Experiments of in-plane moment loaded welded tubular high strength steel T-joints of rectangular sections

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ABSTRACT

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ABSTRACT

The purpose of this Bachelor's thesis was to study high strength steel (HSS) welded joints. In recent times, application of HSS has increased significantly. However, current regulations offer rather conservative design approach by introducing reduction factor (k_{HSS}) and requirements for the minimum throat thickness of the fillet welds. These requirements provide designers with potentially uneconomical solutions, which clearly limit the application of HSS in building industry. The aim of the thesis was to support the claim stated in previous studies by Havula et.al (2018) regarding HSS T-joints design regulations review.

Six specimens of T-joints were made from welded rectangular hollow steel sections (RHSS) of S700 steel grade to be tested. Calculations were done in accordance with EN1993-1-8. The welds were 3D scanned in order to get accurate weld dimensions. The impact of heat affected zone (HAZ) on the joints was estimated by measuring the cooling time using infrared camera and related software. The process of the weld was measured and implemented in the calculations, in order to provide accurate input data for the comparative analysis.

The results of the thesis showed that the need for change of reduction factor in T-joints with S700 steel grade is required, as well as reduction of the minimum throat thickness.

Keywords High strength steel, T-joint, reduction factor, cooling time, fillet weld

Pages 17 pages including appendices 48 pages

CONTENTS

1 INTRODUCTION

High strength steel (HSS) joints can be found in various types of steel framed structures. According to Eurocodes (EN1993-1-12), HSS are steel grades greater than S460 (EN1993-1-12). The importance of the given steel type is explained by its high mechanical properties, which allow to decrease dimensions of a structure and potentially enhance supply chain effectiveness and cost efficiency (Degarmo, 2003, p.116).

1.1 Background

However, the use of HSS is limited due to high material costs and specific reduction factors. These limitations derive from the design regulations stated by the current version of Eurocode 1993-1-8 and 1993-1-12. It provides reduction factor (k_{HSS}) 0.8 to 0.9 (acc. to steel grade) for T-joints composed of axially loaded brace, which is welded to chord at right angle. This reduction results in a decrease in the design resistance, which leads to a need for larger profiles, in other words, increasing the price of certain connection types including T-joints.

The origin of the given reduction factor (k_{HSS}) remains unclear and probably the decision to introduce the factor and, consequently, switching to a more conservative design approach, is motivated by the lack of research (experimental and theoretical data) when the regulations were introduced (Havula et.al, 2018).

Also, the Eurocode 1993-1-8 provides requirements for the minimum throat thickness of the fillet weld joining a chord and a brace, that is $1.65 \cdot t$ (where t is the wall thickness of tube). Welding itself is an expensive process, and inadequate dimensions of the weld significantly increase the price of the final product (Havula et.al, 2018).

1.2 Objectives

The goal of this thesis is to continue the published research work (Havula et.al 2018) by reporting the new experiments and comparing the results to the current Eurocode design rules.

The calculations are done in accordance with currently available Eurocode 1993-1-8, while experiments were done in HAMK Tech laboratory; the tested samples were provided by SSAB Europe Ltd.

The main goals of the thesis are:

1. Describe the project for further studies by reporting all the process in details and explaining important points.
2. Calculate and compare the experimental part of study to present building code and standards.
3. Highlight the importance of reviewing the regulations regarding the HSS welded joints.

1.3 Scope and limitations

The study is limited to 6 T-joints made from welded rectangular hollow steel sections (RHSS) of S700 steel grade. The following steps are performed in order to accomplish the stated goals:

1. Selection and order of sample materials.
2. Estimation of HAZ.
3. 3D scanning of the welded samples.
4. Testing of the samples.
5. Theoretical calculations.
6. Result comparison and discussion.

The thesis workflow is illustrated in the chart below (Figure 1).

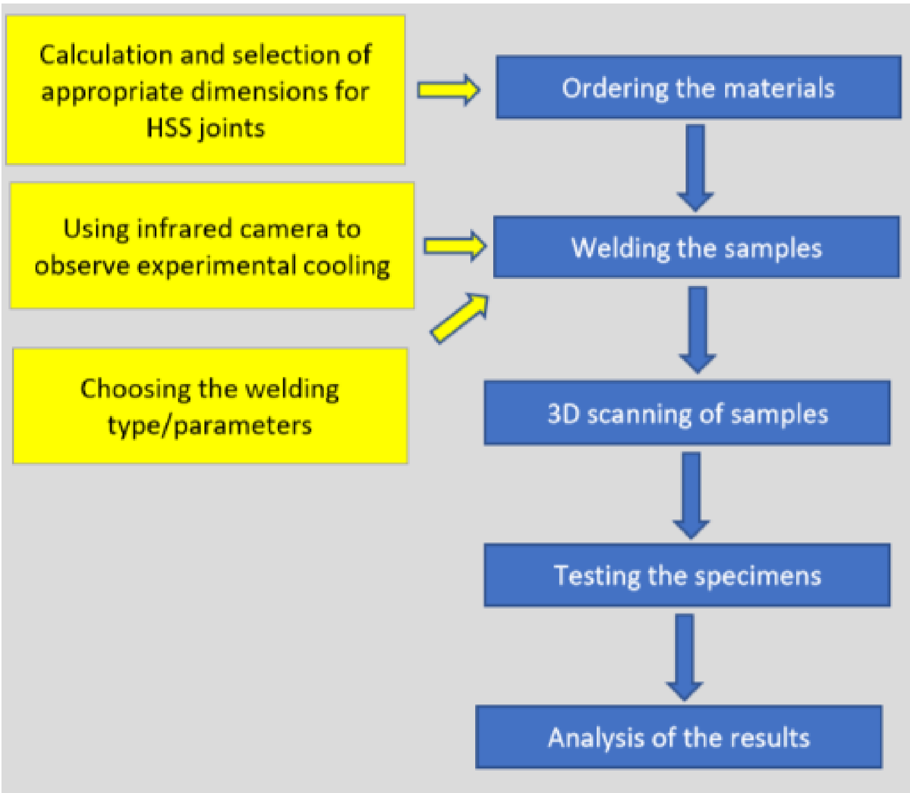

Figure 1. Workflow.

2 PROJECT ARRANGEMENT

2.1 Steel used in study cases

The samples were made from cold-formed steel, provided by SSAB Europe. This steel type is called Strenx®700MC; its nominal mechanical properties and chemical composition are given in Tables 1 and 2, respectively. The material meets the demands for S700MC stated by EN10149-2. All the required information about the mechanical and chemical composition of Strenx®700MC was received from an official steel producer's (SSAB) website (Strenx® 700 E/F).

Table 1. Mechanical properties of Strenx®700MC.

Thickness(mm)	*Yield strength R_{eh} (min MPa)*	*Tensile strength R_m (MPa) 6-10mm*	*Elongation (min%)*
8	700	750-950	12

Along with other typical alloys such as C (Carbon), contaminants S (Sulphur) and P (Phosphorous) etc., the studied steel type contains Manganese (Mn), whose content percentage is estimated as 2.1% (Table 2.). Manganese combines with S (Sulphur) and P (Phosphorous) reducing brittleness, meanwhile enhancing elastic properties and resistance of the product (Black et.al., 2017, p.117). Also, a relatively high content of Vanadium (V) increases strength but retains ductility; the melting point of metal is also increased due to the presence of this alloy (Black et.al., 2017, p.117). Moderate Titanium (Ti) content is implemented in order to increase the toughness of the product, i.e. enhance the ability to absorb energy and deform plastically (Black et.al., 2017, p.117).

It can be concluded that the sample material used for a further comparative analysis has sufficient properties for high bearing capacity performance. However, an increased melting point may affect the welding process and require special attention to be paid to heat input control.

Table 2. Chemical composition of Strenx®700MC

C (max %)	*Si (max %)*	*Mn (max %)*	*P (max %)*	*S (max %)*	*Al_{tot} (min%)*	*Nb (max %)*	*V (max %)*	*Ti (max %)*
0.12	0.21	2.10	0.020	0.010	0.015	0.09	0.20	0.15

2.2 Specimens manufacture

The average measured dimensions of the steel tubes used are presented in Table 3. The dimensions are presented in Figure 2. Three specimens were taken with brace to chord width ratio 0.4 (β -ratio), while other three specimens β -ratio were 0.67.

t_1 *—thickness of the flange under tension [mm]*
t_2 *—thickness of the right web [mm]*
t_3 *—thickness of the compressed flange [mm]*
t_4 *—thickness of the left web [mm]*
b_1 *—width of the flange under tension [mm]*
b_3 *—width of the compressed flange [mm]*
h_2 *—right web height [mm]*
h_4 *—left web height [mm]*
r_0 *—radius of gyration [mm]*

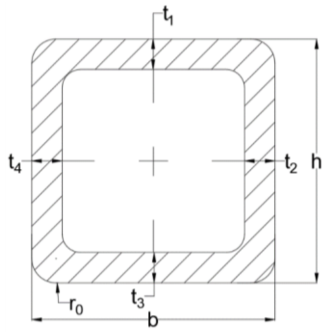

Figure 2. Measured dimensions of the tube.

Table 3. The averaged measured dimensions of section.

Specimen	β	*Member*	*Section*	$t_1[mm]$	$t_2[mm]$	$t_3[mm]$	$t_4[mm]$
3xS700_S700_a3	0.4	Chord	150x150x6	5.884	5.896	5.836	5.896
		Brace	60x60x4	3.973	3.967	3.984	3.967
3xS700_S700_a4	0.67	Chord	120x120x10	9.795	9.771	9.895	9.771
		Brace	80x80x5	4.885	4.909	4.902	4.909

Specimen	$r_0[mm]$	$b_1[mm]$	$b_3[mm]$	$h_2[mm]$	$h_4[mm]$
3xS700_S700_a3	12.864	150.820	150.909	150.684	150.646
	9.172	60.244	60.133	60.039	60.167
3xS700_S700_a4	28.743	120.846	120.867	120.431	120.435
Specimen	11.478	80.054	80.107	80.313	79.969

All the specimens were welded using fillet weld in Tavastia Vocational College, Hämeenlinna. The brace of the sample is welded at the midpoint of the chord at an angle of 90° (Figure 3), the length of both members is 700 mm. At the end of the chord and brace steel plates of S355 were welded corresponding to the dimensions of chord or brace.

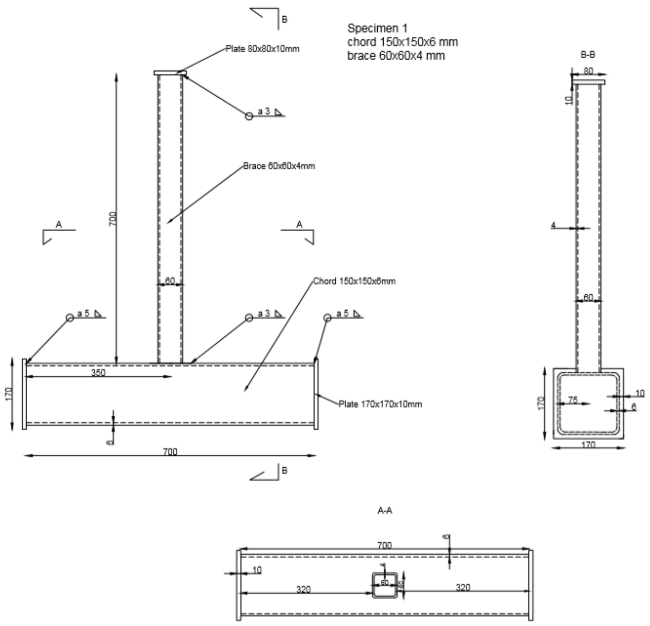

Figure 3. Test specimen 1.

2.3 Welding the samples

The sizes of welds are chosen so that the ratio a_w/a_{wfs} (experimental and required throat thicknesses (Eq.1)) is close to 0,8 (Table 3).

Where:

$$a_{wfs} = 1.65 \cdot t_1 \quad (1)$$

Table 3. Weld sizes.

Specimen	*Member*	*Section*	*Welding process and position*	*Weld*	a_w [mm]	a_{wfs} [mm]	a_w/a_{wfs}
3xS700_ S700_a3	Chord	150x150 x6	MAG & PB	a3	5	6.6	0.45
	Brace	60x60x4					
3xS700_ S700_a4	Chord	120x120 x10		a4	6	8.25	0.48
	Brace	80x80x5					

The MAG, manual arch welding, was done by the welding teacher from Tavastia Vocational College; thus, all the steel manufacturer instructions were followed in order to receive reliable information afterwards. Photographs of the welding process can be seen in Figure 4.

a) b) c)

Figure 4. a) welding setup b) thermographic camera c) welding machine and parameters

For this research, the thermographic camera FLIR A325sc was used to measure cooling time of the welds at several points. The temperature data is then processed by FLIR ResearchIR Max software, then the measurements are formatted into Excel file, which is later on used in cooling time estimation.

2.4 3D scanning of welds

After welding and corresponding measurements, the samples were sent to Riihimäki laboratory at HAMK, Finland. The welds of each of the six samples were 3D scanned in order to provide actual dimensions of welds. Figures 5 and 6 show 3D scans of specimen S1 in two planes.

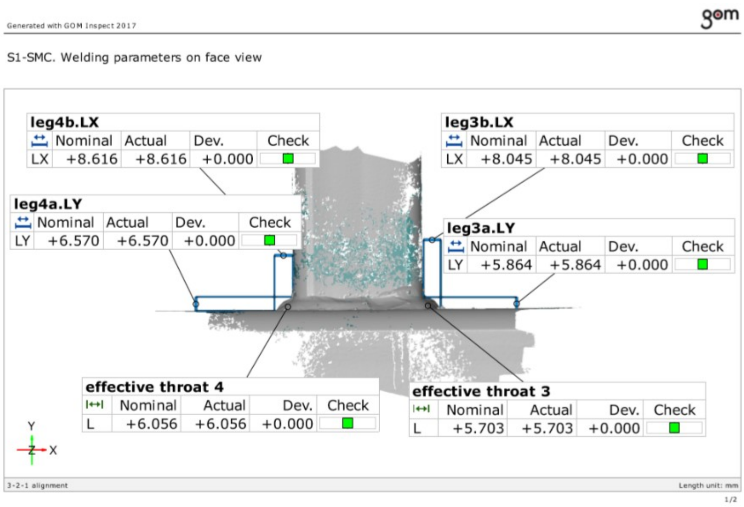

Figure 5. 3D scan of specimen S1, face view

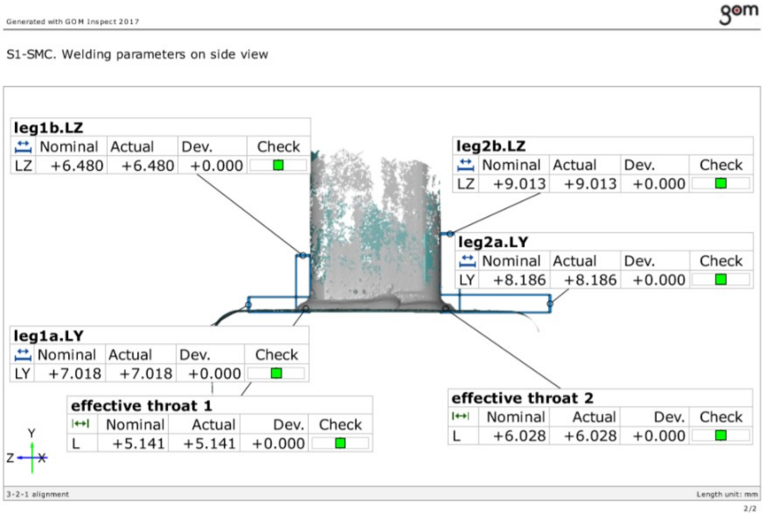

Figure 6. 3D scan of specimen S1, side view

The 3D scans were used in order to obtain the effective throat thickness of the welds, which were used in further evaluation of characteristic and design resistance of the welded joints. The effective throat thickness was estimated as follows (Eq.2):

$$a_w = \frac{LY \cdot LZ}{\sqrt{LY^2 + LZ^2}} \tag{2}$$

Where:

a_w – effective throat thickness [mm]
LY – leg in OY plane see Figure 6 [mm]
LZ – leg in OZ plane see Figure 6 [mm]

Table 4 presents the effective throat thicknesses of the failed welds. As the data of 3D scan for S2 is not available, thus the average measured weld size of S1&S3 is used for S2.

Table 4. 3D scan results

Specimen	*Specimen*	*Member*	*Section*	*Weld size [mm]*	*Measured weld size [mm]*
S700_S700_a3	S1	brace	150x150x6	5	5.703
		chord	60x60x4		
S700_S700_a3	S2	brace	150x150x6	5	5.057
		chord	60x60x4		
S700_S700_a3	S3	brace	150x150x6	5	4.412
		chord	60x60x4		
S700_S700_a4	M1	brace	120x120x10	6	5.289
		chord	80x80x5		
S700_S700_a4	M2	brace	120x120x10	6	6.377
		chord	80x80x5		
S700_S700_a4	M3	brace	120x120x10	6	6.201
		chord	80x80x5		

2.5 T-joint test arrangement

Testing of the samples was performed in HAMK Tech research unit structural testing laboratory located in Hämeenlinna. The specimens were installed in the frame so that the static model (Figure 8) is valid. During the test axil force F is applied to the brace end. The force is gradually increasing till the failure of the T-joint.

Besides, five transducers were installed during the testing to measure the displacement and to obtain the rotation capacity of the joint. The transducers were installed and labelled as: D1, D2, D3, D4 and D5 (Figure 7).

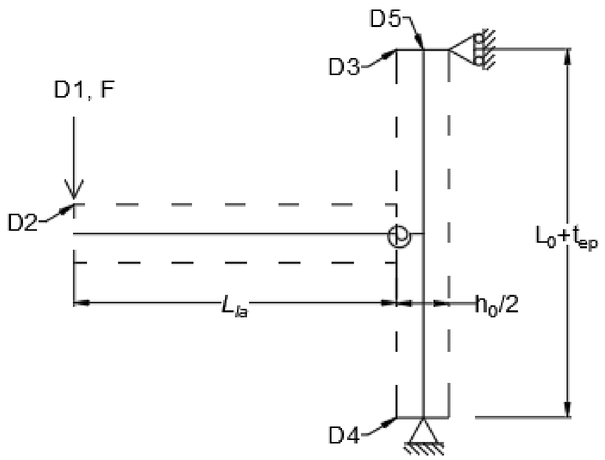

Figure 7. T-joint static model.

The test arrangement is shown on Figure 8.

Figure 8. Test arrangement overview.

The corresponding measured displacement are identified as: v_{D1}, v_{D2}, v_{D3}, v_{D4} and v_{D5} .

The sensor D1 is based inside of the hydraulic cylinder, while D1 and D2 are measuring the same displacement. From this displacement by use of formula (Eq. 3), the vertical displacement of the brace δ_b is calculated:

$$\delta_b = \nu_{D1} - \nu_{D5} - \delta_{rb} = \nu_{D1} - \nu_{D5} - \frac{L_{la}+\frac{h_0}{2}}{L_0+t_{ep}} \cdot (\nu_{D4} - \nu_{D3}) \qquad (3)$$

Where:

ν_{D5} – *the vertical displacement of the joint in relation to the bottom of the chord,* (see Figure.9).

