EXPERIMENTAL INVESTIGATION OF SHS T JOINTS REINFORCED WITH SIDEWALL PLATES

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This paper presents a study on the behaviour of tubular T joints using SHS cold-formed profiles with jointsreinforced with a pair of sidewall plates. This type of reinforcement can be used in tubular joints where the same width is adopted in the chord and the brace and is very efficient when the failure mode involves the chord sidewall. An experimental programme is presented and discussed. The tests covered reinforced joints with a pair of sidewall plates and their unreinforced counterparts, while the braces being subjected to axial compressive forces. The geometry of the reinforcement plates varied in thickness and in length. The results from the experimental tests were discussed and the obtained joint resistances were compared with those forecasted by Eurocode 3 - part 1.8, by ABNT NBR 16239, and with analytical solutions available in the literature. These comparisons indicated that the available methods for the design of these joints lead to scattered predictions, i.e., the analytical and code results for reinforced joints with sidewall plates with similar thickness of the chord overestimate the observed values.

Keywords: steel structures, reinforced tubular joints, experimental tests,design codes.

1 Introduction

The use of tubular structural elements around the world has beenboosted in recent years due to their structural advantages and aesthetical features. Many examples in nature depict the excellent properties of the tubular shape when loaded in compression, tension, torsion or bending in any direction. Furthermore, the section's closed shape, without sharp corners, also reduces the surface area to be painted and protected, extending their corrosion protection life (Wardenier *et al*., 2010). Wardenier et al. (2010) and Zhao et al. (2010) presented the latest design recommendations for tubular joint incorporating the IIW (2009) improvements. More recently, two codes focusing on tubular joints design were also updated with the recent advances in this field (ISO 14346, 2013 and ABNT NBR16239, 2013).

If tubular joints can, atfirst glance, be considered expensive due to the additional requirements of welds, the use of reinforced joints may lead to more economical designs (Lima *et al.* 2018), especially for long spans. Bearing this scenario in mind, the Eurocode 3 (2010) and NBR16239 (2013) cover the design of reinforced joints with side plates, an alternative that

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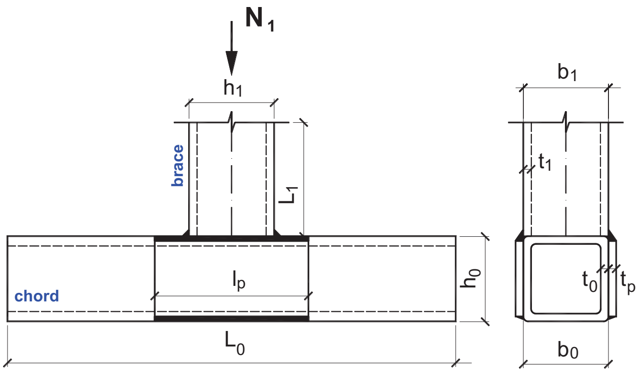
requires the reinforcement plate thickness to be at least twice the thickness of the brace member in this joint.

Other studies focusing on the structural behaviour of reinforced hollow section joints were performed by Choo *et al.*(2005) and Nassiraei *et al.*(2016), mainly focused on the assessment of the CHS joints structural behaviour. For joints of SHS or RHS sections, some results related to the ultimate capacity of reinforced joints under bending may be found in Chen & Chen (2016), while Chang *et al.*(2014) investigated the behaviour of doubler-plate reinforced square hollow section (DPR-SHS) T-joints with a brace under compression. Young-Bo *et al.*(2011) carried out experiments and numerical simulations of reinforced and unreinforced square tubular T-joints subjected to quasi-static cyclic loads. Feng *et al.*(2017) presented experimental and numerical investigations on collar plates and doubler plates as reinforcement for SHS T-joints under axial compression. On the other hand, when reinforced joints with sidewall plates are considered, there is still a lack of information in the literature.

