Effect of fillet welds on initial rotational stiffness of welded tubular joints

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Abstract

Welded tubular joints are widely used in optimization of tubular structures. The most important parameter in optimization of these joints is their initial rotational stiffness. For today there is no any available analytical method that allows calculating rotational stiffness for joints with an angle different from 90 degrees. Conducting computationally intensive finite element analyses (FEA) usually renders the optimization procedure inapplicable. Constructing an approximate surrogate model of the joint responses can lead to a significant reduction of computational efforts. However most of surrogate models are constructed for joints with only butt welds. This article proposes a simple method for implementing fillet welds in surrogate modeling of tubular joints. Using this method the effect of fillet welds on initial rotational stiffness of joints is analyzed.

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Introduction

The Welded joints are widely used for construction of tubular trusses. The structural analysis model of such trusses is frequently constructed using beam finite elements when the braces are connected to the chords using hinges. In reality, when the joints is loaded by the moment it does not behave as a hinge, so the stiffness against the moment has to be taken into account in the global analysis of the structure. When aiming to economic and environmental friendly design the stiffness of the joints must be taken into account. In [2,3] it has been shown that the rotational stiffness of the welded tubular joint is the main parameter when considering buckling of members of tubular trusses. EN 1993-1-8 [28] contains only the equations for the moment resistance of the joint where the angle between the brace and the chord is 90 degrees. In [1] there is the equation which can be used to calculate the initial rotational stiffness for the same case, angle 90 degrees. In design it is possible to define the rotational stiffness for the joint using comprehensive finite element analysis (FEA). In practice, this is impossible, especially when performing optimization of structures when the structural analysis must be done thousands times. In order to avoid these computationally heavy calculations so called surrogate models have been developed.

Surrogate models have been used widely in the aerospace industry [4-8] and civil engineering [9-19]. Diaz [10] presents the optimum design of steel frames using semi-rigid joints and surrogate models. Heinisuo [22] conducted a surrogate modeling for rotational stiffness of welded SHS joints, dealing only with butt welds. However fillet welds widely used for tubular joints have a certain effect on initial rotational stiffness of joints and should be taken into account in design. The article briefly describes a surrogate modeling procedure for initial rotational stiffness for SHS joints made of HSS. Design of experiment is conducted using the comprehensive FEA. After modeling, the article proposes a simple method for implementing the influence of fillet welds and studies the their effect for S500 and S700 steel grades.

Finite element analysis

The Abaqus model was made by using C3D8 brick elements both for the tubes and for the welds. All sections were modeled with round corners, according to EN 10219-2 (2006). Two-layered mesh was created with solid hexahedral elements being refined near the joints, as shown in Fig. 1.

The butt welds were modeled as “no weld” by using TIE constraint of Abaqus. The fillet welds were modeled as steel and using TIE constraint where the welds were in contact with chord. The material does not have influence on the stiffness of joints with butt welds but in case of fillet welds the material of the brace affects considerably to the weld sizes, see Table 2. The material model was elastic: the modulus of elasticity was 210000 MPa and Poisson’s ratio 0.3.

Figure 1. Design model and FEA model for Y-joint.

The meshing and the material model were the same as in [21]. Meshing of butt and fillet welds is shown in Fig. 2.
The FEA models were validated with the tests of LUT [20] in [21]. The verification was done in three steps [22]: moment load in two opposite directions, use of shell elements instead of brick ones and varying the type of brick elements from 8 to 20 nodes. The proposed FEA model seemed to work well and was used with the fillet welds modeled using the exact geometry.

The joint rotation \( C \) was calculated from FEA by extracting the frame behavior from the FEA results, as is given in [21].

**Surrogate model for initial rotational stiffness**

A surrogate model was constructed for initial rotational stiffness as a function of four variables (Fig. 3): \( C = f(b_0, t_0, \beta = b_1/b_0, \phi) \). The effect of brace thickness \( t_1 \) on rotational stiffness was found to be very weak and thus was ignored.

The member sizes were discrete and followed those of Ruukki, meaning cold-formed tubes. The chord sizes \( b_0 \) were restricted by RHS sections between 100x100x4 and 300x300x12.5. HSS up to S700 and also limited the range of the cross-sections (European Committee for Standardisation, 2007).

The main requirement which restricted the range of sections was: \( 0.25 \leq \beta = b_1/b_0 \leq 0.85 \). The ratio \( b_1/t_1 \) was limited \( b_1/t_1 \leq 35 \) and in compression to cross-section class 1 or 2. The ratio \( b_1/t_0 \) was limited \( 10 \leq b_1/t_0 \leq 35 \) and moreover to the cross-section class 1 or 2. The angle \( \phi \) between the brace and the chord is due to welding in the range 30 degrees \( \leq \phi \leq 90 \) degrees.

For the definition of the sample points engineering justification was used [23]. The sample points were chosen in such a way that for every variable there were 3 different values (minimum, middle and maximum) while the others remained constant [24]. Totally, 285 sample points were chosen; their initial rotational stiffness was calculated with comprehensive FEA.