δ_{rb} –*rigid body motion of the test specimen, due to displacement at the supported points D4 and D3 (by measured displacements ν_{D3} and ν_{D4})*, see Figure 9.

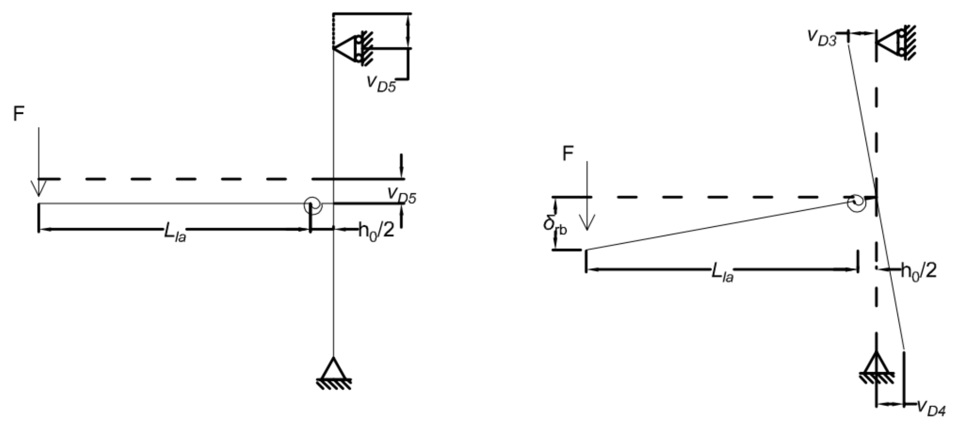

Figure 9. Vertical displacement of the chord.

3 THEORETICAL PART OF CACLULATIONS

The following failure options for RHS joints under pure bending are proposed by EN 1993-1-8:2005:

a) Chord face failure
b) Chord side wall failure (or chord web failure)
c) Chord shear failure
d) Punching shear
e) Brace failure
f) Local buckling

Due to fact that all of the tested samples have brace-to-chord width ratio β <0.85, only chord face failure has to be calculated. Also, as the welds are smaller than full-strength ones, their resistance has also to be estimated.

Thus, the moment joint resistance is defined by means of the following equation (Eq.4):

$$M_{r,Rd} = min\{M_{ip,1,Rd}, M_{w,Rd}\} \tag{4}$$

Where:

$\mathrm{M_{ip,1,Rd}}$ *−bending moment resistance based on the chord face failure*

$M_{w,Rd}$ *−bending moment resistance based of weld failure*

3.1 Moment resistance based on the chord face failure

According to Eurocode (EN 1993-1-8:2005), in order to calculate the moment resistance based on the chord face failure $M_{ip,1,Rd}$, yield strength, section dimensions and reduction factor k_{HSS} should be implied (Eq.5):

$$M_{ip,1,Rd} = k_n \cdot f_{y0} \cdot k_{HSS} \cdot {t_0}^2 \cdot h_1 \cdot \left(\frac{1}{2 \cdot \eta} + \frac{2}{\sqrt{1-\beta}} + \frac{\eta}{1-\beta}\right) / \gamma_{M5} \tag{5}$$

Where:

$\mathrm{k_n}$ *−chord stress function (not needed in this case) [-]*

f_{y0} *−chord yield strength [N/mm²]*

k_{HSS} *−reduction factor for HSS [-]*

t_0 *−thickness of chord RHS profile [mm]*

h_1 *−web height [mm]*

$\eta = \frac{h_1}{b_0}$ *− brace height-to-chord width ratio [-]*

$\beta = \frac{b_1}{b_0}$ *− brace-to-chord width ratio [-]*

b_1 *−width of chord flange [mm]*

b_0 *−width of brace flange [mm]*

3.2 Moment resistance based on the fillet-weld failure

Design moment resistance of the fillet weld is computed by means of the directional method, given in EN 1993-1-8:2005. In accordance with the static model, the axial force P is carried by welds related to b_1, while the shear loads are carried by the welds related to h_1 (Figure 10).

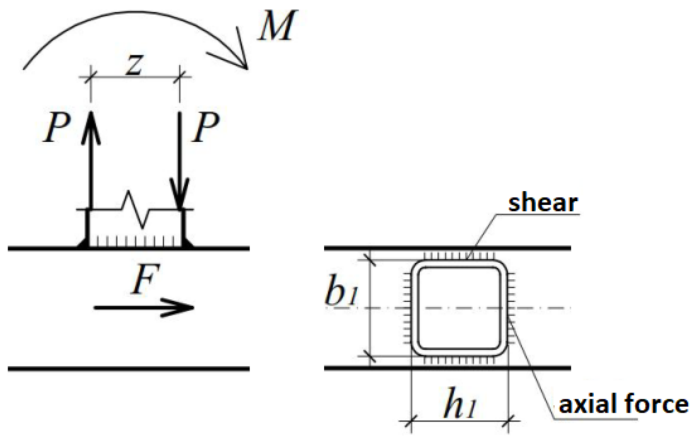

Figure 10. Load components in welding.

The fillet weld resistance is the minimum of the two components (Eq.6):

$$M_{w,Rd} = \min\{M_{w,N,Rd1}, M_{fw,S,Rd1,}\} \quad (6)$$

Where:

$M_{w,N,Rd1}$ *–moment resistance axial loading*

$M_{fw,S,Rd1,}$ *– moment resistance shear loading*

The following formulas are used to determine moment resistance of the corresponding components (Eq.7,8)

$$M_{w,N,Rd1} = \frac{1}{\sqrt{2}} \cdot a_{wfs} \cdot b_b \cdot (h_b - t_b) \quad (7)$$

$$M_{fw,S,Rd1,} = \frac{2}{\sqrt{3}} \cdot h_b \cdot \frac{f_u}{\gamma_{M2}} \cdot L_{la} \quad (8)$$

Where:

a_{wfs} *–design throat thickness [mm]*

b_b *–brace height [mm]*

h_b *–brace width [mm]*

t_b *– thickness of brace RHS profile [mm]*

f_u *–weld ultimate strength [N/mm²]*

γ_{M2} *–partial safety factor [-]*

L_{la} *—brace length [mm]*

According to EN 1993-1-8:2005, properties of the weld must satisfy the following criteria (Eq. 8-11).
The formula (Eq.8) states that the design resistance of the weld must have greater magnitude than the sum of stress components (Eq.9-12) (Figure 11).

$$\frac{f_u}{\gamma_{M2} \cdot \beta_w} > \sqrt{\sigma_{perpendicular}{}^2 + 3 \cdot (\tau_{perpendicular}{}^2 + \tau_{parallel}{}^2)} \quad (9)$$

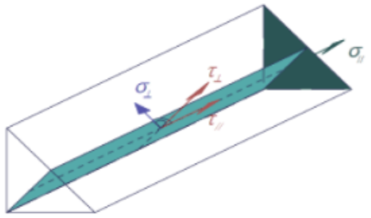

Figure 11. Stress components in weld planes.

$$\sigma_{perpendicular} = \frac{M_{Ed}}{a_{wfs} \cdot b_b \cdot (h_b - t_b)} \quad (10)$$

$$\tau_{perpendicular} = \sigma_{perpendicular} \quad (11)$$

$$\tau_{parallel} = \frac{F}{2 \cdot a_{wfs} \cdot l_{weld}} \quad (12)$$

Where:

M_{Ed} *—bedning moment [kNm]*

F *—axial force acting on cantilever end [kN]*

l_{weld} *—weld length [mm]*

3.3 Theoretical and experimental calculation of cooling time of the weld

Cooling time is an important weld characteristic as it directly affects the quality and performance of the weld. The most critical microstructural changes take place in the welded metal at temperatures between 500 °C and 800 °C, so measuring of this process is exceptionally crucial. The cooling time is dependent upon the heat input which can be controlled by adjusting Voltage, Electric Current and Speed of Welding.

According to Eurocode, the cooling time from 800 °C to 500 °C is estimated as follows (Eq.13,14). The largest number is considered (Feldman et.al., 2016):

$$t_{8/5} = (4300 - 4{,}3 \cdot T_0) \cdot 10^5 \cdot \left(\frac{Q^2}{d^2}\right) \cdot \left[\left(\frac{1}{500 - T_0}\right)^2 - \left(\frac{1}{800 - T_0}\right)^2\right] \cdot F_2 \qquad (13)$$

$$t_{8/5} = (6700 - 5 \cdot T_0) \cdot Q \cdot \left[\left(\frac{1}{500 - T_0}\right) - \left(\frac{1}{800 - T_0}\right)\right] \cdot F_3 \qquad (14)$$

Where:

T_0 – *working temperature [°C]*

Q – *heat input [kJ/mm]*

d – *thickness of the samples [mm]*

F_2 and F_3 – *shape factors taken as 0,9 from EN 1011-2 [1], Table D.1.*

In this project, the thermographic camera was used during the welding to measure experimental cooling time. The camera converts heat into an electronic signal, which is then processed to produce a thermal image on a video monitor and perform temperature calculations. After receiving data from it, the cooling time is measured by subtracting the time, when steel is 500 °C, by the time, when the steel's temperature was 800 °C. Consequently, experimental cooling time was obtained and is presented in Table 5, as well as calculated cooling time.

Table 5. Cooling time.

Specimen	*Average working temperature [°C]*	*Calculated $t_{8/5}$ [s]*	*Recorder $t_{8/5}$ [s]*
S1	20	27.446	32
S2		42.964	43
S3		34.991	38
M1		83.348	85
M2		69.427	76
M3		77.164	81

4 EXPERIMENTAL PART OF THE PROJECT

All six samples were tested under pure bending until a total failure of specimens happened. Three modes of failure predictably occur during testing:

- chord face failure
- chord side wall failure
- punching shear.

In all the tested T-joints the punching shear or HAZ was the reason of final failures. The corner of welding is the frailest segment of welding, so the final failure started precisely from it (Figure 12).

Figure 12. Failure of the joint S2.

The moment-rotation curve of S700_S700_a3, S1, is shown in Figure 13, while the other specimen's curves are given in Appendix 2. All the joints showed the same patterns during the testing, with the following phases:

- linear elastic phase, corresponding to elastic deformations with the initial rotational stiffness, $S_{j,ini}$;
- Transitional phase, when the yielding of the joint starts and the slope changes from linear (elastic) to rounded.
- Hardening phase, corresponding to the hardening stiffness, $S_{j,h}$;
- The final failure, when the load starts to drop, corresponding to the failure in the weld or HAZ.

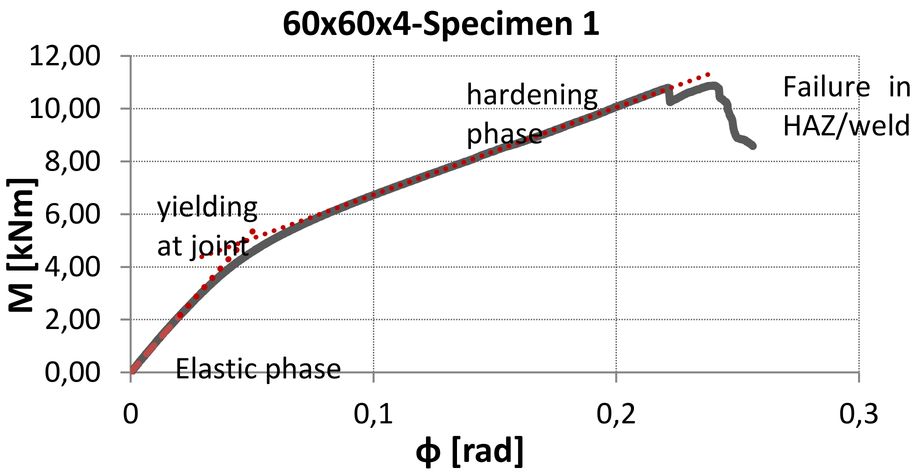

Figure 13. Typical moment-rotational curve of S1.

The following parameters were taken from the test data and are presented in Table 6:

Table 6. Experimental results.

$Specimen$	β	$M_{pl.exp}$	$M_{u.exp}$
$S1$	0.399	4.8791	13.1348
$S2$	0.399	4.9904	12.4571
$S3$	0.399	4.9588	10.8758
$M1$	0.655	21.037	25.7103
$M2$	0.655	20.155	25.4198
$M3$	0.655	19.276	25.5060

Where:

$M_{pl.exp}$ *– the plastic moment resistance*

$M_{u.exp}$ *– the ultimate moment resistance*

The theoretically calculated data are gathered in Table 7, with the following parameters:

Table 7. Calculated values.

$Specimen$	β	$M^*{}_{ip,1,Rd}$	k_{HSS}	$M_{ip,1,Rd}$	$M^*{}_{w,Rd}$	$M_{w,Rd}$	$M^*{}_{j,Rd}$	$M_{j,Rd}$	*Lim.factor*
$S1$	0.39	5.659	0.8	4.52	6.66	8.49	5.659	4.528	chord
$S2$	0.39	5.659	0.8	4.52	6.80	8.49	5.659	4.528	chord
$S3$	0.39	5.659	0.8	4.52	7.34	8.49	5.659	4.528	chord
$M1$	0.65	29.043	0.8	23.23	15.42	18.63	15.42	18.63	weld
$M2$	0.65	29.043	0.8	23.23	15.82	18.63	15.82	18.63	weld
$M3$	0.65	29.043	0.8	23.23	13.10	18.63	13.10	18.63	Weld

Where:

$M^*{}_{ip,1,Rd}$ *– the moment resistance based on chord face failure without* k_{HSS}

$M_{ip,1,Rd}$ *–the moment resistance based on chord face failure (current Eurocode; with* k_{HSS}*)*

$M^*{}_{w,Rd}$ *–moment resistance based of fillet weld failure*

$M_{w,Rd}$ *– the moment resistance based on fillet weld failure*

$M_{j,Rd}$ *– – the moment resistance of the joint with* k_{HSS}

$M^*{}_{j,Rd}$ *– the moment resistance of the joint without* k_{HSS}

It can be concluded from the data above that the weakest part of the connection is the chord, which should fail first. This condition satisfies the requirements stated by Eurocode 1993-1-8 that declares the following: the moment capacity of welded tubular T-joints must be restricted by properties of either brace or chord, but not by resistance of the weld.

In Table 8 the experimental results were compared with theoretical values. Thus, the experimental plastic resistances $M_{pl.exp}$ were compared to the theoretical moment resistances based on the chord face failure $M_{ip,1,Rd}$, with and without k_{HSS}.

Table 8. Comparison of theoretical and experimental results.

Specimen	β	a_w/a_{wfs}	$M^*{}_{ip,1,Rd}/M_{pl.exp}$		$M_{ip,1,Rd}/M_{pl.exp}$	
$S1$	0.399	0.7854	1.1598	1.1449	0.928	0.9161
$S2$	0.399	0.8018	1.1339		0.9073	
$S3$	0.399	0.8649	1.1412		0.9131	
$M1$	0.655	0.8279	1.3806	1.4427	1.1045	1.1542
$M2$	0.655	0.8494	1.4409		1.1528	
$M3$	0.655	0.7031	1.5067		1.2054	

4.1 Discussion

The results of the comparative analysis show (Table 8) that by implementation of the safety factor for HSS of 0.8, moment resistance of the T-joints is underestimated. It is possible to increase the factor to 0.85 for S700 steel T-joint with brace-to-chord width ratio of 0.4-0.65.

Also, in tests S1-S3 the limiting factor was the chord properties, which failed first. The weld resistance has sufficient capacity, even without the implementation of the Eurocode provisions regarding the minimum throat thickness $1.65 \cdot t$. The test results allow to conclude that the factor 1.65 can be reduced to 1.15.

However, the tests M1-M3 have shown that the limiting factor for the specimens appeared to be the weld strength, even though ratio a_w/a_{wfs} remains at a range of 0.7-0.85. Basically, this can be explained in two ways. When β exceeds 0.65 in S700 steel, the weld should be at least $1.65 \cdot t$ or even thicker. Another alternative, which is likely true, is that these results can be explained by long cooling time of the welds, which affected the properties of the weld, which resulted in reduction of bearing capacity. Indeed, the first welds that failed were the ones with a longer cooling time.

5 CONCLUSION

This result of the thesis confirms that the development of more precise design methods for HSS joints is required. The reduction factor k_{HSS}, and the throat thickness of full-strength fillet weld $t \cdot 1.65$ $[mm]$ should be reconsidered.

According to the theoretical estimation and experimental measuring the cooling time plays a significant role in performance of the weld. By using a thermographic camera, better performance was observed in the welds which have a shorter cooling time duration. Therefore, it confirms the idea that shorter cooling time gives less time for the crystal structure to transform. Also, heat input and welding speed are two factors, which affect the material's properties afterwards. This aspect turns to be a corner stone of the proper weld performance and must be properly controlled during welding and considered in the design procedures.