With this scenario in mind, for a better understanding of the reinforcement plate effect on the ultimate joint capacity, an experimental study has been carried out comprising the static behaviour of T joints reinforced by a sidewall plate reinforcement with the same thickness as the chord. This joint can be observed in Figure 1 and was shown to provide a more economical design when the brace is axially loaded in compression. The main variables of the study were the reinforcing plate length and thickness. The experimental results were finally compared to Eurocode 3 (2010), NBR 16239 (2013), ISO 14346 (2013) and other authors design recommendations.



$$\beta = \frac{b_1}{b_0} \quad (1) \qquad 2\gamma = \frac{b_0}{t_0} \geq 10 \quad (2)$$

$$\frac{b_i}{t_i} \leq 35 \quad (3) \qquad \frac{h_i}{t_i} \leq 35 \quad (4)$$

$$l_p \geq \frac{1.5h_1}{\sin\theta_1} \quad (5) \qquad t_p \geq 2t_1 \quad (6)$$

$$0.5 \leq \frac{h_0}{b_0} \leq 2.0 \quad (7) \qquad 0.5 \leq \frac{h_1}{b_1} \leq 2.0 \quad (8)$$

Figure1.Reinforced tubular joints with sidewall plates – geometrical properties.

2 Tubular joints with sidewall failure mode

Packer (1984) investigated the behaviour of rectangular hollow section tubes subjected to transverse compressive loads in an experimental programme on isolated, equal-width, cross joints. The results of 31 tests covering a wall slenderness range of $15.3 \leq h_0/t_0 \leq 42.2$ were discussed together with more 40 tests fromother authors. Based on this discussion, the author proposed an equation to predict the ultimate resistance of full-width tee or cross joint that will be presented further in Table 1. The application of this equation resulted in mean value between the predicted and experimental values of 1.36 with a small scatter (COV=0.16) with only 3% of the values out of the range 1.0 – 2.0. However, neither the chord depth (h_0) nor the axial chord preload was explicitly included in the equation, as they were believed to have little effect on the joints ultimate strength. Afterwards, Davies and Packer (1987) rejected this conclusion and instead postulated that the joint strength depends on the chord slenderness (h_0/t_0) and the non-dimensional bearing length (h_1/h_0).Zhang *et al.*(1989) performed a total of 12 experimental tests in RHS joints (in which 6 where T joints) followed by a numerical evaluation to investigate joints with $\beta = 1.0$. Based on the obtained results, the authors proposed an equivalent frame tube model to estimate the ultimate strength of this joint type where the web crippling governs the joint design. The author's formula was applied to 85 tests associated with a mean value of 1.22, and a small data scatter corresponding to a COV = 0.11.

3 Tubular joints design equations for sidewall failure mode

The design codes that consider the resistance of reinforced SHS/RHS T joints use currently the equations for unreinforced joints modifying the considered thickness. Initially, the cases of unreinforced SHS/RHS T with a width ratio β= 1.0 will be considered in this discussion. Wardenier *et al.*(2010) proposed a design equation based on web crippling in the form of either a bearing or buckling failure mode. For bearing, a dispersion force at 22º through the tube wall is considered being very similar to the case of bearing loads on wide flange sections webs, such as the well-known value of 45º dispersion angle. For the cases where the buckling of the chord sidewall governs the joint failure ($h_0/t_0 \geq 20$-25), the yield stress f_{y0} should be changed by the f_b based on Eurocode 3 (2010) buckling curve a. The equation (9) may be observed in Table 1. Furthermore, as previously mentioned, Packer (1984) developed an equation (10) for sidewall failure mode of SHS/RHS unreinforced T joints considering the h_0/t_0 ratio, see also Table 1.

Table1. Design equations for sidewall failure mode of T tubular joints with $\beta = 1.0$.