The surrogate modeling was conducted using Kriging via the ooDACE toolbox for Matlab [25]. The original number of sample points did not allow constructing a physically reasonable surrogate model. The problem was solved by adding pseudo points, thus increasing the number of sample points up to 2154. To increase the accuracy
of the model certain improvements were also undertaken. Final surrogate model (Fig. 4) had the 4% average relative error and 16% maximum error. The detailed procedure of the model construction is described in [23].

![Figure 4. Behavior of the surrogate model in respect to couples of variables](image)

**Proposed method**

In our previous research we investigated the rotational stiffness of tubular joints considering only butt welds. This assumption simplifies FE analysis and surrogate modeling and allows not taking into account the influence of steel grade on rotational stiffness. However, fillet welds, used in practice instead of butt ones, can increase the stiffness of the joints. This increase might be considerable for joints made of tubes with little sections (100-120 mm) for which the weld size is comparative to the size of the section. More to the point, it was shown before that full strength weld size depends on the steel grade (Table 1). So, for fillet welds material properties cannot be neglected. It can be seen in Table 1 that the full strength weld size for e.g. S500 and S700 are about the same, so in this study the weld size effect was considered only for steel grades S355 and S700.

For calculation of rotational stiffness of tubular joints with fillet welds we proposed the following idea:

1. Replace an original joint with fillet welds by a joint with butt welds. The effect of welding should be implemented by replacing the original brace width $b_1$ by the equivalent brace width $b_{eq}$.
2. Calculate the rotational stiffness using the constructed surrogate model for joints with butt welds using $b_{eq}$ for fillet welded joints.

Obviously, $b_{eq}$ lies in the interval:

$$b_1 < b_{eq} < b_1 + 2\sqrt{2}a,$$

where $a$ is weld size. So, for calculating $b_{eq}$ we suggested the following formula:

$$b_{eq} = b_1 + 2\sqrt{2}a \cdot k_{fw},$$

where $k_{fw}$ is a factor accounting for the increase in rotational stiffness due to welding.
where

- $a$ is weld size, see Fig. 5;
- $k_{fw}$ is a correlation coefficient.

This idea is illustrated in Fig. 5.

The object of this study was to determine the correlation coefficients $k_{fw}$.

For calculation the values of correlation coefficient a number of cases were chosen covering the whole range of our interest. Then we used the following algorithm:

- Calculate rotational stiffness for joints with fillet welds using FEM.
- Calculate rotational stiffness for joints with butt welds for equivalent brace width using FEM. Equivalent brace width was first determined randomly and then refined through iterations.
- Calculate correlation coefficients.

For simplicity we proposed using instead of the exact values $k_{fw}$ the discrete values $k_{fw,\text{dis}}$ of correlation factors: 0.6 for S355 steel and 0.7 for S700 steel. For the discrete values rotational stiffness $C_{\text{dis}}$ was also calculated and the loss of accuracy was analyzed. All the results are presented in Table 1.

### Table 1. Correlation coefficients.

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<th>$t_1$</th>
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The average error arisen when using the discrete values instead of the exact ones was 4.6%, maximum was 10.8%. This justifies the use of discrete values.

Effect of fillet welds

To determine the qualitative and quantitative picture of the effect of fillet weld size on rotational stiffness we provided a comparative analysis for joints with butt and fillet welds for S355 and S700 steel grades (Table 2).

Table 2. Butt vs. fillet welds

| №  | Chord | Brace | φ [°] | β | C [kNm/rad] | C / C Butt
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Average 1.53  1.95

* - no FEM results available, calculated by surrogate model.

Graphically it is shown in Fig. 6. For convenience, only relative results are presented (cases are arranged in ascending order of β).
Looking at the results of the analysis the following conclusions can be made:

- Fillet welds increase considerably rotational stiffness of welded joints, in mean 1.5 times for S355 steel grade and 2.0 times for S700.
- The influence of welding is more noticeable for small sections. This might be explained by the fact that for small sections the difference between weld size and chord width is not as high as for large sections.
- The increase of rotational stiffness is higher for sections with high $\beta$. This might be explained by a nonlinear $C/\beta$ curve on which a considerable growth for high values of $\beta$ is observed.

Conclusions

Today no analytical method exists to calculate initial rotational stiffness of welded tubular RHS joints. Surrogate modeling [24], based on comprehensive FEA, might represent a very valuable method for solving this task, without considering the influence of fillet welds, though.

The effect of the full strength fillet weld is considerable for the rotational stiffness, even with the factor up to 3 compared to the stiffness with butt welds in some cases for the high strength steel. The mean factor in our cases was 1.5 for S355 steel grade and 2.0 for S700 steel grade. The simple rule which is connected to Eq. 2, can be used with the correlation factors $k_{fw} = 0.6$ (S355) and 0.7 (S700, linear interpolation between) to predict the effect of the weld size.

References