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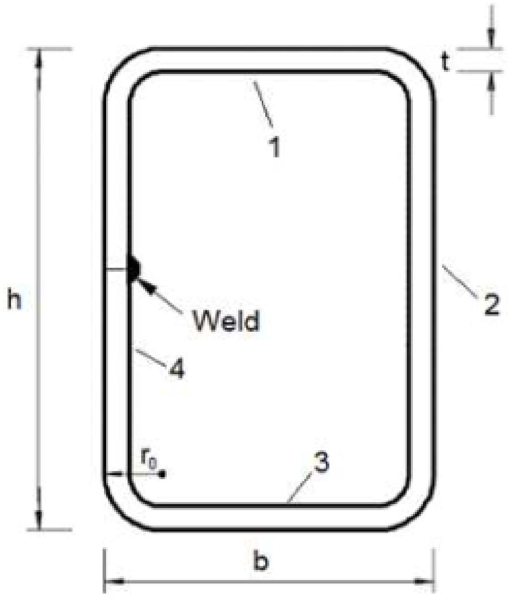
Appendix 1

Sample calculations

Specimen S1

Brace 60x60x4



$t_{1.b} := 3.973\ mm$	*thickness of upper (compressed) flange [brace]*
$t_{2.b} := 3.967\ mm$	*thickness of the right web [brace]*
$t_{3.b} := 3.984\ mm$	*thickness of lower (under tensile) flange [brace]*
$t_{4.b} := t_{2.b} = 3.967\ mm$	*thickness of the left web [brace]*
$b_{1.b} := 60.244\ mm$	*width of upper (compressed) flange [brace]*
$b_{3.b} := 60.133\ mm$	*width of lower (under tensile) flange [brace]*
$h_{2.b} := 60.039\ mm$	*height of right web [brace]*
$h_{4.b} := 60.167\ mm$	*height of left web [brace]*

$t_b := min\left(t_{1.b}, t_{2.b}, t_{3.b}, t_{4.b}\right) = 3.967\ mm$	*design brace thickness*
$b_b := min\left(b_{1.b}, b_{3.b}\right) = 60.133\ mm$	*design brace width*
$h_b := min\left(h_{2.b}, h_{4.b}\right) = 60.039\ mm$	*design brace height*

Chord 150x150x6

$t_{1.ch} := 5.884\ mm$	*thickness of upper (compressed) flange [chord]*
$t_{2.ch} := 5.896\ mm$	*thickness of the right web [chord]*
$t_{3.ch} := 5.836\ mm$	*thickness of lower (under tensile) flange [chord]*
$t_{4.ch} := t_{2.ch} = 5.896\ mm$	*thickness of the left web [chord]*
$b_{1.ch} := 150.82\ mm$	*width of upper (compressed) flange [chord]*
$b_{3.ch} := 150.909\ mm$	*width of lower (under tensile) flange [chord]*
$h_{2.ch} := 150.684\ mm$	*height of right web [chord]*
$h_{4.ch} := 150.646\ mm$	*height of left web [chord]*

$t_{ch} := min\left(t_{1.ch}, t_{2.ch}, t_{3.ch}, t_{4.ch}\right) = 5.836\ mm$	*design chord thickness*
$b_{ch} := min\left(b_{1.ch}, b_{3.ch}\right) = 150.82\ mm$	*design chord width*
$h_{ch} := min\left(h_{2.ch}, h_{4.ch}\right) = 150.646\ mm$	*design chord height*

Factors

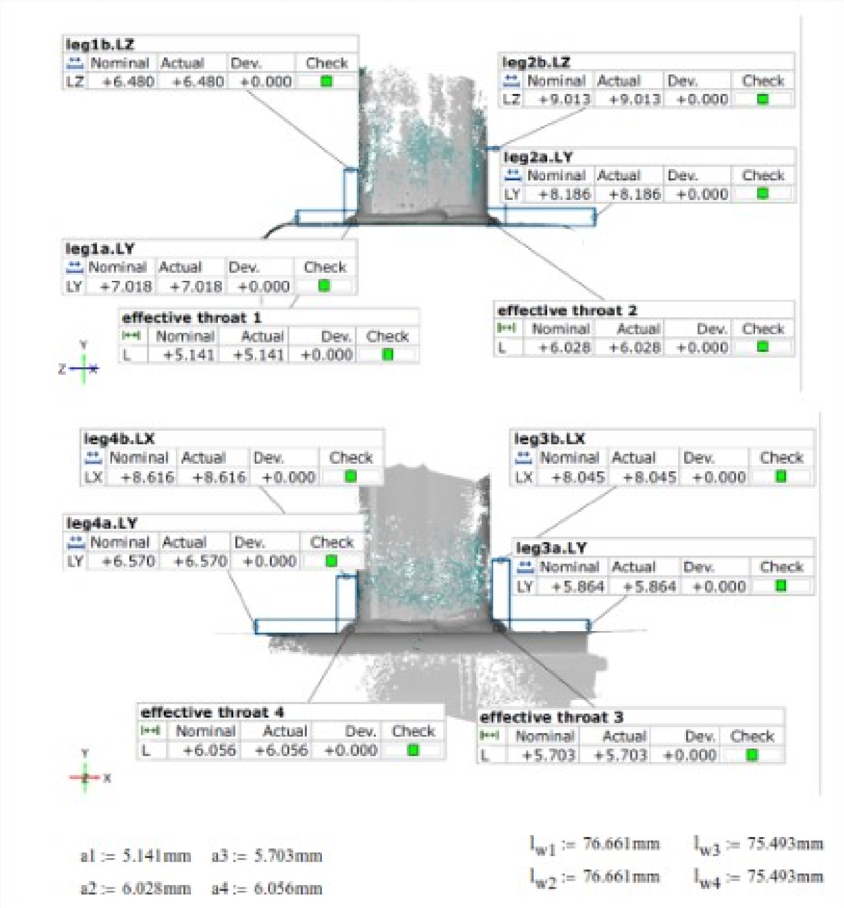
$k_{HSS} := 0.8$	*HSS reduction factor*	$\beta := \frac{b_b}{h_{ch}} = 0.399$	*brace to chord width ratio*
$\gamma_{M0} := 1$		$\eta := \frac{h_b}{b_{ch}} = 0.398$	*brace width to chord height ratio*
$\gamma_{M2} := 1.25$	*partial safety factors*	$k_n := 1$	*chord stress function*
$\gamma_{M5} := 1$			

$L_0 := 700\ mm$	*tube height*
$f_{y.ch} := \frac{769}{\gamma_{M2}} \frac{N}{mm^2} = 615.2\ \frac{N}{mm^2}$	*design yield strength*
$f_u := \frac{850}{\gamma_{M2}} \frac{N}{mm^2} = 680\ \frac{N}{mm^2}$	*design ultimate strength*

$L_{la} := 705\ mm$ *tube length*

$$f_{y.b} := \frac{734}{\gamma_{M2}} \frac{N}{mm^2} = 587.2\ \frac{N}{mm^2}$$ *yield strength*

Weld



$a_1 := 5.141\ mm$ *effective throat thickness (left vertical)*

$a_2 := 6.028\ mm$ *effective throat thickness (right vertical)*

$a_3 := 5.703\ mm$ *effective throat thickness (top horizontal)*

$a_4 := 6.056\ mm$ *effective throat thickness (bottom horizontal)*

$l_1 := 76.661\ mm$ *weld length (left vertical)*

$l_2 := 76.661\ mm$ *weld length (right vertical)*

$l_3 := 75.493\ mm$ *weld length (top horizontal)*

$l_4 := 75.493\ mm$ *weld length (bottom horizontal)*

$\beta_w := 1$ *correlation factor*

Critical loading

$F := 18.63\ kN$ *force acting on contiliver end*

$M_{Ed} := F \cdot L_{la} = 13.134\ kN \cdot m$ *moment*

Moment resistance based on chord face failure
Theoretical

With coefficient

$$M_{ip.1.Rd.theoretical.wk} := k_n \cdot f_{y.ch} \cdot k_{HSS} \cdot t_{ch}^{\ 2} \cdot h_b \cdot \frac{\left(\frac{1}{2 \cdot \eta} + \frac{2}{\sqrt{1-\beta}} + \frac{\eta}{1-\beta}\right)}{\gamma_{M5}} = 4.528\ kN \cdot m$$

Without coefficient

$$M_{ip.1.Rd.theoretical.nk} := k_n \cdot f_{y.ch} \cdot t_{ch}^{\ 2} \cdot h_b \cdot \frac{\left(\frac{1}{2 \cdot \eta} + \frac{2}{\sqrt{1-\beta}} + \frac{\eta}{1-\beta}\right)}{\gamma_{M5}} = 5.659\ kN \cdot m$$

Moment resistance based on fillet weld failure
According to Eurocode

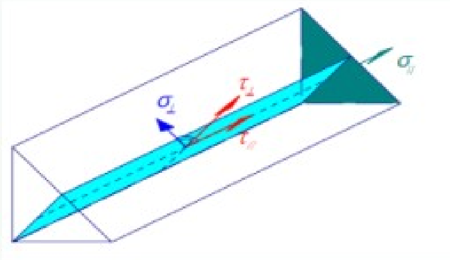
$a_{wfs} := 1.65 \cdot t_b = 6.546\ mm$ *design throat thickness*

$l_{weld1} := min\left(l_1, l_2, l_3, l_4\right) = 75.493\ mm$ *design length of the weld*

$$\sigma_{perp1} := \frac{M_{Ed}}{a_{wfs} \cdot b_b \cdot (h_b - t_b)} = 595.11 \ \frac{N}{mm^2}$$

$$\tau_{perp1} := \sigma_{perp1} = 595.11 \ \frac{N}{mm^2}$$

$$\tau_{paral1} := \frac{F}{2 \cdot a_{wfs} \cdot l_{weld1}} = 18.851 \ \frac{N}{mm^2}$$



$$\sigma_w := \frac{f_u}{\gamma_{M2} \cdot \beta_w} = 544 \ \frac{N}{mm^2} \qquad \sqrt{\tau_{paral1}^{\ 2} + 3 \cdot \left(\tau_{perp1}^{\ 2} + \sigma_{perp1}^{\ 2}\right)} = \left(1.458 \cdot 10^3\right) \ \frac{N}{mm^2}$$

$$M_{fw.N.Rd1} := \frac{1}{\sqrt{2}} \cdot a_{wfs} \cdot b_b \cdot (h_b - t_b) \cdot \frac{f_u}{\gamma_{M2}} = 8.49 \ kN \cdot m$$ *moment resistance (axial loading)*

$$M_{fw.S.Rd1} := \frac{2}{\sqrt{3}} \cdot a_{wfs} \cdot h_b \cdot \frac{f_u}{\gamma_{M2}} \cdot L_{la} = 174.035 \ kN \cdot m$$ *moment resistance (shear loading)*

$$M_{w.Rd.theoretical.wk} := min\left(M_{fw.N.Rd1}, M_{fw.S.Rd1}\right) = 8.49 \ kN \cdot m$$

<u>Moment resistance based on fillet weld failure</u>
Testing

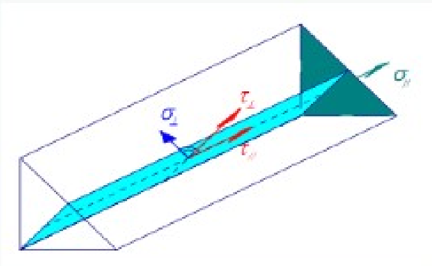
$a_{weld1} := 5.141 \ mm$ *throat thickness of the failed weld*

$l_{weld2} := 76.661 \ mm$ *length of the failed weld*

$$\sigma_{perp2} := \frac{M_{Ed}}{a_{weld1} \cdot b_b \cdot (h_b - t_b)} = 757.697 \ \frac{N}{mm^2}$$

$$\tau_{perp2} := \sigma_{perp2} = 757.697 \ \frac{N}{mm^2}$$

$$\tau_{paral2} := \frac{F}{2 \cdot a_{weld1} \cdot l_{weld2}} = 23.635 \ \frac{N}{mm^2}$$



$$\sigma_w := \frac{f_u}{\gamma_{M2} \cdot \beta_w} = 544 \ \frac{N}{mm^2} \qquad \sqrt{\tau_{paral2}^{\ 2} + 3 \cdot \left(\tau_{perp2}^{\ 2} + \sigma_{perp2}^{\ 2}\right)} = \left(1.856 \cdot 10^3\right) \ \frac{N}{mm^2}$$

$$M_{fw.N.Rd2} := \frac{1}{\sqrt{2}} \cdot a_{weld1} \cdot b_b \cdot (h_b - t_b) \cdot \frac{f_u}{\gamma_{M2}} = 6.668 \ kN \cdot m$$

moment resistance (axial loading)

$$M_{fw.S.Rd2} := \frac{2}{\sqrt{3}} \cdot a_{weld1} \cdot h_b \cdot \frac{f_u}{\gamma_{M2}} \cdot L_{la} = 136.691 \ kN \cdot m$$

moment resistance (shear loading)

$$M_{w.Rd.theoretical.nk} := min\left(M_{fw.N.Rd2}, M_{fw.S.Rd2}\right) = 6.668 \ kN \cdot m$$

Moment resistance of the joint

Theoretical

$$M_{j.Rd.wk} := min\left(M_{ip.1.Rd.theoretical.wk}, M_{w.Rd.theoretical.wk}\right) = 4.528 \ kN \cdot m$$

$$M_{j.Rd.nk} := min\left(M_{ip.1.Rd.theoretical.nk}, M_{w.Rd.theoretical.nk}\right) = 5.659 \ kN \cdot m$$

Heat Affected Zone

$\varepsilon := 0.85$ — *thermal effieciency coefficient*

$F_2 := 0.9$

$F_3 := 0.9$

welding geometry factors

$U_1 := 23.2 \ V$	$U_2 := 23.5 \ V$	$U_3 := 23.4 \ V$	$U_4 := 22.7 \ V$	*voltage*
$I_1 := 220.2 \ A$	$I_2 := 221.1 \ A$	$I_3 := 221.6 \ A$	$I_4 := 221.6 \ A$	*electric current*
$t_{1.b} := 3.973 \ mm$	$t_{2.b} := 3.967 \ mm$	$t_{3.b} := 3.984 \ mm$	$t_{4.b} := t_{2.b} = 3.967 \ mm$	*plate thickness*
$t_1 := 12.2 \ s$	$t_2 := 8.9 \ s$	$t_3 := 10.4 \ s$	$t_4 := 11 \ s$	*time*

$T_p := 20 \ °C$ — *preheating temperature*

$$v_1 := \frac{l_1}{t_1} = 6.284 \ \frac{mm}{s}$$

welding speed 1

$$v_2 := \frac{l_2}{t_2} = 8.614 \ \frac{mm}{s}$$

welding speed 2

$$v_3 := \frac{l_3}{t_3} = 7.259 \ \frac{mm}{s}$$

welding speed 3

$v_4 := \frac{l_4}{t_4} = 6.863\ \frac{mm}{s}$ *welding speed 4*

$Q_1 := \varepsilon \cdot U_1 \cdot \frac{I_1}{v_1 \cdot 1000} = 0.691\ \frac{J}{mm}$ *effective heat input 1*

$Q_2 := \varepsilon \cdot U_2 \cdot \frac{I_2}{v_2 \cdot 1000} = 0.513\ \frac{J}{mm}$ *effective heat input 2*

$Q_3 := \varepsilon \cdot U_3 \cdot \frac{I_3}{v_3 \cdot 1000} = 0.607\ \frac{J}{mm}$ *effective heat input 3*

$Q_4 := \varepsilon \cdot U_4 \cdot \frac{I_4}{v_4 \cdot 1000} = 0.623\ \frac{J}{mm}$ *effective heat input 4*

Calculated cooling time

Weld 1

$$t_{8.5.1} := (6700\ °C - 5 \cdot T_p) \cdot Q_1 \cdot \left(\frac{1}{(500\ °C - T_p)} - \frac{1}{(800\ °C - T_p)} \right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 27.446\ s$$

$$t_{8.5.2} := (4300\ °C - 4.3 \cdot T_p) \cdot 10^5 \cdot \frac{Q_1^{\ 2}}{t_{1.b}^{\ 2}} \cdot \left(\frac{1}{(500\ °C - T_p)^2} - \frac{1}{(800\ °C - T_p)^2} \right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 24.323\ s$$

$t_{8.5.1} := \max(t_{8.5.1}, t_{8.5.2}) = 27.446\ s$ **real number: 32 sec**

Weld 2

$$t_{8.5.1} := (6700\ °C - 5 \cdot T_p) \cdot Q_2 \cdot \left(\frac{1}{(500\ °C - T_p)} - \frac{1}{(800\ °C - T_p)} \right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 20.364\ s$$

$$t_{8.5.2} := (4300\ °C - 4.3 \cdot T_p) \cdot 10^5 \cdot \frac{Q_2^{\ 2}}{t_{2.b}^{\ 2}} \cdot \left(\frac{1}{(500\ °C - T_p)^2} - \frac{1}{(800\ °C - T_p)^2} \right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 13.43\ s$$

$t_{8.5.2} := \max(t_{8.5.1}, t_{8.5.2}) = 20.364\ s$

Weld 3

$$t_{8.5.1} := (6700\ °C - 5 \cdot T_p) \cdot Q_3 \cdot \left(\frac{1}{(500\ °C - T_p)} - \frac{1}{(800\ °C - T_p)} \right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 24.116\ s$$

$$t_{8.5.2} := (4300\ °C - 4.3 \cdot T_p) \cdot 10^5 \cdot \frac{{Q_3}^2}{{t_{3.b}}^2} \cdot \left(\frac{1}{(500\ °C - T_p)^2} - \frac{1}{(800\ °C - T_p)^2} \right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 18.675\ s$$

$$t_{8.5.3} := \max\left(t_{8.5.1}, t_{8.5.2}\right) = 24.116\ s$$

Weld 4

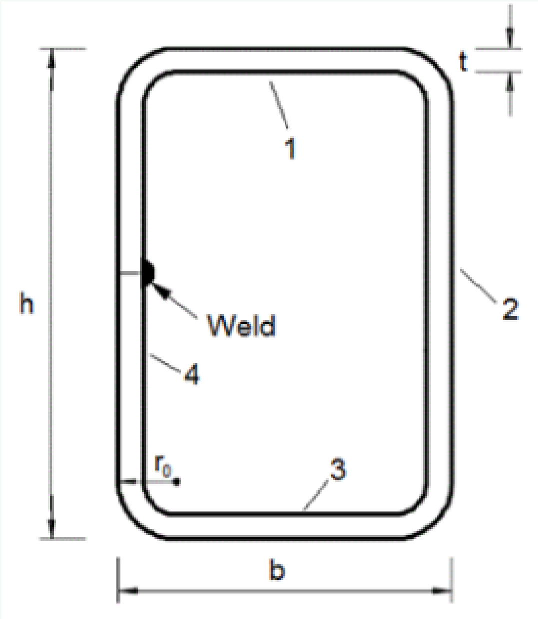
$$t_{8.5.1} := (6700\ °C - 5 \cdot T_p) \cdot Q_4 \cdot \left(\frac{1}{(500\ °C - T_p)} - \frac{1}{(800\ °C - T_p)} \right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 24.744\ s$$

$$t_{8.5.2} := (4300\ °C - 4.3 \cdot T_p) \cdot 10^5 \cdot \frac{{Q_4}^2}{{t_{4.b}}^2} \cdot \left(\frac{1}{(500\ °C - T_p)^2} - \frac{1}{(800\ °C - T_p)^2} \right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 19.829\ s$$

$$t_{8.5.4} := \max\left(t_{8.5.1}, t_{8.5.2}\right) = 24.744\ s$$

Specimen S2

Brace 60x60x4



$t_{1.b} := 3.973\ mm$ — *thickness of upper (compressed) flange [brace]*

$t_{2.b} := 3.967\ mm$ — *thickness of the right web [brace]*

$t_{3.b} := 3.984\ mm$ — *thickness of lower (under tensile) flange [brace]*

$t_{4.b} := t_{2.b} = 3.967\ mm$ — *thickness of the left web [brace]*

$b_{1.b} := 60.244\ mm$ — *width of upper (compressed) flange [brace]*

$b_{3.b} := 60.133\ mm$ — *width of lower (under tensile) flange [brace]*

$h_{2.b} := 60.039\ mm$ — *height of right web [brace]*

$h_{4.b} := 60.167\ mm$ — *height of left web [brace]*

$t_b := min\left(t_{1.b}, t_{2.b}, t_{3.b}, t_{4.b}\right) = 3.967\ mm$ — *design brace thickness*

$b_b := min\left(b_{1.b}, b_{3.b}\right) = 60.133\ mm$ — *design brace width*

$h_b := min\left(h_{2.b}, h_{4.b}\right) = 60.039\ mm$ — *design brace height*

Chord 150x150x6

$t_{1.ch} := 5.884\ mm$	*thickness of upper (compressed) flange [chord]*
$t_{2.ch} := 5.896\ mm$	*thickness of the right web [chord]*
$t_{3.ch} := 5.836\ mm$	*thickness of lower (under tensile) flange [chord]*
$t_{4.ch} := t_{2.ch} = 5.896\ mm$	*thickness of the left web [chord]*
$b_{1.ch} := 150.82\ mm$	*width of upper (compressed) flange [chord]*
$b_{3.ch} := 150.909\ mm$	*width of lower (under tensile) flange [chord]*
$h_{2.ch} := 150.684\ mm$	*height of right web [chord]*
$h_{4.ch} := 150.646\ mm$	*height of left web [chord]*
$t_{ch} := min\left(t_{1.ch}, t_{2.ch}, t_{3.ch}, t_{4.ch}\right) = 5.836\ mm$	*design chord thickness*
$b_{ch} := min\left(b_{1.ch}, b_{3.ch}\right) = 150.82\ mm$	*design chord width*
$h_{ch} := min\left(h_{2.ch}, h_{4.ch}\right) = 150.646\ mm$	*design chord height*

