. Validation of the proposed solution, initial stiffness

Joint	β	a_w (mm)	a_w / a_{fs}	$S_{j,ini}$ (kNm/rad)	$S^*_{j,ini}$ (kNm/rad)	$S_{j,exp}$ (kNm/rad)	$S_{j,ini}$ / $S_{j,exp}$	$S^*_{j,ini}$ / $S_{j,exp}$
S420_S420_a6	0.67	6	0.51	941	1236	1115	0.84	1.11
S500_S420_a6	0.67	6	0.51	941	1236	1083	0.87	1.14
S500_S500_a6	0.67	6	0.47	941	1236	995	0.95	1.24
S700_S420_a6	0.67	6	0.51	941	1236	1082	0.87	1.14
S700_S500_a6	0.67	6	0.47	941	1236	1108	0.85	1.12
S700_S700_a6	0.80	6	0.45	2176	2960	1990	1.09	1.49
Average							**0.91**	**1.21**
S420_S420_a10	0.67	10	0.84	941	1492	1692	0.56	0.88
S500_S420_a10	0.67	10	0.84	941	1492	1701	0.55	0.88
S500_S500_a10	0.67	10	0.78	941	1492	1452	0.65	1.03
S700_S420_a10	0.67	10	0.84	941	1492	1521	0.62	0.98
S700_S500_a10	0.67	10	0.78	941	1492	1705	0.55	0.87
S700_S700_a10	0.80	10	0.76	2176	3636	2268	0.96	1.60
Average							**0.65**	**1.04**
S420_S420_1/2v	0.67	butt	-	941	941	893	1.05	1.05
S500_S420_1/2v	0.67	butt	-	941	941	977	0.96	0.96
S500_S500_1/2v	0.67	butt	-	941	941	1003	0.94	0.94
S700_S420_1/2v	0.67	butt	-	941	941	971	0.97	0.97
S700_S500_1/2v	0.67	butt	-	941	941	961	0.98	0.98

S700_S700_1/2v	0.80	butt	-	2176	2176	1990	1.09	1.09
Average							**1.00**	**1.00**

The worst prediction of initial stiffness is observed for the joints S700_S700_1/2v, S700_S700_a6 and S700_S700_a10. This might be explained by the fact that these joints have $\beta = 0.80$ and even greater β_{eq}; thus violating the validity range of the proposed method ($\beta \leq$ 0.67). It should be noted that in the global design of structures, the predicted initial stiffness should not necessarily be below the experimental value, and the deviations in both directions are possible.

7 Conclusions

This paper conducts a numerical study to investigate the influence of fillet welds on the behavior of RHS T joints under-in-plane bending. The obtained numerical results demonstrated that fillet welds considerably improve the resistance and stiffness of RHS T joints. The existing building standards do not consider this phenomenon, noticeably underestimating the structural properties of joints. To overcome the observed underestimation, the paper proposes an approach that takes into account the effect of fillet welds by enlarging the cross-section of the brace in the connection area, leading to greater resistance and initial stiffness of joints.

The conducted validation against experimental data showed that the proposed approach leads to more accurate structural properties of joints, particularly reducing the considerable underestimation of the resistance and stiffness for joints with large fillet welds. Additional numerical studies might be conducted to extend the presented method for other loading cases, such as axial loading and out-of-plane bending.

8 References

CEN, 2005. *Eurocode 3: Design of steel structures – Part 1-8: Design of joints (EN 1993-1-8:2005)*, Brussels.

CEN, 2007. *Eurocode 3 – Design of steel structures – Part 1-12: Additional rules for the extension of EN 1993 up to steel grades S 700 (EN 1993-1-12: 2007)*, Brussels.

Garifullin, M., 2019. *Component Method for High Strength Steel Rectangular Hollow Section T Joints*, Doctoral dissertation. Tampere: Tampere University.

Garifullin, M., Pajunen, S., Mela, K. & Heinisuo, M., 2018. Finite element model for rectangular hollow section T joints. *Raken. Mek.*, 51(3), pp. 15–40.

Garifullin, M., Pajunen, S., Mela, K., Heinisuo, M. & Havula, J., 2017. Initial in-plane rotational stiffness of welded RHS T joints with axial force in main member. *J. Constr. Steel Res.*, 139, pp. 353–362.

Havula, J., Garifullin, M., Heinisuo, M., Mela, K. & Pajunen, S., 2018. Moment-rotation behavior of welded tubular high strength steel T joint. *Eng. Struct.*, 172, pp. 523–537.

Heinisuo, M., Garifullin, M., Jokinen, T., Tiainen, T. & Mela, K., 2016. Surrogate modeling for rotational stiffness of welded tubular Y-joints. In C. J. Carter & J. F. Hajjar, eds. *Connections in Steel Structures VIII*. Chicago, Illinois: American Institute of Steel Construction, pp. 285–294.

Lu, L.H., de Winkel, G.D., Yu, Y. & Wardenier, J., 1994. Deformation limit for the ultimate strength of hollow section joints. In P. Grundy, A. Holgate, & B. Wong, eds. *Tubular Structures VI, 6th International Symposium on Tubular Structures, Melbourne, Australia*. Rotterdam: Balkema, pp. 341–347.

de Matos, R.M.M.P., Costa-Neves, L.F., Lima, L.R.O. de, Vellasco, P.C.G.S. & da Silva, J.G.S., 2015. Resistance and elastic stiffness of RHS "T" joints: part I – axial brace loading. *Lat. Am. J. Solids Struct.*, 12(11), pp. 2159–2179.

Ongelin, P. & Valkonen, I., 2016. *SSAB Domex Tube. Structural hollow sections. EN 1993 – Handbook 2016*, SSAB Europe Oy.

Packer, J.A., Wardenier, J., Zhao, X.-L., van der Vegte, G.J. & Kurobane, Y., 2009. *Design guide for*