Wardenier *et al.*(2010)	$N_{1,W}= 2f_{y0}\ (\text{or } f_b)t_0\left(\frac{h_1}{\sin\theta_1}+5t_0\right)\frac{1}{\sin\theta_1}$	(9)
Packer (1984)	$N_{1u,P}=\frac{f_y\, b_0^{0.3} t_0^{1.7}}{\sin\theta_1}\cdot\left\{3.8+10.75\left[\frac{b_1+h_1}{2b_0}\right]^2\right\}$	(10)
Eurocode 3, part 1.8 (2010)	$N_{1,Rd,EC3}=\frac{k_n\,\chi f_y\, t_0}{\gamma_{M5}\text{sen}\theta_1}\left(\frac{2h_1}{\text{sen}\theta_1}+11\ t_0\right)$with $k_n = 1$ for tension chord stress and $k_n = 1.3-0.4n/\beta$ for compression on the chord and $\bar{\lambda}=3{,}46\frac{\left(\frac{h_0}{t_0}-2\right)\sqrt{\frac{1}{\sin\theta_1}}}{\pi\sqrt{\frac{E}{f_{y0}}}}$ also used for NBR 16239 (2013)	(11)
ABNT NBR16239 (2013)	$N_{1,Rd,NBR}=\frac{k_n\,\chi f_y\, t_0}{\gamma_{a1}\text{sen}\theta_1}\left(\frac{2{,}2h_1}{\text{sen}\theta_1}+11\ t_0\right)$ with$\chi=\frac{1}{\left(1+\lambda_0^{4{,}48}\right)^{1/2{,}24}}$	(12)
Zhang *et al.*(1989)	$N_{1u}= 2f_y\,.t_0.h_{1e}.k_1$ with $k_1=1.75-0{,}03\frac{h_0}{t_0}$ if $\frac{h_0}{t_0}\leq 25$ or $k_1=1.40-0.016\frac{h_0}{t_0}$ if $\frac{h_0}{t_0}>25$ and $h_{1e}=h_1.k_2$ with $k_2=\left(0.7\frac{h_0}{h_1}\right)^{0{,}7}$ if $\frac{h_1}{h_0}\leq 0.7$ or$k_2=\left(0.7\frac{h_0}{h_1}\right)^{0{,}2}$ if $\frac{h_1}{h_0}>0.7$	(13)
Geometrical parameters, according to Figure 1.		

According to Eurocode 3 part 1.8 (2010) andfor unreinforced joints, the sidewall failure mode is verified by equation (11) presented in Table 1, where χ is also evaluated using the Eurocode 3 (2010) buckling curve a. The Brazilian code ABNT NBR 16239 (2013) is based on Eurocode 3, part 1.8 (2010) and considers a similar equation to evaluate the joints with sidewall failure mode - Table 1. On the other hand, the buckling reduction factor is evaluated using a different equation, see Table 1.Moreover, the equation (13) proposed by Zhang *et al.*(1989)

considers the influence of the two main parameters, h_0/t_0 and h_0/h_1 as described in Table 1 for unreinforced joints.

For reinforced joints, the Eurocode 3 part 1.8 (2010) and the ABNT NBR 16239 (2013)use a common procedure for the joint resistanceusing equations (11) and (12) and replacing the chord thickness t_0 by the (t_0+t_p) and $t_p \geq 2t_1$ as presented in equation (6). For the cases where the same section is used for the chord and the brace members, this condition conducts to a reinforcement plate thickness of twice the reference value. As mentioned before, to achieve a more economical solution, this work considers the reinforcement plate thickness equal to the chord thickness ($t_p = t_0$).The equations proposed by Packer (1984) and Zhang *et al.*(1989), were proposed for joints without the sidewall plate reinforcements. As an initial assessment for the reinforced joints capacity, these equations will be used in this work following the procedure proposed by Eurocode 3 part 1-8 (2010) and ABNT NBR 16239 (2013), where the chord thickness, t_0, is simply replaced in the main equation by the sum of t_0 with the used reinforcement plate thickness ($t_0 + t_p$).