Factors

$k_{HSS} := 0.8$	*HSS reduction factor*	$\beta := \dfrac{b_b}{h_{ch}} = 0.399$	*brace to chord width ratio*
$\gamma_{M0} := 1$		$\eta := \dfrac{h_b}{b_{ch}} = 0.398$	*brace width to chord height ratio*
$\gamma_{M2} := 1.25$	*partial safety factors*	$k_n := 1$	*chord stress function*
$\gamma_{M5} := 1$			

$L_0 := 700\ mm$	*tube height*
$f_{y.ch} := \dfrac{769}{\gamma_{M2}} \dfrac{N}{mm^2} = 615.2\ \dfrac{N}{mm^2}$	*yield strength*
$f_u := \dfrac{850}{\gamma_{M2}} \dfrac{N}{mm^2} = 680\ \dfrac{N}{mm^2}$	*ultimate strength*
$L_{la} := 705\ mm$	*tube length*

$f_{y.b} := \frac{734}{\gamma_{M2}} \frac{N}{mm^2} = 587.2 \frac{N}{mm^2}$ *yield strength*

Weld

$a_1 := 5.249\ mm$	*effective throat thickness (left vertical)*
$a_2 := 6.028\ mm$	*effective throat thickness (right vertical)*
$a_3 := 5.703\ mm$	*effective throat thickness (top horizontal)*
$a_4 := 6.056\ mm$	*effective throat thickness (bottom horizontal)*
$l_1 := 72\ mm$	*weld length (left vertical)*
$l_2 := 70\ mm$	*weld length (right vertical)*
$l_3 := 80\ mm$	*weld length (top horizontal)*
$l_4 := 75\ mm$	*weld length (bottom horizontal)*
$\beta_w := 1$	*correlation factor*

Critical loading

$F := 17.67\ kN$ *force acting on contiliver end*

$M_{Ed} := F \cdot L_{la} = 12.457\ kN \cdot m$ *moment*

Moment resistance based on chord face failure

Theoretical

With coefficient

$$M_{ip.1.Rd.theoretical.wk} := k_n \cdot f_{y.ch} \cdot k_{HSS} \cdot t_{ch}^{\ 2} \cdot h_b \cdot \frac{\left(\frac{1}{2 \cdot \eta} + \frac{2}{\sqrt{1-\beta}} + \frac{\eta}{1-\beta}\right)}{\gamma_{M5}} = 4.528\ kN \cdot m$$

Without coefficient

$$M_{ip.1.Rd.theoretical.nk} := k_n \cdot f_{y.ch} \cdot t_{ch}^{\ 2} \cdot h_b \cdot \frac{\left(\frac{1}{2 \cdot \eta} + \frac{2}{\sqrt{1-\beta}} + \frac{\eta}{1-\beta}\right)}{\gamma_{M5}} = 5.659\ kN \cdot m$$

Moment resistance based on fillet weld failure
Theoretical

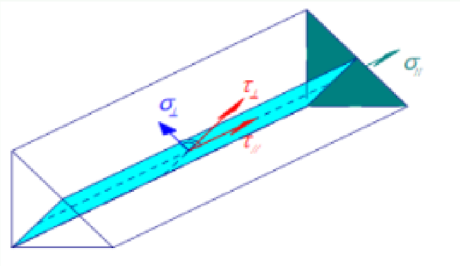
$a_{wfs} := 1.65 \cdot t_b = 6.546\ mm$ *design throat thickness*

$l_{weld1} := min(l_1, l_2, l_3, l_4) = 70\ mm$ *design length of the weld*

$$\sigma_{perp1} := \frac{M_{Ed}}{a_{wfs} \cdot b_b \cdot (h_b - t_b)} = 564.444\ \frac{N}{mm^2}$$

$$\tau_{perp1} := \sigma_{perp1} = 564.444\ \frac{N}{mm^2}$$

$$\tau_{paral1} := \frac{F}{2 \cdot a_{wfs} \cdot l_{weld1}} = 19.282\ \frac{N}{mm^2}$$



$$\sigma_w := \frac{f_u}{\gamma_{M2} \cdot \beta_w} = 544\ \frac{N}{mm^2}$$

$$\sqrt{\tau_{paral1}^2 + 3 \cdot (\tau_{perp1}^2 + \sigma_{perp1}^2)} = (1.383 \cdot 10^3)\ \frac{N}{mm^2}$$

$$M_{fw.N.Rd1} := \frac{1}{\sqrt{2}} \cdot a_{wfs} \cdot b_b \cdot (h_b - t_b) \cdot \frac{f_u}{\gamma_{M2}} = 8.49\ kN \cdot m$$ *moment resistance (axial loading)*

$$M_{fw.S.Rd1} := \frac{2}{\sqrt{3}} \cdot a_{wfs} \cdot h_b \cdot \frac{f_u}{\gamma_{M2}} \cdot L_{la} = 174.035\ kN \cdot m$$ *moment resistance (shear loading)*

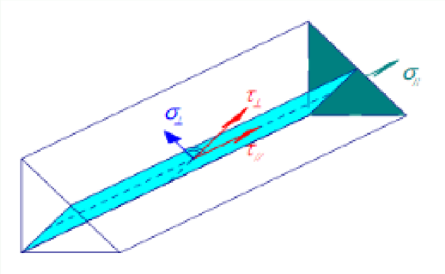
$$M_{w.Rd.theoretical.wk} := min(M_{fw.N.Rd1}, M_{fw.S.Rd1}) = 8.49\ kN \cdot m$$

Moment resistance based on fillet weld failure
Testing

$a_{weld1} := 5.249\ mm$ + *throat thickness of the failed weld*

$l_{weld2} := 76.661\ mm$ *length of the failed weld*

$$\sigma_{perp2} := \frac{M_{Ed}}{a_{weld1} \cdot b_b \cdot (h_b - t_b)} = 703.866\ \frac{N}{mm^2}$$



$$\tau_{perp2} := \sigma_{perp2} = 703.866 \ \frac{N}{mm^2}$$

$$\tau_{paral2} := \frac{F}{2 \cdot a_{weld1} \cdot l_{weld2}} = 21.956 \ \frac{N}{mm^2}$$

$$\sigma_w := \frac{f_u}{\gamma_{M2} \cdot \beta_w} = 544 \ \frac{N}{mm^2} \qquad \sqrt{\tau_{paral2}^{\ 2} + 3 \cdot \left(\tau_{perp2}^{\ 2} + \sigma_{perp2}^{\ 2}\right)} = \left(1.724 \cdot 10^3\right) \ \frac{N}{mm^2}$$

$$M_{fw.N.Rd2} := \frac{1}{\sqrt{2}} \cdot a_{weld1} \cdot b_b \cdot \left(h_b - t_b\right) \cdot \frac{f_u}{\gamma_{M2}} = 6.808 \ kN \cdot m$$ *moment resistance (axial loading)*

$$M_{fw.S.Rd2} := \frac{2}{\sqrt{3}} \cdot a_{weld1} \cdot h_b \cdot \frac{f_u}{\gamma_{M2}} \cdot L_{la} = 139.562 \ kN \cdot m$$ *moment resistance (shear loading)*

$$M_{w.Rd.theoretical.nk} := min\left(M_{fw.N.Rd2}, M_{fw.S.Rd2}\right) = 6.808 \ kN \cdot m$$

Moment resistance of the joint
Theoretical

$$M_{j.Rd.wk} := min\left(M_{ip.1.Rd.theoretical.wk}, M_{w.Rd.theoretical.wk}\right) = 4.528 \ kN \cdot m$$

$$M_{j.Rd.nk} := min\left(M_{ip.1.Rd.theoretical.nk}, M_{w.Rd.theoretical.nk}\right) = 5.659 \ kN \cdot m$$

Heat Affected Zone

$\varepsilon := 0.85$ — *thermal effieciency coefficient*

$F_2 := 0.9$

$F_3 := 0.9$

welding geometry factors

$U_1 := 21.6 \ V$	$U_2 := 21.8 \ V$	$U_3 := 22.5 \ V$	$U_4 := 22.4 \ V$	*voltage*
$I_1 := 204.7 \ A$	$I_2 := 207.6 \ A$	$I_3 := 213.3 \ A$	$I_4 := 217.5 \ A$	*electric current*
$t_{1.b} := 3.973 \ mm$	$t_{2.b} := 3.967 \ mm$	$t_{3.b} := 3.984 \ mm$	$t_{4.b} := t_{2.b} = 3.967 \ mm$	*plate thickness*

$t_1 := 11.4\ s$ $t_2 := 10.5\ s$ $t_3 := 11.2\ s$ $t_4 := 11\ s$ *time*

$T_p := 20\ °C$ *preheating temperature*

$v_1 := \frac{l_1}{t_1} = 6.316\ \frac{mm}{s}$ *welding speed 1*

$v_2 := \frac{l_2}{t_2} = 6.667\ \frac{mm}{s}$ *welding speed 2*

$v_3 := \frac{l_3}{t_3} = 7.143\ \frac{mm}{s}$ *welding speed 3*

$v_4 := \frac{l_4}{t_4} = 6.818\ \frac{mm}{s}$ *welding speed 4*

$Q_1 := \varepsilon \cdot U_1 \cdot \frac{I_1}{v_1 \cdot 1000} = 0.595\ \frac{J}{mm}$ *effective heat input 1*

$Q_2 := \varepsilon \cdot U_2 \cdot \frac{I_2}{v_2 \cdot 1000} = 0.577\ \frac{J}{mm}$ *effective heat input 2*

$Q_3 := \varepsilon \cdot U_3 \cdot \frac{I_3}{v_3 \cdot 1000} = 0.571\ \frac{J}{mm}$ *effective heat input 3*

$Q_4 := \varepsilon \cdot U_4 \cdot \frac{I_4}{v_4 \cdot 1000} = 0.607\ \frac{J}{mm}$ *effective heat input 4*

Calculated cooling time

Weld 1

$$t_{8.5.1} := \left(6700\ °C - 5 \cdot T_p\right) \cdot Q_1 \cdot \left(\frac{1}{\left(500\ °C - T_p\right)} - \frac{1}{\left(800\ °C - T_p\right)}\right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 23.634\ s$$

$$t_{8.5.2} := \left(4300\ °C - 4.3 \cdot T_p\right) \cdot 10^5 \cdot \frac{{Q_1}^2}{{t_{1.b}}^2} \cdot \left(\frac{1}{\left(500\ °C - T_p\right)^2} - \frac{1}{\left(800\ °C - T_p\right)^2}\right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 18.035\ s$$

$$t_{8.5.1} := \max\left(t_{8.5.1}, t_{8.5.2}\right) = 23.634\ s$$

Weld 2

$$t_{8.5.1} := \left(6700\ °C - 5 \cdot T_p\right) \cdot Q_2 \cdot \left(\frac{1}{\left(500\ °C - T_p\right)} - \frac{1}{\left(800\ °C - T_p\right)}\right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 22.918\ s$$

$$t_{8.5.2} := \left(4300\ °C - 4.3 \cdot T_p\right) \cdot 10^5 \cdot \frac{{Q_2}^2}{{t_{2.b}}^2} \cdot \left(\frac{1}{\left(500\ °C - T_p\right)^2} - \frac{1}{\left(800\ °C - T_p\right)^2}\right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 17.01\ s$$

$$t_{8.5.2} := \max\left(t_{8.5.1}, t_{8.5.2}\right) = 22.918\ s$$

Weld 3

$$t_{8.5.1} := \left(6700\ °C - 5 \cdot T_p\right) \cdot Q_3 \cdot \left(\frac{1}{\left(500\ °C - T_p\right)} - \frac{1}{\left(800\ °C - T_p\right)}\right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 22.683\ s$$

$$t_{8.5.2} := \left(4300\ °C - 4.3 \cdot T_p\right) \cdot 10^5 \cdot \frac{{Q_3}^2}{{t_{3.b}}^2} \cdot \left(\frac{1}{\left(500\ °C - T_p\right)^2} - \frac{1}{\left(800\ °C - T_p\right)^2}\right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 16.521\ s$$

$$t_{8.5.3} := \max\left(t_{8.5.1}, t_{8.5.2}\right) = 22.683\ s$$

Weld 4

$$t_{8.5.1} := \left(6700\ °C - 5 \cdot T_p\right) \cdot Q_4 \cdot \left(\frac{1}{\left(500\ °C - T_p\right)} - \frac{1}{\left(800\ °C - T_p\right)}\right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 24.123\ s$$

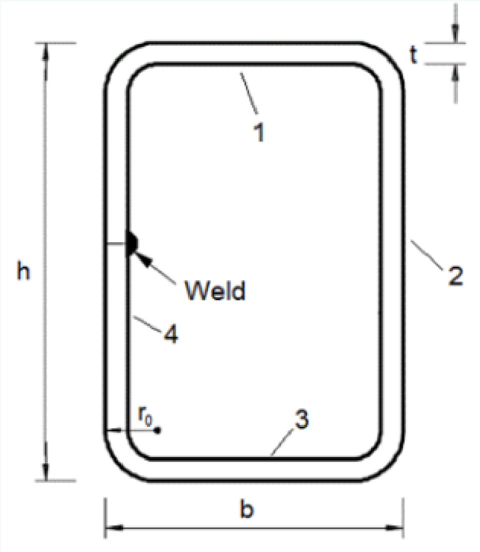
$$t_{8.5.2} := \left(4300\ °C - 4.3 \cdot T_p\right) \cdot 10^5 \cdot \frac{{Q_4}^2}{{t_{4.b}}^2} \cdot \left(\frac{1}{\left(500\ °C - T_p\right)^2} - \frac{1}{\left(800\ °C - T_p\right)^2}\right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 18.846\ s$$

$$t_{8.5.4} := \max\left(t_{8.5.1}, t_{8.5.2}\right) = 24.123\ s$$

real number: 25sec

Specimen S3

Brace 60x60x4



$t_{1.b} := 3.973\ mm$ *thickness of upper (compressed) flange [brace]*

$t_{2.b} := 3.967\ mm$ *thickness of the right web [brace]*

$t_{3.b} := 3.984\ mm$ *thickness of lower (under tensile) flange [brace]*

$t_{4.b} := t_{2.b} = 3.967\ mm$ *thickness of the left web [brace]*

$b_{1.b} := 60.244\ mm$ *width of upper (compressed) flange [brace]*

$b_{3.b} := 60.133\ mm$ *width of lower (under tensile) flange [brace]*

$h_{2.b} := 60.039\ mm$ *height of right web [brace]*

$h_{4.b} := 60.167\ mm$ *height of left web [brace]*

$t_b := min\left(t_{1.b}, t_{2.b}, t_{3.b}, t_{4.b}\right) = 3.967\ mm$ *design brace thickness*

$b_b := min\left(b_{1.b}, b_{3.b}\right) = 60.133\ mm$ *design brace width*

$h_b := min\left(h_{2.b}, h_{4.b}\right) = 60.039\ mm$ *design brace height*

Chord 150x150x6

$t_{1.ch} := 5.884\ mm$	*thickness of upper (compressed) flange [chord]*
$t_{2.ch} := 5.896\ mm$	*thickness of the right web [chord]*
$t_{3.ch} := 5.836\ mm$	*thickness of lower (under tensile) flange [chord]*
$t_{4.ch} := t_{2.ch} = 5.896\ mm$	*thickness of the left web [chord]*
$b_{1.ch} := 150.82\ mm$	*width of upper (compressed) flange [chord]*
$b_{3.ch} := 150.909\ mm$	*width of lower (under tensile) flange [chord]*
$h_{2.ch} := 150.684\ mm$	*height of right web [chord]*
$h_{4.ch} := 150.646\ mm$	*height of left web [chord]*

$t_{ch} := min\left(t_{1.ch}, t_{2.ch}, t_{3.ch}, t_{4.ch}\right) = 5.836\ mm$	*design chord thickness*
$b_{ch} := min\left(b_{1.ch}, b_{3.ch}\right) = 150.82\ mm$	*design chord width*
$h_{ch} := min\left(h_{2.ch}, h_{4.ch}\right) = 150.646\ mm$	*design chord height*

Factors

$k_{HSS} := 0.8$	*HSS reduction factor*	$\beta := \frac{b_b}{h_{ch}} = 0.399$	*brace to chord width ratio*
$\gamma_{M2} := 1.25$		$\eta := \frac{h_b}{b_{ch}} = 0.398$	*brace width to chord height ratio*
$\gamma_{M0} := 1$	*partial safety factors*	$k_n := 1$	*chord stress function*
$\gamma_{M5} := 1$			

$L_0 := 700\ mm$	*tube height*
$f_{y.ch} := \frac{769}{\gamma_{M2}} \frac{N}{mm^2} = 615.2\ \frac{N}{mm^2}$	*yield strength*
$f_u := \frac{850}{\gamma_{M2}} \frac{N}{mm^2} = 680\ \frac{N}{mm^2}$	*ultimate strength*

$L_{la} := 705\ mm$ *tube length*

$$f_{y.b} := \frac{734}{\gamma_{M2}} \frac{N}{mm^2} = 587.2\ \frac{N}{mm^2}$$ *yield strength*

Weld

$a_1 := 5.357\ mm$ *effective throat thickness (left vertical)*

$a_2 := 4.412\ mm$ *effective throat thickness (right vertical)*

$a_3 := 5.662\ mm$ *effective throat thickness (top horizontal)*

$a_4 := 4.801\ mm$ *effective throat thickness (bottom horizontal)*

$l_1 := 75.52\ mm$ *weld length (left vertical)*

$l_2 := 75.52\ mm$ *weld length (right vertical)*

$l_3 := 75.93\ mm$ *weld length (top horizontal)*

$l_4 := 75.93\ mm$ *weld length (bottom horizontal)*

$\beta_w := 1$ *correlation factor*

Critical loading

$F := 15.43\ kN$ *force acting on contiliver end*

$M_{Ed} := F \cdot L_{la} = 10.878\ kN \cdot m$ *moment*

Moment resistance based on chord face failure
Theoretical

With coefficient

$$M_{ip.1.Rd.theoretical.wk} := k_n \cdot f_{y.ch} \cdot k_{HSS} \cdot t_{ch}^{\ 2} \cdot h_b \cdot \frac{\left(\frac{1}{2 \cdot \eta} + \frac{2}{\sqrt{1-\beta}} + \frac{\eta}{1-\beta}\right)}{\gamma_{M5}} = 4.528\ kN \cdot m$$

Without coefficient

$$M_{ip.1.Rd.theoretical.nk} := k_n \cdot f_{y.ch} \cdot t_{ch}^{\ 2} \cdot h_b \cdot \frac{\left(\frac{1}{2 \cdot \eta} + \frac{2}{\sqrt{1-\beta}} + \frac{\eta}{1-\beta}\right)}{\gamma_{M5}} = 5.659\ kN \cdot m$$

Moment resistance based on fillet weld failure
Theoretical

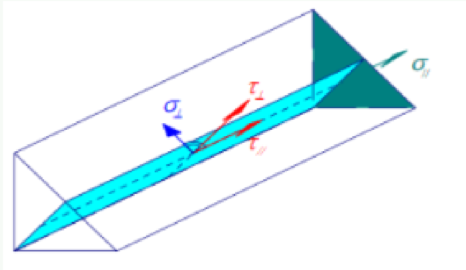
$a_{wfs} := 1.65 \cdot t_b = 6.546\ mm$ *design throat thickness*

$l_{weld1} := min\left(l_1, l_2, l_3, l_4\right) = 75.52\ mm$ *design length of the weld*

$$\sigma_{perp1} := \frac{M_{Ed}}{a_{wfs} \cdot b_b \cdot (h_b - t_b)} = 492.89 \ \frac{N}{mm^2}$$

$$\tau_{perp1} := \sigma_{perp1} = 492.89 \ \frac{N}{mm^2}$$

$$\tau_{paral1} := \frac{F}{2 \cdot a_{wfs} \cdot l_{weld1}} = 15.607 \ \frac{N}{mm^2}$$



$$\sigma_w := \frac{f_u}{\gamma_{M2} \cdot \beta_w} = 544 \ \frac{N}{mm^2} \qquad \sqrt{\tau_{paral1}{}^2 + 3 \cdot \left(\tau_{perp1}{}^2 + \sigma_{perp1}{}^2\right)} = \left(1.207 \cdot 10^3\right) \ \frac{N}{mm^2}$$

$$M_{fw.N.Rd1} := \frac{1}{\sqrt{2}} \cdot a_{wfs} \cdot b_b \cdot (h_b - t_b) \cdot \frac{f_u}{\gamma_{M2}} = 8.49 \ kN \cdot m$$

moment resistance (axial loading)

$$M_{fw.S.Rd1} := \frac{2}{\sqrt{3}} \cdot a_{wfs} \cdot h_b \cdot \frac{f_u}{\gamma_{M2}} \cdot L_{la} = 174.035 \ kN \cdot m$$

moment resistance (shear loading)

$$M_{w.Rd.theoretical.wk} := min\left(M_{fw.N.Rd1}, M_{fw.S.Rd1}\right) = 8.49 \ kN \cdot m$$

Moment resistance based on fillet weld failure
Testing

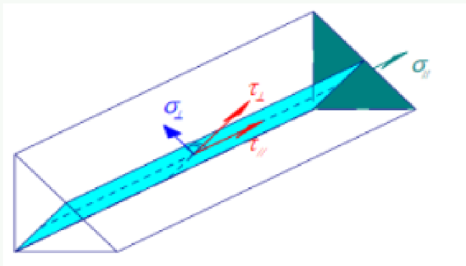
$a_{weld1} := 5.662 \ mm$ *throat thickness of the failed weld*

$l_{weld2} := 75.93 \ mm$ *length of the failed weld*

$$\sigma_{perp2} := \frac{M_{Ed}}{a_{weld1} \cdot b_b \cdot (h_b - t_b)} = 569.805 \ \frac{N}{mm^2}$$

$$\tau_{perp2} := \sigma_{perp2} = 569.805 \ \frac{N}{mm^2}$$

$$\tau_{paral2} := \frac{F}{2 \cdot a_{weld1} \cdot l_{weld2}} = 17.945 \ \frac{N}{mm^2}$$



$$\sigma_w := \frac{f_u}{\gamma_{M2} \cdot \beta_w} = 544 \ \frac{N}{mm^2} \qquad \sqrt{\tau_{paral2}{}^2 + 3 \cdot \left(\tau_{perp2}{}^2 + \sigma_{perp2}{}^2\right)} = \left(1.396 \cdot 10^3\right) \ \frac{N}{mm^2}$$

$$M_{fw.N.Rd2} := \frac{1}{\sqrt{2}} \cdot a_{weld1} \cdot b_b \cdot (h_b - t_b) \cdot \frac{f_u}{\gamma_{M2}} = 7.344 \ kN \cdot m$$

moment resistance (axial loading)

$$M_{fw.S.Rd2} := \frac{2}{\sqrt{3}} \cdot a_{weld1} \cdot h_b \cdot \frac{f_u}{\gamma_{M2}} \cdot L_{la} = 150.543 \ kN \cdot m$$

moment resistance (shear loading)

$$M_{w.Rd.theoretical.nk} := min\left(M_{fw.N.Rd2}, M_{fw.S.Rd2}\right) = 7.344 \ kN \cdot m$$

Moment resistance of the joint
Theoretical

$$M_{j.Rd.1wk} := min\left(M_{ip.1.Rd.theoretical.wk}, M_{w.Rd.theoretical.wk}\right) = 4.528 \ kN \cdot m$$

$$M_{j.Rd.1nk} := min\left(M_{ip.1.Rd.theoretical.nk}, M_{w.Rd.theoretical.nk}\right) = 5.659 \ kN \cdot m$$

Heat Affected Zone

$\varepsilon := 0.85$ — *thermal effiecency coefficient*

$F_2 := 0.9$

$F_3 := 0.9$

welding geometry factors

$U_1 := 23.5 \ V$	$U_2 := 23.2 \ V$	$U_3 := 32.2 \ V$	$U_4 := 23.4 \ V$	*voltage*
$I_1 := 224.7 \ A$	$I_2 := 225.7 \ A$	$I_3 := 219.6 \ A$	$I_4 := 222.2 \ A$	*electric current*
$t_{1.b} := 3.973 \ mm$	$t_{2.b} := 3.967 \ mm$	$t_{3.b} := 3.984 \ mm$	$t_{4.b} := t_{2.b} = 3.967 \ mm$	*plate thickness*
$t_1 := 10.5 \ s$	$t_2 := 10.5 \ s$	$t_3 := 10.5 \ s$	$t_4 := 10.5 \ s$	*time*

$T_p := 20 \ °C$ — *preheating temperature*

$v_1 := \frac{l_1}{t_1} = 7.192 \ \frac{mm}{s}$ — *welding speed 1*

$v_2 := \frac{l_2}{t_2} = 7.192 \ \frac{mm}{s}$ — *welding speed 2*

$v_3 := \frac{l_3}{t_3} = 7.231 \ \frac{mm}{s}$ — *welding speed 3*

$$v_4 := \frac{l_4}{t_4} = 7.231\ \frac{mm}{s}$$ *welding speed 4*

$$Q_1 := \varepsilon \cdot U_1 \cdot \frac{I_1}{v_1 \cdot 1000} = 0.624\ \frac{J}{mm}$$ *effective heat input 1*

$$Q_2 := \varepsilon \cdot U_2 \cdot \frac{I_2}{v_2 \cdot 1000} = 0.619\ \frac{J}{mm}$$ *effective heat input 2*

$$Q_3 := \varepsilon \cdot U_3 \cdot \frac{I_3}{v_3 \cdot 1000} = 0.831\ \frac{J}{mm}$$ *effective heat input 3*

$$Q_4 := \varepsilon \cdot U_4 \cdot \frac{I_4}{v_4 \cdot 1000} = 0.611\ \frac{J}{mm}$$ *effective heat input 4*

<u>Calculated cooling time</u>

Weld 1

$$t_{8.5.1} := \left(6700\ °C - 5 \cdot T_p\right) \cdot Q_1 \cdot \left(\frac{1}{\left(500\ °C - T_p\right)} - \frac{1}{\left(800\ °C - T_p\right)}\right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 24.785\ s$$

$$t_{8.5.2} := \left(4300\ °C - 4.3 \cdot T_p\right) \cdot 10^5 \cdot \frac{{Q_1}^2}{{t_{1.b}}^2} \cdot \left(\frac{1}{\left(500\ °C - T_p\right)^2} - \frac{1}{\left(800\ °C - T_p\right)^2}\right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 19.835\ s$$

$$t_{8.5.1} := \max\left(t_{8.5.1}, t_{8.5.2}\right) = 24.785\ s$$

Weld 2

$$t_{8.5.1} := \left(6700\ °C - 5 \cdot T_p\right) \cdot Q_2 \cdot \left(\frac{1}{\left(500\ °C - T_p\right)} - \frac{1}{\left(800\ °C - T_p\right)}\right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 24.578\ s$$

$$t_{8.5.2} := \left(4300\ °C - 4.3 \cdot T_p\right) \cdot 10^5 \cdot \frac{{Q_2}^2}{{t_{2.b}}^2} \cdot \left(\frac{1}{\left(500\ °C - T_p\right)^2} - \frac{1}{\left(800\ °C - T_p\right)^2}\right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 19.563\ s$$

$$t_{8.5.2} := \max\left(t_{8.5.1}, t_{8.5.2}\right) = 24.578\ s$$

Weld 3

$$t_{8.5.1} := \left(6700\ °C - 5 \cdot T_p\right) \cdot Q_3 \cdot \left(\frac{1}{\left(500\ °C - T_p\right)} - \frac{1}{\left(800\ °C - T_p\right)}\right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 33.011\ s$$

$$t_{8.5.2} := \left(4300\ °C - 4.3 \cdot T_p\right) \cdot 10^5 \cdot \frac{{Q_3}^2}{{t_{3.b}}^2} \cdot \left(\frac{1}{\left(500\ °C - T_p\right)^2} - \frac{1}{\left(800\ °C - T_p\right)^2}\right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 34.991\ s$$

$$t_{8.5.3} := \max\left(t_{8.5.1}, t_{8.5.2}\right) = 34.991\ s$$

real number: 38 sec

Weld 4

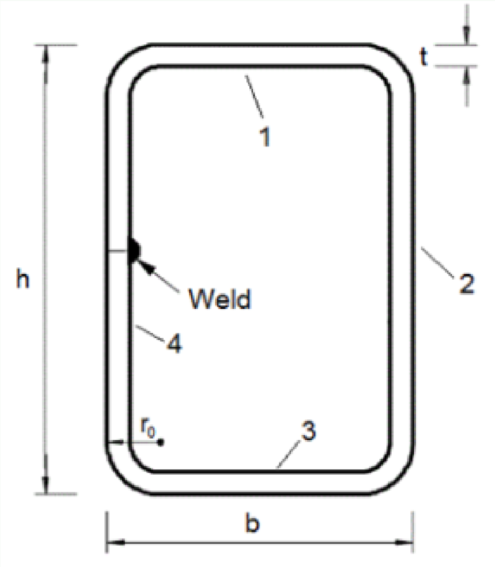
$$t_{8.5.1} := \left(6700\ °C - 5 \cdot T_p\right) \cdot Q_4 \cdot \left(\frac{1}{\left(500\ °C - T_p\right)} - \frac{1}{\left(800\ °C - T_p\right)}\right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 24.273\ s$$

$$t_{8.5.2} := \left(4300\ °C - 4.3 \cdot T_p\right) \cdot 10^5 \cdot \frac{{Q_4}^2}{{t_{4.b}}^2} \cdot \left(\frac{1}{\left(500\ °C - T_p\right)^2} - \frac{1}{\left(800\ °C - T_p\right)^2}\right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 19.082\ s$$

$$t_{8.5.4} := \max\left(t_{8.5.1}, t_{8.5.2}\right) = 24.273\ s$$

Specimen M1

Brace 80x80x5



$t_{1.b} := 4.885\ mm$ *thickness of upper (compressed) flange [brace]*

$t_{2.b} := 4.909\ mm$ *thickness of the right web [brace]*

$t_{3.b} := 4.902\ mm$ *thickness of lower (under tensile) flange [brace]*

$t_{4.b} := t_{2.b} = 4.909\ mm$ *thickness of the left web [brace]*

$b_{1.b} := 80.054\ mm$ *width of upper (compressed) flange [brace]*

$b_{3.b} := 80.107\ mm$ *width of lower (under tensile) flange [brace]*

$h_{2.b} := 80.313\ mm$ *height of right web [brace]*

$h_{4.b} := 79.969\ mm$ *height of left web [brace]*

$t_b := min\left(t_{1.b}, t_{2.b}, t_{3.b}, t_{4.b}\right) = 4.885\ mm$ *design brace thickness*

$b_b := min\left(b_{1.b}, b_{3.b}\right) = 80.054\ mm$ *design brace width*

$h_b := min\left(h_{2.b}, h_{4.b}\right) = 79.969\ mm$ *design brace height*

Chord 120x120x10

$t_{1.ch} := 9.795\ mm$	*thickness of upper (compressed) flange [chord]*
$t_{2.ch} := 9.771\ mm$	*thickness of the right web [chord]*
$t_{3.ch} := 9.895\ mm$	*thickness of lower (under tensile) flange [chord]*
$t_{4.ch} := t_{2.ch} = 9.771\ mm$	*thickness of the left web [chord]*
$b_{1.ch} := 120.846\ mm$	*width of upper (compressed) flange [chord]*
$b_{3.ch} := 120.867\ mm$	*width of lower (under tensile) flange [chord]*
$h_{2.ch} := 120.431\ mm$	*height of right web [chord]*
$h_{4.ch} := 120.435\ mm$	*height of left web [chord]*

$t_{ch} := min\left(t_{1.ch}, t_{2.ch}, t_{3.ch}, t_{4.ch}\right) = 9.771\ mm$	*design chord thickness*
$b_{ch} := min\left(b_{1.ch}, b_{3.ch}\right) = 120.846\ mm$	*design chord width*
$h_{ch} := min\left(h_{2.ch}, h_{4.ch}\right) = 120.431\ mm$	*design chord height*

Factors

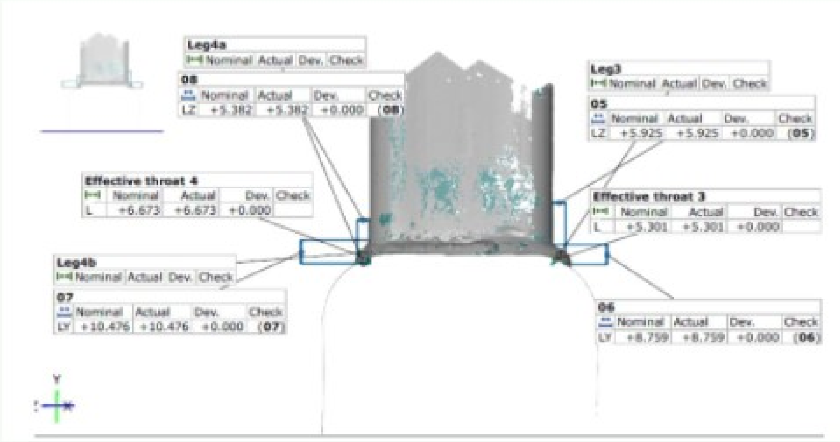
$k_{HSS} := 0.8$	*HSS reduction factor*	$\beta := \dfrac{b_b}{h_{ch}} = 0.665$	*brace to chord width ratio*
$\gamma_{M2} := 1.25$	*partial factor*	$\eta := \dfrac{h_b}{b_{ch}} = 0.662$	*brace width to chord height ratio*
$\gamma_{M0} := 1$		$k_n := 1$	*chord stress function*
$\gamma_{M5} := 1$			

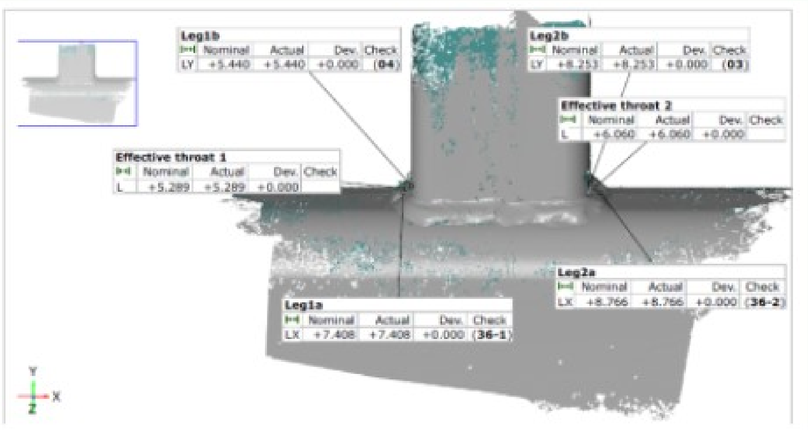
$L_0 := 700\ mm$	*tube height*
$f_{y.ch} := \dfrac{769}{\gamma_{M2}} \dfrac{N}{mm^2} = 615.2 \dfrac{N}{mm^2}$	*yield strength*
$f_u := \dfrac{850}{\gamma_{M2}} \dfrac{N}{mm^2} = 680 \dfrac{N}{mm^2}$	*ultimate strength*

$L_{la} := 705\ mm$ *tube length*

$f_{y.b} := \frac{734}{\gamma_{M2}} \frac{N}{mm^2} = 587.2\ \frac{N}{mm^2}$ *yield strength*

Weld





$a_1 := 6.673\ mm$ *effective throat thickness (left vertical)*

$a_2 := 5.301\ mm$ *effective throat thickness (right vertical)*

$a_3 := 6.06\ mm$ *effective throat thickness (top horizontal)*

$a_4 := 5.289\ mm$ *effective throat thickness (bottom horizontal)*

$l_1 := 93.693\ mm$ *weld length (left vertical)*

$l_2 := 93.693\ mm$ *weld length (right vertical)*

$l_3 := 91.307\ mm$ *weld length (top horizontal)*

$l_4 := 91.307\ mm$ *weld length (bottom horizontal)*

$\beta_w := 1$ *correlation factor*

Critical loading

$F := 36.47\ kN$ *force acting on contiliver end*

$M_{Ed} := F \cdot L_{la} = 25.711\ kN \cdot m$ *moment*

Moment resistance based on chord face failure
Theoretical

With coefficient

$$M_{ip.1.Rd.theoretical.wk} := k_n \cdot f_{y.ch} \cdot k_{HSS} \cdot t_{ch}^{\ 2} \cdot h_b \cdot \frac{\left(\frac{1}{2 \cdot \eta} + \frac{2}{\sqrt{1-\beta}} + \frac{\eta}{1-\beta}\right)}{\gamma_{M5}} = 23.235\ kN \cdot m$$

Without coefficient

$$M_{ip.1.Rd.theoretical.nk} := k_n \cdot f_{y.ch} \cdot t_{ch}^{\ 2} \cdot h_b \cdot \frac{\left(\frac{1}{2 \cdot \eta} + \frac{2}{\sqrt{1-\beta}} + \frac{\eta}{1-\beta}\right)}{\gamma_{M5}} = 29.043\ kN \cdot m$$

Moment resistance based on fillet weld failure
Theoretical

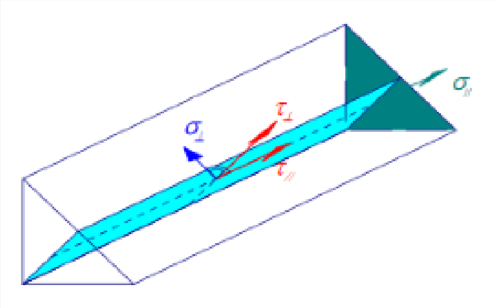
$a_{wfs} := 1.65 \cdot t_b = 8.06\ mm$ *design throat thickness*

$l_{weld1} := min\left(l_1, l_2, l_3, l_4\right) = 91.307\ mm$ *design length of the weld*

$$\sigma_{perp1} := \frac{M_{Ed}}{a_{wfs} \cdot b_b \cdot (h_b - t_b)} = 530.696 \ \frac{N}{mm^2}$$

$$\tau_{perp1} := \sigma_{perp1} = 530.696 \ \frac{N}{mm^2}$$

$$\tau_{paral1} := \frac{F}{2 \cdot a_{wfs} \cdot l_{weld1}} = 24.777 \ \frac{N}{mm^2}$$



$$\sigma_w := \frac{f_u}{\gamma_{M2} \cdot \beta_w} = 544 \ \frac{N}{mm^2} \qquad \sqrt{\tau_{paral1}^2 + 3 \cdot (\tau_{perp1}^2 + \sigma_{perp1}^2)} = (1.3 \cdot 10^3) \ \frac{N}{mm^2}$$

$$M_{fw.N.Rd1} := \frac{1}{\sqrt{2}} \cdot a_{wfs} \cdot b_b \cdot (h_b - t_b) \cdot \frac{f_u}{\gamma_{M2}} = 18.636 \ kN \cdot m$$ *moment resistance (axial loading)*

$$M_{fw.S.Rd1} := \frac{2}{\sqrt{3}} \cdot a_{wfs} \cdot h_b \cdot \frac{f_u}{\gamma_{M2}} \cdot L_{la} = 285.448 \ kN \cdot m$$ *moment resistance (shear loading)*

$$M_{w.Rd.theoretical.wk} := min(M_{fw.N.Rd1}, M_{fw.S.Rd1}) = 18.636 \ kN \cdot m$$

Moment resistance based on fillet weld failure
Testing

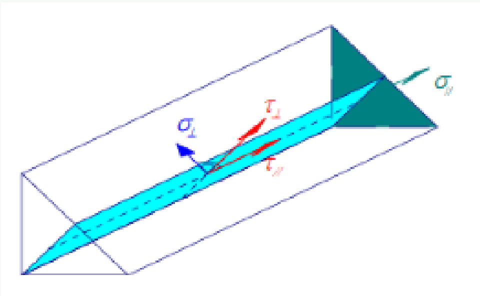
$a_{weld1} := 6.673 \ mm$ *throat thickness of the failed weld*

$l_{weld2} := 93.693 \ mm$ *length of the failed weld*

$$\sigma_{perp2} := \frac{M_{Ed}}{a_{weld1} \cdot b_b \cdot (h_b - t_b)} = 641.023 \ \frac{N}{mm^2}$$

$$\tau_{perp2} := \sigma_{perp2} = 641.023 \ \frac{N}{mm^2}$$

$$\tau_{paral2} := \frac{F}{2 \cdot a_{weld1} \cdot l_{weld2}} = 29.166 \ \frac{N}{mm^2}$$



$$\sigma_w := \frac{f_u}{\gamma_{M2} \cdot \beta_w} = 544 \ \frac{N}{mm^2} \qquad \sqrt{\tau_{paral2}^2 + 3 \cdot (\tau_{perp2}^2 + \sigma_{perp2}^2)} = (1.57 \cdot 10^3) \ \frac{N}{mm^2}$$

$$M_{fw.N.Rd2} := \frac{1}{\sqrt{2}} \cdot a_{weld1} \cdot b_b \cdot (h_b - t_b) \cdot \frac{f_u}{\gamma_{M2}} = 15.429 \ kN \cdot m$$ *moment resistance (axial loading)*

$M_{fw.S.Rd2} := \frac{2}{\sqrt{3}} \cdot a_{weld1} \cdot h_b \cdot \frac{f_u}{\gamma_{M2}} \cdot L_{la} = 236.32\ kN \cdot m$ *moment resistance (shear loading)*

$M_{w.Rd.theoretical.nk} := min\left(M_{fw.N.Rd2}, M_{fw.S.Rd2}\right) = 15.429\ kN \cdot m$

Moment resistance of the joint

Theoretical

$M_{j.Rd.1wk} := min\left(M_{ip.1.Rd.theoretical.wk}, M_{w.Rd.theoretical.wk}\right) = 18.636\ kN \cdot m$

$M_{j.Rd.1nk} := min\left(M_{ip.1.Rd.theoretical.nk}, M_{w.Rd.theoretical.nk}\right) = 15.429\ kN \cdot m$

Heat Affected Zone

$\varepsilon := 0.85$ *thermal effieciency coefficient*

$F_2 := 0.9$

$F_3 := 0.9$ *welding geometry factors*

$U_1 := 31.5\ V$	$U_2 := 30\ V$	$U_3 := 30.8\ V$	$U_4 := 31\ V$	*voltage*
$I_1 := 294.5\ A$	$I_2 := 278.2\ A$	$I_3 := 267.2\ A$	$I_4 := 281.8\ A$	*electric current*
$t_{1.b} := 3.973\ mm$	$t_{2.b} := 3.967\ mm$	$t_{3.b} := 3.984\ mm$	$t_{4.b} := t_{2.b} = 3.967\ mm$	*plate thickness*
$t_1 := 15.2\ s$	$t_2 := 14.7\ s$	$t_3 := 12.8\ s$	$t_4 := 12.9\ s$	*time*

$T_p := 20\ °C$ *preheating temperature*

$v_1 := \frac{l_1}{t_1} = 6.164\ \frac{mm}{s}$ *welding speed 1*

$v_2 := \frac{l_2}{t_2} = 6.374\ \frac{mm}{s}$ *welding speed 2*

$v_3 := \frac{l_3}{t_3} = 7.133\ \frac{mm}{s}$ *welding speed 3*

$$v_4 := \frac{l_4}{t_4} = 7.078\ \frac{mm}{s}$$ *welding speed 4*

$$Q_1 := \varepsilon \cdot U_1 \cdot \frac{I_1}{v_1 \cdot 1000} = 1.279\ \frac{J}{mm}$$ *effective heat input 1*

$$Q_2 := \varepsilon \cdot U_2 \cdot \frac{I_2}{v_2 \cdot 1000} = 1.113\ \frac{J}{mm}$$ *effective heat input 2*

$$Q_3 := \varepsilon \cdot U_3 \cdot \frac{I_3}{v_3 \cdot 1000} = 0.981\ \frac{J}{mm}$$ *effective heat input 3*

$$Q_4 := \varepsilon \cdot U_4 \cdot \frac{I_4}{v_4 \cdot 1000} = 1.049\ \frac{J}{mm}$$ *effective heat input 4*

Calculated cooling time

Weld 1

$$t_{8.5.1} := (6700\ °C - 5 \cdot T_p) \cdot Q_1 \cdot \left(\frac{1}{(500\ °C - T_p)} - \frac{1}{(800\ °C - T_p)} \right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 50.807\ s$$

$$t_{8.5.2} := (4300\ °C - 4.3 \cdot T_p) \cdot 10^5 \cdot \frac{Q_1^{\ 2}}{t_{1.b}^{\ 2}} \cdot \left(\frac{1}{(500\ °C - T_p)^2} - \frac{1}{(800\ °C - T_p)^2} \right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 83.348\ s$$

$$t_{8.5.1} := \max(t_{8.5.1}, t_{8.5.2}) = 83.348\ s$$ **real number: 85 sec**

Weld 2

$$t_{8.5.1} := (6700\ °C - 5 \cdot T_p) \cdot Q_2 \cdot \left(\frac{1}{(500\ °C - T_p)} - \frac{1}{(800\ °C - T_p)} \right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 44.206\ s$$

$$t_{8.5.2} := (4300\ °C - 4.3 \cdot T_p) \cdot 10^5 \cdot \frac{Q_2^{\ 2}}{t_{2.b}^{\ 2}} \cdot \left(\frac{1}{(500\ °C - T_p)^2} - \frac{1}{(800\ °C - T_p)^2} \right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 63.288\ s$$

$$t_{8.5.2} := \max(t_{8.5.1}, t_{8.5.2}) = 63.288\ s$$

Weld 3

$$t_{8.5.1} := (6700\ °C - 5 \cdot T_p) \cdot Q_3 \cdot \left(\frac{1}{(500\ °C - T_p)} - \frac{1}{(800\ °C - T_p)} \right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 38.948\ s$$

$$t_{8.5.2} := (4300\ °C - 4.3 \cdot T_p) \cdot 10^5 \cdot \frac{Q_3^{\,2}}{t_{3.b}^{\,2}} \cdot \left(\frac{1}{(500\ °C - T_p)^2} - \frac{1}{(800\ °C - T_p)^2} \right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 48.71\ s$$

$$t_{8.5.3} := \max(t_{8.5.1}, t_{8.5.2}) = 48.71\ s$$

Weld 4

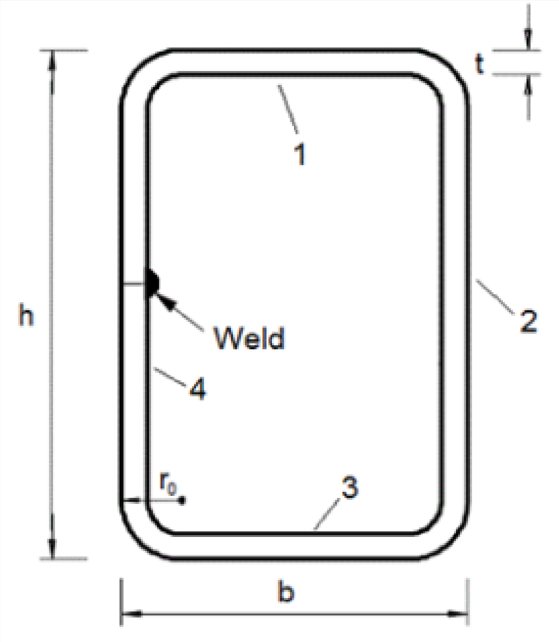
$$t_{8.5.1} := (6700\ °C - 5 \cdot T_p) \cdot Q_4 \cdot \left(\frac{1}{(500\ °C - T_p)} - \frac{1}{(800\ °C - T_p)} \right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 41.666\ s$$

$$t_{8.5.2} := (4300\ °C - 4.3 \cdot T_p) \cdot 10^5 \cdot \frac{Q_4^{\,2}}{t_{4.b}^{\,2}} \cdot \left(\frac{1}{(500\ °C - T_p)^2} - \frac{1}{(800\ °C - T_p)^2} \right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 56.224\ s$$

$$t_{8.5.4} := \max(t_{8.5.1}, t_{8.5.2}) = 56.224\ s$$

Specimen M2

Brace 80x80x5



$t_{1.b} := 4.885\ mm$ — *thickness of upper (compressed) flange [brace]*

$t_{2.b} := 4.909\ mm$ — *thickness of the right web [brace]*

$t_{3.b} := 4.902\ mm$ — *thickness of lower (under tensile) flange [brace]*

$t_{4.b} := t_{2.b} = 4.909\ mm$ — *thickness of the left web [brace]*

$b_{1.b} := 80.054\ mm$ — *width of upper (compressed) flange [brace]*

$b_{3.b} := 80.107\ mm$ — *width of lower (under tensile) flange [brace]*

$h_{2.b} := 80.313\ mm$ — *height of right web [brace]*

$h_{4.b} := 79.969\ mm$ — *height of left web [brace]*

$t_b := min\left(t_{1.b}, t_{2.b}, t_{3.b}, t_{4.b}\right) = 4.885\ mm$ — *design brace thickness*

$b_b := min\left(b_{1.b}, b_{3.b}\right) = 80.054\ mm$ — *design brace width*

$h_b := min\left(h_{2.b}, h_{4.b}\right) = 79.969\ mm$ — *design brace height*

Chord 120x120x10

$t_{1.ch} := 9.795\ mm$	*thickness of upper (compressed) flange [chord]*
$t_{2.ch} := 9.771\ mm$	*thickness of the right web [chord]*
$t_{3.ch} := 9.895\ mm$	*thickness of lower (under tensile) flange [chord]*
$t_{4.ch} := t_{2.ch} = 9.771\ mm$	*thickness of the left web [chord]*
$b_{1.ch} := 120.846\ mm$	*width of upper (compressed) flange [chord]*
$b_{3.ch} := 120.867\ mm$	*width of lower (under tensile) flange [chord]*
$h_{2.ch} := 120.431\ mm$	*height of right web [chord]*
$h_{4.ch} := 120.435\ mm$	*height of left web [chord]*

$t_{ch} := min\left(t_{1.ch}, t_{2.ch}, t_{3.ch}, t_{4.ch}\right) = 9.771\ mm$	*design chord thickness*
$b_{ch} := min\left(b_{1.ch}, b_{3.ch}\right) = 120.846\ mm$	*design chord width*
$h_{ch} := min\left(h_{2.ch}, h_{4.ch}\right) = 120.431\ mm$	*design chord height*

Factors

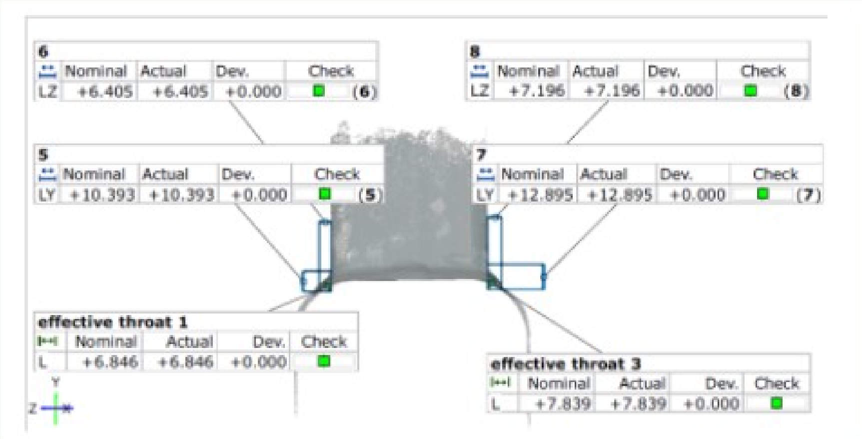
$k_{HSS} := 0.8$	*HSS reduction factor*	$\beta := \frac{b_b}{h_{ch}} = 0.665$	*brace to chord width ratio*
$\gamma_{M2} := 1.25$		$\eta := \frac{h_b}{b_{ch}} = 0.662$	*brace width to chord height ratio*
$\gamma_{M0} := 1$	*partial safetu factor*	$k_n := 1$	*chord stress function*
$\gamma_{M5} := 1$			

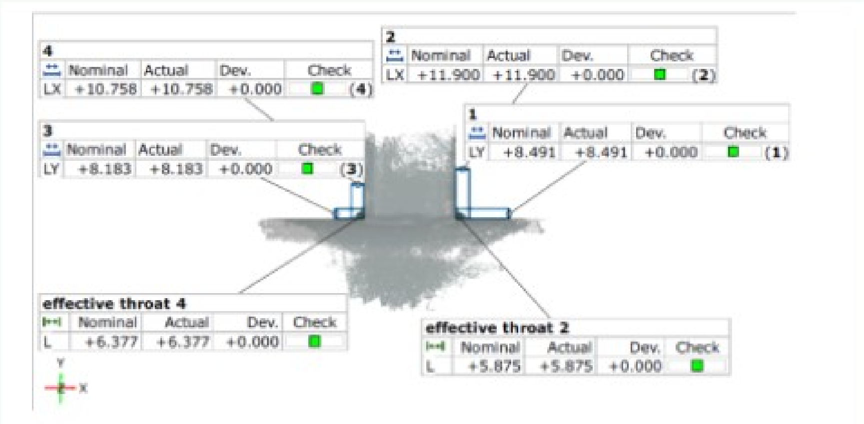
$L_0 := 700\ mm$	*tube height*
$f_{y.ch} := \frac{769}{\gamma_{M2}} \frac{N}{mm^2} = 615.2\ \frac{N}{mm^2}$	*yield strength*
$f_u := \frac{850}{\gamma_{M2}} \frac{N}{mm^2} = 680\ \frac{N}{mm^2}$	*ultimate strength*

$L_{la} := 705\ mm$ — *tube length*

$f_{y.b} := \frac{734}{\gamma_{M2}} \frac{N}{mm^2} = 587.2\ \frac{N}{mm^2}$ — *yield strength*

Weld





$a_1 := 6.846\ mm$ — *effective throat thickness (left vertical)*

$a_2 := 7.839\ mm$ — *effective throat thickness (right vertical)*

$a_3 := 6.337\ mm$ — *effective throat thickness (top horizontal)*

$a_4 := 5.875\ mm$ — *effective throat thickness (bottom horizontal)*

$l_1 := 102.658\ mm$ *weld length (left vertical)*

$l_2 := 102.658\ mm$ *weld length (right vertical)*

$l_3 := 93.601\ mm$ *weld length (top horizontal)*

$l_4 := 93.601\ mm$ *weld length (bottom horizontal)*

$\beta_w := 1$ *correlation factor*

Critical loading

$F := 36.06\ kN$ *force acting on contiliver end*

$M_{Ed} := F \cdot L_{la} = 25.422\ kN \cdot m$ *moment*

Moment resistance based on chord face failure
Theoretical

With coefficient

$$M_{ip.1.Rd.theoretical.wk} := k_n \cdot f_{y.ch} \cdot k_{HSS} \cdot t_{ch}^{\ 2} \cdot h_b \cdot \frac{\left(\frac{1}{2 \cdot \eta} + \frac{2}{\sqrt{1-\beta}} + \frac{\eta}{1-\beta}\right)}{\gamma_{M5}} = 23.235\ kN \cdot m$$

Without coefficient

$$M_{ip.1.Rd.theoretical.nk} := k_n \cdot f_{y.ch} \cdot t_{ch}^{\ 2} \cdot h_b \cdot \frac{\left(\frac{1}{2 \cdot \eta} + \frac{2}{\sqrt{1-\beta}} + \frac{\eta}{1-\beta}\right)}{\gamma_{M5}} = 29.043\ kN \cdot m$$

Moment resistance based on fillet weld failure
Theoretical

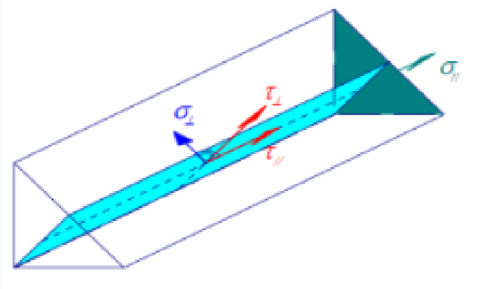
$a_{wfs} := 1.65 \cdot t_b = 8.06\ mm$ *design throat thickness*

$l_{weld1} := min\left(l_1, l_2, l_3, l_4\right) = 93.601\ mm$ *design length of the weld*

$$\sigma_{perp1} := \frac{M_{Ed}}{a_{wfs} \cdot b_b \cdot (h_b - t_b)} = 524.73 \ \frac{N}{mm^2}$$

$$\tau_{perp1} := \sigma_{perp1} = 524.73 \ \frac{N}{mm^2}$$

$$\tau_{paral1} := \frac{F}{2 \cdot a_{wfs} \cdot l_{weld1}} = 23.898 \ \frac{N}{mm^2}$$



$$\sigma_w := \frac{f_u}{\gamma_{M2} \cdot \beta_w} = 544 \ \frac{N}{mm^2} \qquad \sqrt{\tau_{paral1}{}^2 + 3 \cdot \left(\tau_{perp1}{}^2 + \sigma_{perp1}{}^2\right)} = \left(1.286 \cdot 10^3\right) \ \frac{N}{mm^2}$$

$$M_{fw.N.Rd1} := \frac{1}{\sqrt{2}} \cdot a_{wfs} \cdot b_b \cdot (h_b - t_b) \cdot \frac{f_u}{\gamma_{M2}} = 18.636 \ kN \cdot m$$ *moment resistance (axial loading)*

$$M_{fw.S.Rd1} := \frac{2}{\sqrt{3}} \cdot a_{wfs} \cdot h_b \cdot \frac{f_u}{\gamma_{M2}} \cdot L_{la} = 285.448 \ kN \cdot m$$ *moment resistance (shear loading)*

$$M_{w.Rd.theoretical.wk} := min\left(M_{fw.N.Rd1}, M_{fw.S.Rd1}\right) = 18.636 \ kN \cdot m$$

<u>Moment resistance based on fillet weld failure</u>
Testing

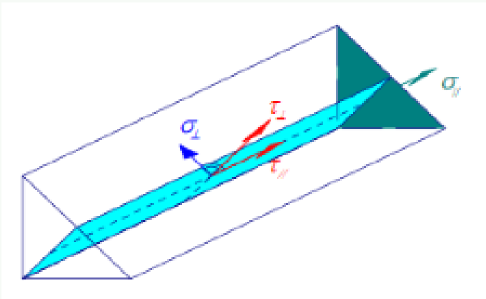
$a_{weld1} := 6.846 \ mm$ *throat thickness of the failed weld*

$l_{weld2} := 102.658 \ mm$ *length of the failed weld*

$$\sigma_{perp2} := \frac{M_{Ed}}{a_{weld1} \cdot b_b \cdot (h_b - t_b)} = 617.799 \ \frac{N}{mm^2}$$

$$\tau_{perp2} := \sigma_{perp2} = 617.799 \ \frac{N}{mm^2}$$

$$\tau_{paral2} := \frac{F}{2 \cdot a_{weld1} \cdot l_{weld2}} = 25.655 \ \frac{N}{mm^2}$$



$$\sigma_w := \frac{f_u}{\gamma_{M2} \cdot \beta_w} = 544 \ \frac{N}{mm^2} \qquad \sqrt{\tau_{paral2}{}^2 + 3 \cdot \left(\tau_{perp2}{}^2 + \sigma_{perp2}{}^2\right)} = \left(1.514 \cdot 10^3\right) \ \frac{N}{mm^2}$$

$$M_{fw.N.Rd2} := \frac{1}{\sqrt{2}} \cdot a_{weld1} \cdot b_b \cdot (h_b - t_b) \cdot \frac{f_u}{\gamma_{M2}} = 15.829 \ kN \cdot m$$

moment resistance (axial loading)

$$M_{fw.S.Rd2} := \frac{2}{\sqrt{3}} \cdot a_{weld1} \cdot h_b \cdot \frac{f_u}{\gamma_{M2}} \cdot L_{la} = 242.447 \ kN \cdot m$$

moment resistance (shear loading)

$$M_{w.Rd.theoretical.nk} := min(M_{fw.N.Rd2}, M_{fw.S.Rd2}) = 15.829 \ kN \cdot m$$

Moment resistance of the joint

Theoretical

$$M_{j.Rd.1wk} := min(M_{ip.1.Rd.theoretical.wk}, M_{w.Rd.theoretical.wk}) = 18.636 \ kN \cdot m$$

$$M_{j.Rd.1nk} := min(M_{ip.1.Rd.theoretical.nk}, M_{w.Rd.theoretical.nk}) = 15.829 \ kN \cdot m$$

Heat Affected Zone

$\varepsilon := 0.85$ — *thermal effieciency coefficient*

$F_2 := 0.9$

$F_3 := 0.9$ — *welding geometry factors*

$U_1 := 31.5 \ V$	$U_2 := 30 \ V$	$U_3 := 30.8 \ V$	$U_4 := 31 \ V$	*voltage*
$I_1 := 294.5 \ A$	$I_2 := 278.2 \ A$	$I_3 := 267.2 \ A$	$I_4 := 281.8 \ A$	*electric current*
$t_{1.b} := 3.973 \ mm$	$t_{2.b} := 3.967 \ mm$	$t_{3.b} := 3.984 \ mm$	$t_{4.b} := t_{2.b} = 3.967 \ mm$	*plate thickness*
$t_1 := 15.2 \ s$	$t_2 := 14.7 \ s$	$t_3 := 12.8 \ s$	$t_4 := 12.9 \ s$	*time*

$T_p := 20 \ °C$ — *preheating temperature*

$v_1 := \frac{l_1}{t_1} = 6.754 \ \frac{mm}{s}$ — *welding speed 1*

$v_2 := \frac{l_2}{t_2} = 6.984 \ \frac{mm}{s}$ — *welding speed 2*

$v_3 := \frac{l_3}{t_3} = 7.313 \ \frac{mm}{s}$ — *welding speed 3*

$v_4 := \frac{l_4}{t_4} = 7.256\ \frac{mm}{s}$ *welding speed 4*

$Q_1 := \varepsilon \cdot U_1 \cdot \frac{I_1}{v_1 \cdot 1000} = 1.168\ \frac{J}{mm}$ *effective heat input 1*

$Q_2 := \varepsilon \cdot U_2 \cdot \frac{I_2}{v_2 \cdot 1000} = 1.016\ \frac{J}{mm}$ *effective heat input 2*

$Q_3 := \varepsilon \cdot U_3 \cdot \frac{I_3}{v_3 \cdot 1000} = 0.957\ \frac{J}{mm}$ *effective heat input 3*

$Q_4 := \varepsilon \cdot U_4 \cdot \frac{I_4}{v_4 \cdot 1000} = 1.023\ \frac{J}{mm}$ *effective heat input 4*

Calculated cooling time

Weld 1

$$t_{8.5.1} := (6700\ °C - 5 \cdot T_p) \cdot Q_1 \cdot \left(\frac{1}{(500\ °C - T_p)} - \frac{1}{(800\ °C - T_p)}\right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 46.37\ s$$

$$t_{8.5.2} := (4300\ °C - 4.3 \cdot T_p) \cdot 10^5 \cdot \frac{{Q_1}^2}{{t_{1.b}}^2} \cdot \left(\frac{1}{(500\ °C - T_p)^2} - \frac{1}{(800\ °C - T_p)^2}\right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 69.427\ s$$

$t_{8.5.1} := \max(t_{8.5.1}, t_{8.5.2}) = 69.427\ s$ **real number: 76 sec**

Weld 2

$$t_{8.5.1} := (6700\ °C - 5 \cdot T_p) \cdot Q_2 \cdot \left(\frac{1}{(500\ °C - T_p)} - \frac{1}{(800\ °C - T_p)}\right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 40.346\ s$$

$$t_{8.5.2} := (4300\ °C - 4.3 \cdot T_p) \cdot 10^5 \cdot \frac{{Q_2}^2}{{t_{2.b}}^2} \cdot \left(\frac{1}{(500\ °C - T_p)^2} - \frac{1}{(800\ °C - T_p)^2}\right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 52.717\ s$$

$t_{8.5.2} := \max(t_{8.5.1}, t_{8.5.2}) = 52.717\ s$

Weld 3

$$t_{8.5.1} := (6700\ °C - 5 \cdot T_p) \cdot Q_3 \cdot \left(\frac{1}{(500\ °C - T_p)} - \frac{1}{(800\ °C - T_p)}\right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 37.994\ s$$

$$t_{8.5.2} := (4300\ °C - 4.3 \cdot T_p) \cdot 10^5 \cdot \frac{{Q_3}^2}{{t_{3.b}}^2} \cdot \left(\frac{1}{(500\ °C - T_p)^2} - \frac{1}{(800\ °C - T_p)^2}\right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 46.352\ s$$

$$t_{8.5.3} := \max\left(t_{8.5.1}, t_{8.5.2}\right) = 46.352\ s$$

Weld 4

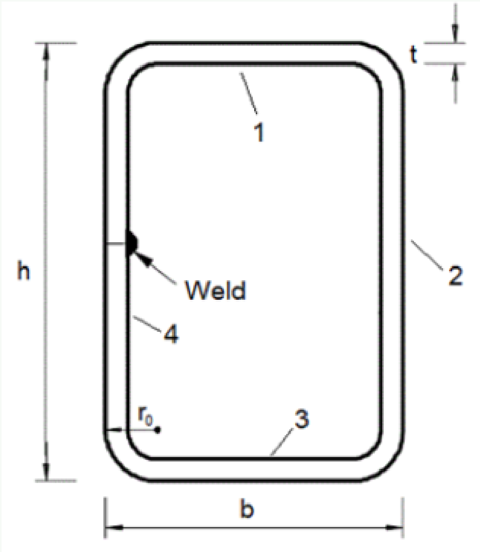
$$t_{8.5.1} := \left(6700\ °C - 5 \cdot T_p\right) \cdot Q_4 \cdot \left(\frac{1}{\left(500\ °C - T_p\right)} - \frac{1}{\left(800\ °C - T_p\right)}\right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 40.645\ s$$

$$t_{8.5.2} := \left(4300\ °C - 4.3 \cdot T_p\right) \cdot 10^5 \cdot \frac{{Q_4}^2}{{t_{4.b}}^2} \cdot \left(\frac{1}{\left(500\ °C - T_p\right)^2} - \frac{1}{\left(800\ °C - T_p\right)^2}\right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 53.502\ s$$

$$t_{8.5.4} := \max\left(t_{8.5.1}, t_{8.5.2}\right) = 53.502\ s$$

Specimen M3

Brace 80x80x5



$t_{1.b} := 4.885\ mm$	*thickness of upper (compressed) flange [brace]*
$t_{2.b} := 4.909\ mm$	*thickness of the right web [brace]*
$t_{3.b} := 4.902\ mm$	*thickness of lower (under tensile) flange [brace]*
$t_{4.b} := t_{2.b} = 4.909\ mm$	*thickness of the left web [brace]*
$b_{1.b} := 80.054\ mm$	*width of upper (compressed) flange [brace]*
$b_{3.b} := 80.107\ mm$	*width of lower (under tensile) flange [brace]*
$h_{2.b} := 80.313\ mm$	*height of right web [brace]*
$h_{4.b} := 79.969\ mm$	*height of left web [brace]*

$t_b := min(t_{1.b}, t_{2.b}, t_{3.b}, t_{4.b}) = 4.885\ mm$	*design brace thickness*
$b_b := min(b_{1.b}, b_{3.b}) = 80.054\ mm$	*design brace width*
$h_b := min(h_{2.b}, h_{4.b}) = 79.969\ mm$	*design brace height*

Chord 120x120x10

$t_{1.ch} := 9.795\ mm$ — *thickness of upper (compressed) flange [chord]*

$t_{2.ch} := 9.771\ mm$ — *thickness of the right web [chord]*

$t_{3.ch} := 9.895\ mm$ — *thickness of lower (under tensile) flange [chord]*

$t_{4.ch} := t_{2.ch} = 9.771\ mm$ — *thickness of the left web [chord]*

$b_{1.ch} := 120.846\ mm$ — *width of upper (compressed) flange [chord]*

$b_{3.ch} := 120.867\ mm$ — *width of lower (under tensile) flange [chord]*

$h_{2.ch} := 120.431\ mm$ — *height of right web [chord]*

$h_{4.ch} := 120.435\ mm$ — *height of left web [chord]*

$t_{ch} := min\left(t_{1.ch}, t_{2.ch}, t_{3.ch}, t_{4.ch}\right) = 9.771\ mm$ — *design chord thickness*

$b_{ch} := min\left(b_{1.ch}, b_{3.ch}\right) = 120.846\ mm$ — *design chord width*

$h_{ch} := min\left(h_{2.ch}, h_{4.ch}\right) = 120.431\ mm$ — *design chord height*

Factors

$k_{HSS} := 0.8$ — *HSS reduction factor*

$\beta := \frac{b_b}{h_{ch}} = 0.665$ — *brace to chord width ratio*

$\gamma_{M2} := 1.25$

$\eta := \frac{h_b}{b_{ch}} = 0.662$ — *brace width to chord height ratio*

$\gamma_{M0} := 1$ — *partial safety factors*

$k_n := 1$ — *chord stress function*

$\gamma_{M5} := 1$

$L_0 := 700\ mm$ — *tube height*

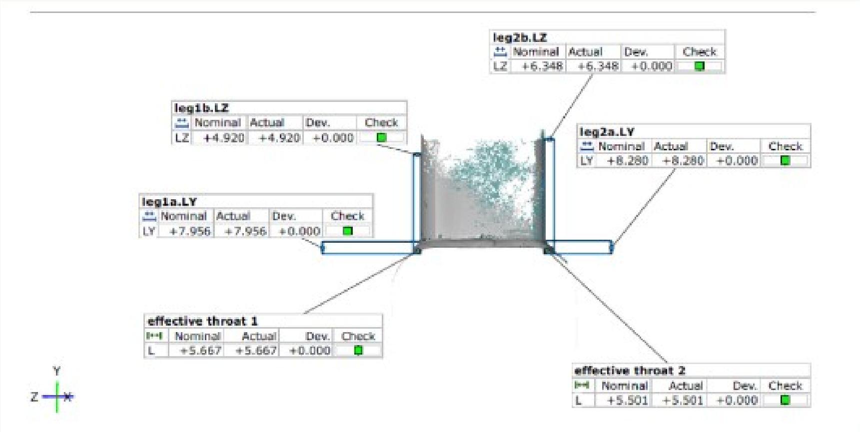
$f_{y.ch} := \frac{769}{\gamma_{M2}} \frac{N}{mm^2} = 615.2\ \frac{N}{mm^2}$ — *yield strength*

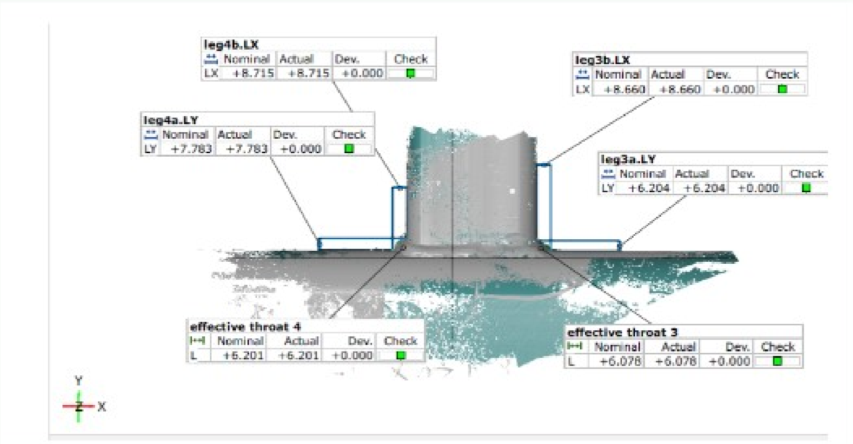
$f_u := \frac{850}{\gamma_{M2}} \frac{N}{mm^2} = 680\ \frac{N}{mm^2}$ — *ultimate strength*

$L_{la} := 705\ mm$ *tube length*

$f_{y.b} := \frac{734}{\gamma_{M2}} \frac{N}{mm^2} = 587.2\ \frac{N}{mm^2}$ *yield strength*

Weld





$a_1 := 5.667\ mm$ *effective throat thickness (left vertical)*

$a_2 := 5.501\ mm$ *effective throat thickness (right vertical)*

$a_3 := 6.078\ mm$ *effective throat thickness (top horizontal)*

$a_4 := 6.291\ mm$ *effective throat thickness (bottom horizontal)*

$l_1 := 97.375\ mm$ weld length (left vertical)

$l_2 := 97.375\ mm$ weld length (right vertical)

$l_3 := 93.2\ mm$ weld length (top horizontal)

$l_4 := 93.2\ mm$ weld length (bottom horizontal)

$\beta_w := 1$ correlation factor

Critical loading

$F := 36.18\ kN$ force acting on contiliver end

$M_{Ed} := F \cdot L_{la} = 25.507\ kN \cdot m$ moment

Moment resistance based on chord face failure
Theoretical
With coefficient

$$M_{ip.1.Rd.theoretical.wk} := k_n \cdot f_{y.ch} \cdot k_{HSS} \cdot t_{ch}^{\ 2} \cdot h_b \cdot \frac{\left(\frac{1}{2 \cdot \eta} + \frac{2}{\sqrt{1-\beta}} + \frac{\eta}{1-\beta}\right)}{\gamma_{M5}} = 23.235\ kN \cdot m$$

Without coefficient

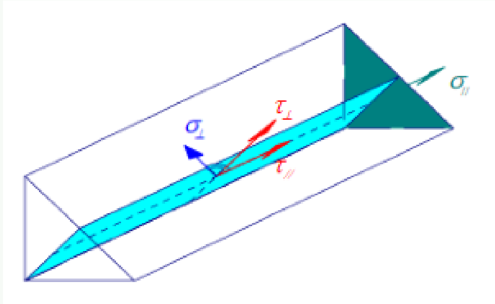
$$M_{ip.1.Rd.theoretical.nk} := k_n \cdot f_{y.ch} \cdot t_{ch}^{\ 2} \cdot h_b \cdot \frac{\left(\frac{1}{2 \cdot \eta} + \frac{2}{\sqrt{1-\beta}} + \frac{\eta}{1-\beta}\right)}{\gamma_{M5}} = 29.043\ kN \cdot m$$

Moment resistance based on fillet weld failure
Theoretical

$a_{wfs} := 1.65 \cdot t_b = 8.06\ mm$ design throat thickness

$l_{weld1} := min\left(l_1, l_2, l_3, l_4\right) = 93.2\ mm$ design length of the weld

$$\sigma_{perp1} := \frac{M_{Ed}}{a_{wfs} \cdot b_b \cdot (h_b - t_b)} = 526.476 \ \frac{N}{mm^2}$$



$$\tau_{perp1} := \sigma_{perp1} = 526.476 \ \frac{N}{mm^2}$$

$$\tau_{paral1} := \frac{F}{2 \cdot a_{wfs} \cdot l_{weld1}} = 24.081 \ \frac{N}{mm^2}$$

$$\sigma_w := \frac{f_u}{\gamma_{M2} \cdot \beta_w} = 544 \ \frac{N}{mm^2} \qquad \sqrt{\tau_{paral1}^{\ 2} + 3 \cdot \left(\tau_{perp1}^{\ 2} + \sigma_{perp1}^{\ 2}\right)} = \left(1.29 \cdot 10^3\right) \ \frac{N}{mm^2}$$

$$M_{fw.N.Rd1} := \frac{1}{\sqrt{2}} \cdot a_{wfs} \cdot b_b \cdot (h_b - t_b) \cdot \frac{f_u}{\gamma_{M2}} = 18.636 \ kN \cdot m$$

moment resistance (axial loading)

$$M_{fw.S.Rd1} := \frac{2}{\sqrt{3}} \cdot a_{wfs} \cdot h_b \cdot \frac{f_u}{\gamma_{M2}} \cdot L_{la} = 285.448 \ kN \cdot m$$

moment resistance (shear loading)

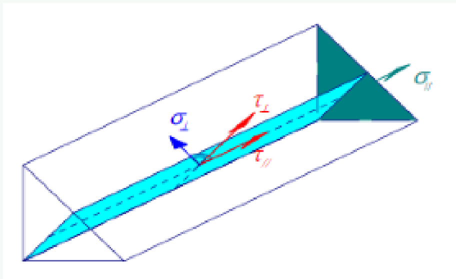
$$M_{w.Rd.theoretical.wk} := min\left(M_{fw.N.Rd1}, M_{fw.S.Rd1}\right) = 18.636 \ kN \cdot m$$

Moment resistance based on fillet weld failure
Testing

$a_{weld1} := 5.667 \ mm$ *throat thickness of the failed weld*

$l_{weld2} := 97.375 \ mm$ *length of the failed weld*

$$\sigma_{perp2} := \frac{M_{Ed}}{a_{weld1} \cdot b_b \cdot (h_b - t_b)} = 748.814 \ \frac{N}{mm^2}$$



$$\tau_{perp2} := \sigma_{perp2} = 748.814 \ \frac{N}{mm^2}$$

$$\tau_{paral2} := \frac{F}{2 \cdot a_{weld1} \cdot l_{weld2}} = 32.782 \ \frac{N}{mm^2}$$

$$\sigma_w := \frac{f_u}{\gamma_{M2} \cdot \beta_w} = 544 \ \frac{N}{mm^2} \qquad \sqrt{\tau_{paral2}^{\ 2} + 3 \cdot \left(\tau_{perp2}^{\ 2} + \sigma_{perp2}^{\ 2}\right)} = \left(1.835 \cdot 10^3\right) \ \frac{N}{mm^2}$$

$$M_{fw.N.Rd2} := \frac{1}{\sqrt{2}} \cdot a_{weld1} \cdot b_b \cdot (h_b - t_b) \cdot \frac{f_u}{\gamma_{M2}} = 13.103\ kN \cdot m$$

moment resistance (axial loading)

$$M_{fw.S.Rd2} := \frac{2}{\sqrt{3}} \cdot a_{weld1} \cdot h_b \cdot \frac{f_u}{\gamma_{M2}} \cdot L_{la} = 200.693\ kN \cdot m$$

moment resistance (shear loading)

$$M_{w.Rd.theoretical.nk} := min(M_{fw.N.Rd2}, M_{fw.S.Rd2}) = 13.103\ kN \cdot m$$

Moment resistance of the joint

Theoretical

$$M_{j.Rd.1wk} := min(M_{ip.1.Rd.theoretical.wk}, M_{w.Rd.theoretical.wk}) = 18.636\ kN \cdot m$$

$$M_{j.Rd.1nk} := min(M_{ip.1.Rd.theoretical.nk}, M_{w.Rd.theoretical.nk}) = 13.103\ kN \cdot m$$

Heat Affected Zone

$\varepsilon := 0.85$ — *thermal effieciency coefficient*

$F_2 := 0.9$

$F_3 := 0.9$

welding geometry factors

$U_1 := 31.5\ V$	$U_2 := 30\ V$	$U_3 := 30.8\ V$	$U_4 := 31\ V$	*voltage*
$I_1 := 294.5\ A$	$I_2 := 278.2\ A$	$I_3 := 267.2\ A$	$I_4 := 281.8\ A$	*electric current*
$t_{1.b} := 3.973\ mm$	$t_{2.b} := 3.967\ mm$	$t_{3.b} := 3.984\ mm$	$t_{4.b} := t_{2.b} = 3.967\ mm$	*plate thickness*
$t_1 := 15.2\ s$	$t_2 := 14.7\ s$	$t_3 := 12.8\ s$	$t_4 := 12.9\ s$	*time*

$T_p := 20\ °C$ — *preheating temperature*

$$v_1 := \frac{l_1}{t_1} = 6.406\ \frac{mm}{s}$$

welding speed 1

$$v_2 := \frac{l_2}{t_2} = 6.624\ \frac{mm}{s}$$

welding speed 2

$v_3 := \frac{l_3}{t_3} = 7.281 \frac{mm}{s}$ *welding speed 3*

$v_4 := \frac{l_4}{t_4} = 7.225 \frac{mm}{s}$ *welding speed 4*

$Q_1 := \varepsilon \cdot U_1 \cdot \frac{I_1}{v_1 \cdot 1000} = 1.231 \frac{J}{mm}$ *effective heat input 1*

$Q_2 := \varepsilon \cdot U_2 \cdot \frac{I_2}{v_2 \cdot 1000} = 1.071 \frac{J}{mm}$ *effective heat input 2*

$Q_3 := \varepsilon \cdot U_3 \cdot \frac{I_3}{v_3 \cdot 1000} = 0.961 \frac{J}{mm}$ *effective heat input 3*

$Q_4 := \varepsilon \cdot U_4 \cdot \frac{I_4}{v_4 \cdot 1000} = 1.028 \frac{J}{mm}$ *effective heat input 4*

Calculated cooling time

Weld 1

$$t_{8.5.1} := (6700\ °C - 5 \cdot T_p) \cdot Q_1 \cdot \left(\frac{1}{(500\ °C - T_p)} - \frac{1}{(800\ °C - T_p)} \right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 48.886\ s$$

$$t_{8.5.2} := (4300\ °C - 4.3 \cdot T_p) \cdot 10^5 \cdot \frac{{Q_1}^2}{{t_{1.b}}^2} \cdot \left(\frac{1}{(500\ °C - T_p)^2} - \frac{1}{(800\ °C - T_p)^2} \right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 77.164\ s$$

$t_{8.5.1} := \max(t_{8.5.1}, t_{8.5.2}) = 77.164\ s$ **real number: 81 sec**

Weld 2

$$t_{8.5.1} := (6700\ °C - 5 \cdot T_p) \cdot Q_2 \cdot \left(\frac{1}{(500\ °C - T_p)} - \frac{1}{(800\ °C - T_p)} \right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 42.535\ s$$

$$t_{8.5.2} := (4300\ °C - 4.3 \cdot T_p) \cdot 10^5 \cdot \frac{{Q_2}^2}{{t_{2.b}}^2} \cdot \left(\frac{1}{(500\ °C - T_p)^2} - \frac{1}{(800\ °C - T_p)^2} \right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 58.593\ s$$

$t_{8.5.2} := \max(t_{8.5.1}, t_{8.5.2}) = 58.593\ s$

Weld 3

$$t_{8.5.1} := \left(6700\ °C - 5 \cdot T_p\right) \cdot Q_3 \cdot \left(\frac{1}{\left(500\ °C - T_p\right)} - \frac{1}{\left(800\ °C - T_p\right)}\right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 38.157\ s$$

$$t_{8.5.2} := \left(4300\ °C - 4.3 \cdot T_p\right) \cdot 10^5 \cdot \frac{Q_3^{\ 2}}{t_{3.b}^{\ 2}} \cdot \left(\frac{1}{\left(500\ °C - T_p\right)^2} - \frac{1}{\left(800\ °C - T_p\right)^2}\right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 46.751\ s$$

$$t_{8.5.3} := \max\left(t_{8.5.1}, t_{8.5.2}\right) = 46.751\ s$$

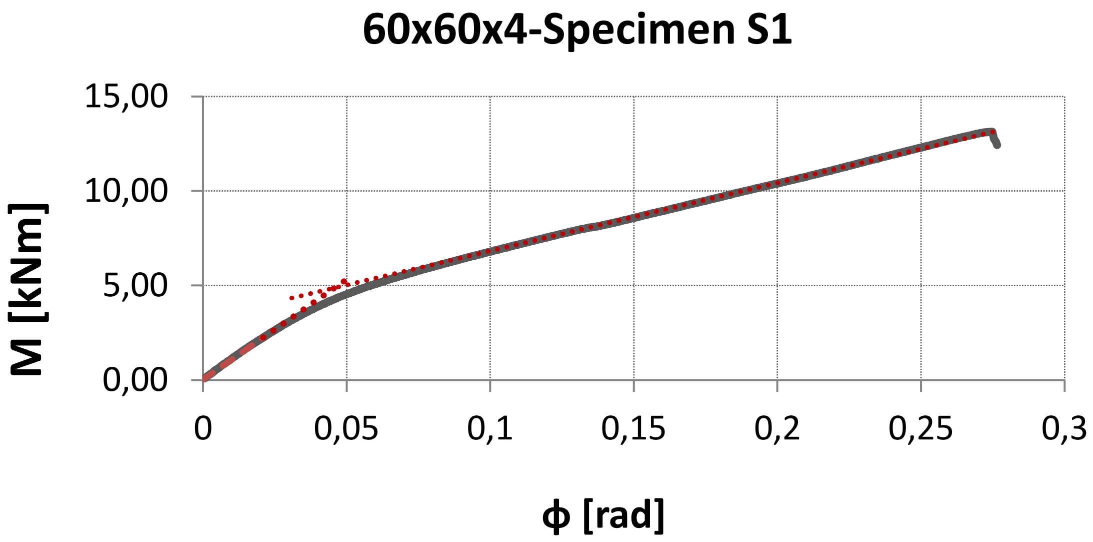
Weld 4

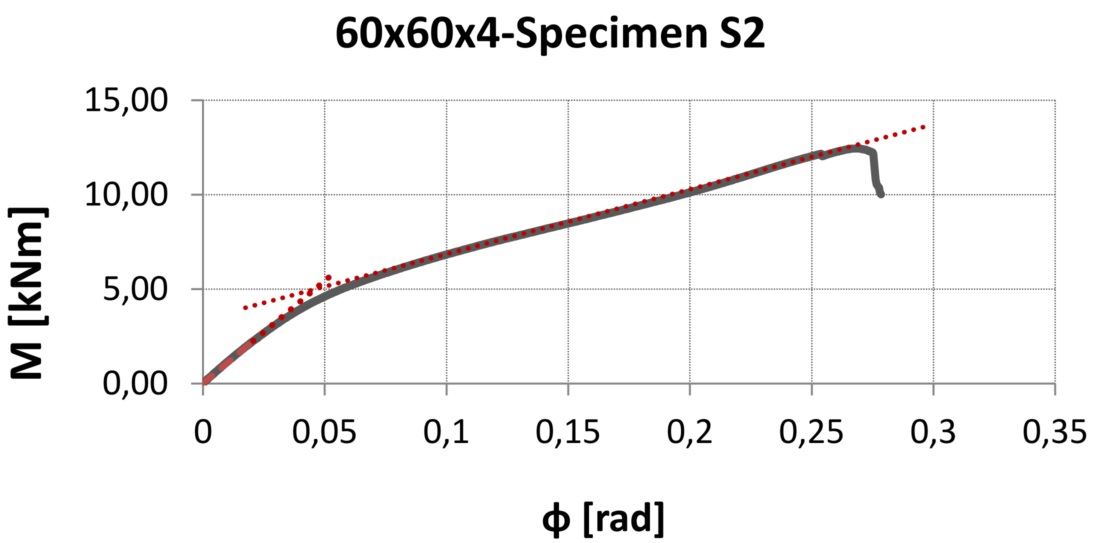
$$t_{8.5.1} := \left(6700\ °C - 5 \cdot T_p\right) \cdot Q_4 \cdot \left(\frac{1}{\left(500\ °C - T_p\right)} - \frac{1}{\left(800\ °C - T_p\right)}\right) \cdot F_3 \cdot \frac{s^3}{kg \cdot m \cdot 10^2} = 40.82\ s$$

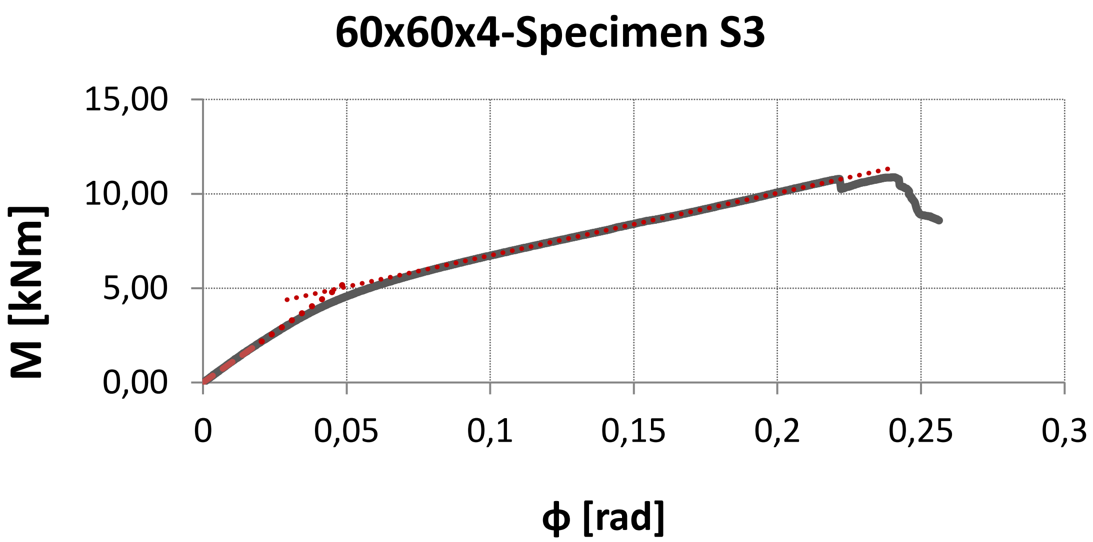
$$t_{8.5.2} := \left(4300\ °C - 4.3 \cdot T_p\right) \cdot 10^5 \cdot \frac{Q_4^{\ 2}}{t_{4.b}^{\ 2}} \cdot \left(\frac{1}{\left(500\ °C - T_p\right)^2} - \frac{1}{\left(800\ °C - T_p\right)^2}\right) \cdot F_2 \cdot \frac{s^5 \cdot K}{kg^2 \cdot 10^{12}} = 53.963\ s$$

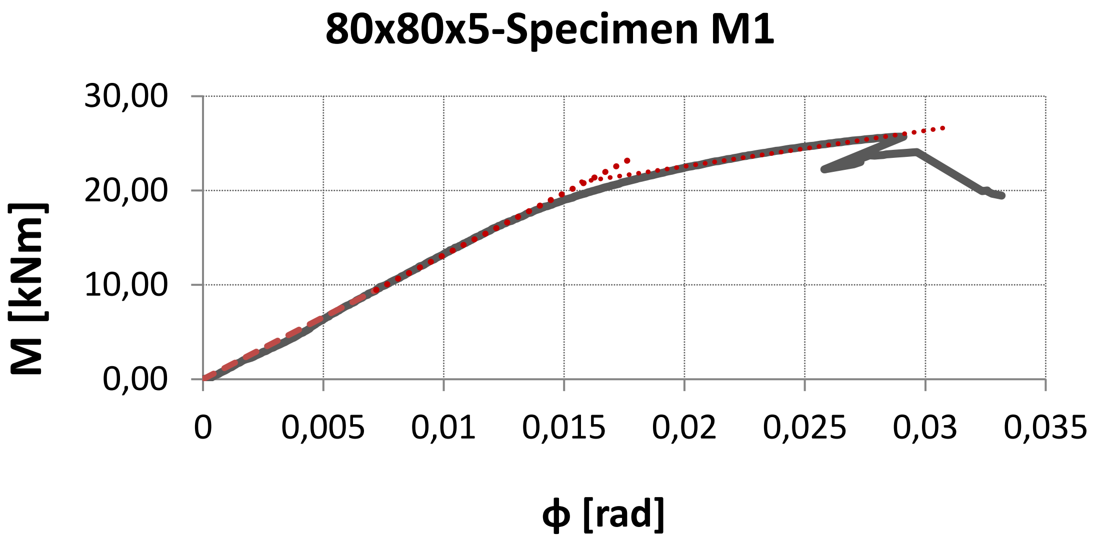
$$t_{8.5.4} := \max\left(t_{8.5.1}, t_{8.5.2}\right) = 53.963\ s$$

Moment-rotation graphs








80x80x5-Specimen M1
30,00
20,00
10,00
0,00
M [kNm]
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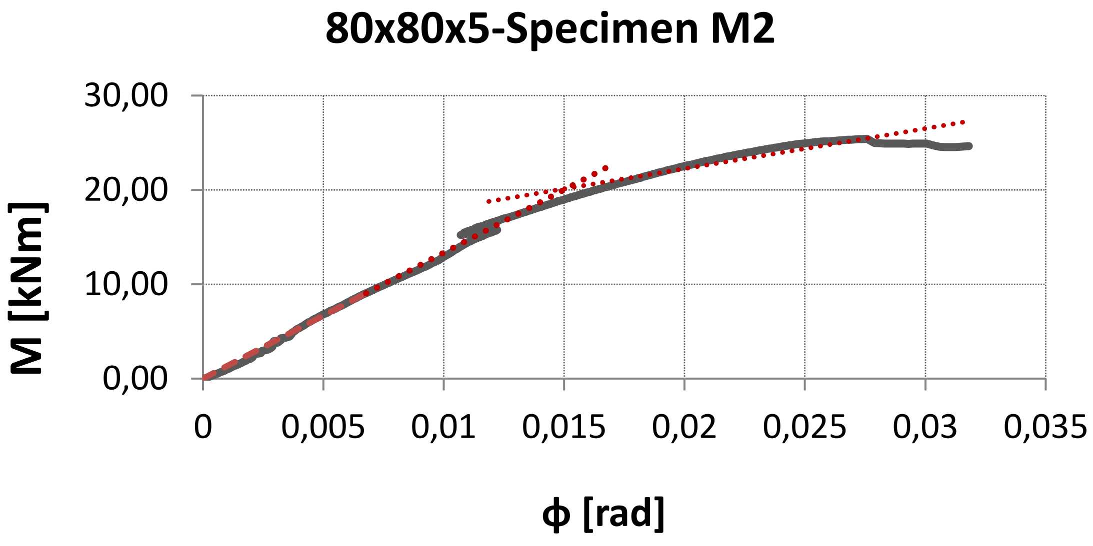
0,005
0,01
0,015
0,02
0,025
0,03
0,035
ϕ [rad]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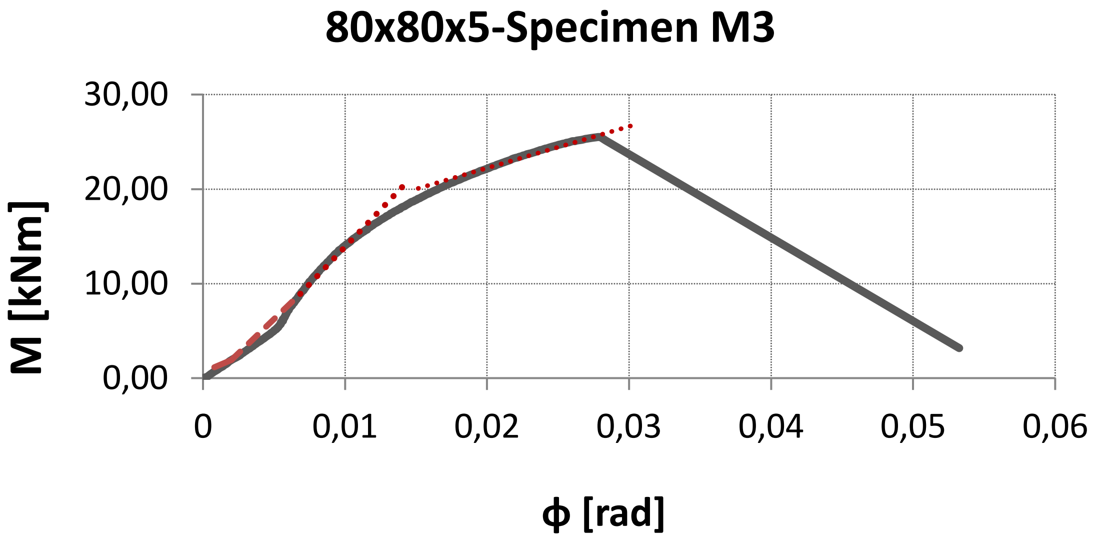
0,03
0,035
ϕ [rad]


80x80x5-Specimen M3
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20,00
10,00
0,00
M [kNm]
0
0,01
0,02
0,03
0,04
0,05
0,06
ϕ [rad]