4 Experimental programme

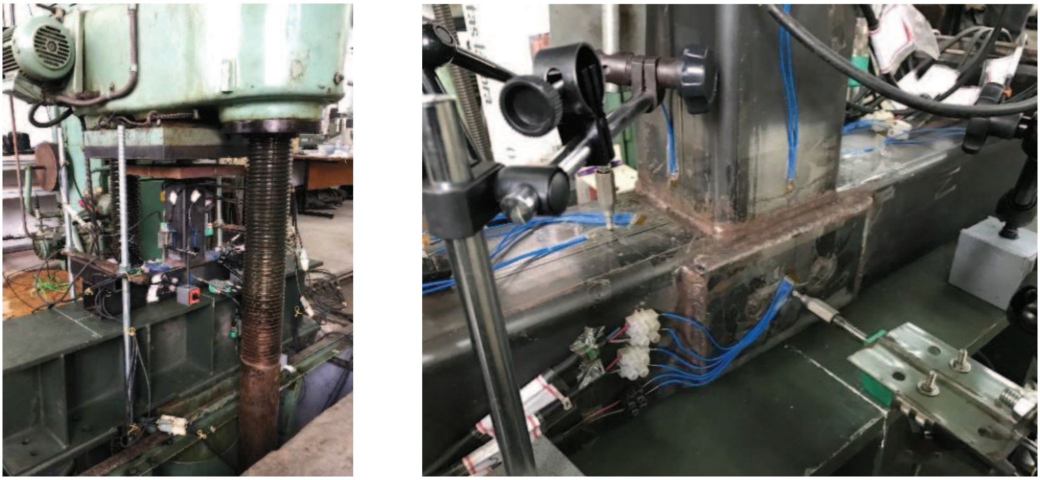
The experimental programme for SHS brace to SHS chord T joints is summarised in Table 2. All six prototypes adopted ASTM-A36 steel grade: four reinforced tests using a chord wall thickness of 6.35 mm (with three different l_p); 9.6 mm sidewall plates; and two unreinforced joints. This sidewall plate thickness does not comply with the $t_p \geq 2t_1$ limit presented in Figure 1, but leads in-stead, as discussed, to a more economical design. The chords and the braces were square hollow SHS 110x110x6.35 sections with 800 mm and 300mm length, respectively, as depicted in Figure 3. The reinforcement plates were cut from sections identical to the chords. The non-dimensional parameters related to the adopted sections were β=1.0 and 2γ=17.32. The specimens were instrumented with strain gauges, rosettes and LVDTs – Gomes (2017) to monitor their behaviour according to the layout presented in Figure 3.

Table 2. Design equations for sidewall failure mode of T tubular joints with $\beta = 1.0$.

Test	Chord and brace [mm]	L_0 [mm]	L_1 [mm]	l_p [mm]	t_p [mm]
SR1	110x110x6.35	800	300	-	-
SR2	110x110x6.35	800	300	-	-
CR1	110x110x6.35	800	300	165	6.6
CR2	110x110x635	800	300	165	6.6
CR3	110x110x6.35	800	300	250	6.6
CR4	110x110x6.35	800	300	165	9.6

The tests were performed with the specimen fully supported on its entire length,and the ends were fixed to avoid vertical displacements. A pure concentrated force was applied to the chord by the brace - Figure 2, that was the only member loaded in the tests (in compression)using a 3000 kN universal Lousenhausen test machine under displacement control with a 0.003mm/s load rate.

The properties of the carbon steel tubes were obtained from tensile coupon tests leading to the following average results: 321.10 MPa for the yield stress, 439.16 MPa for the ultimate stress, 205044MPa for Young's modulus (E) and 20.7% for the elongation at fracture based on a 50mm gauge length. The tensile coupon test results are detailed in Gomes (2017).



a) test SR2 b) test CR4

Figure 2.Test layout overview.

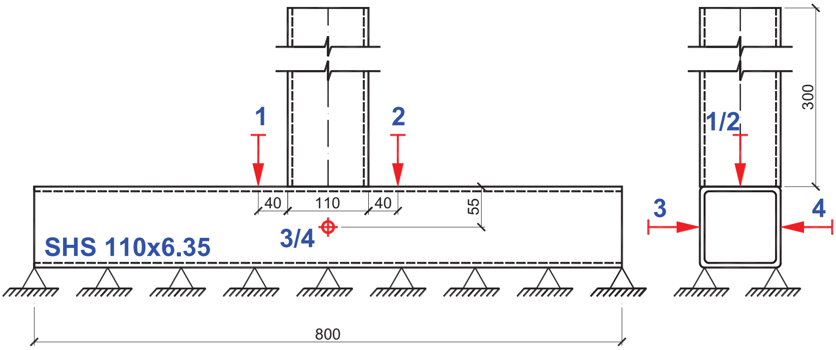


Figure 3.Tests boundary conditions and LVDT's location

5 Experimental results

The load-lateral displacements, with the laterobtained from LVDT´s placed 55mm from the chord top face for the investigated T-joints are presented in Figure 4, while the results are summarised in Table 3.For the unreinforced joints (tests SR1 and SR2), the resistances were obtained from the peak load (N_{peak}) reached before the load leading to a displacement equal to the deformation limit criteria of 3%b_0 ($N_{3\%b0}$). For these unreinforced joints, the peak loads were 852.9kN and 860.4 kN, respectively, where the sidewall failure mode was observed as pointed out in Figure 5.

The two first reinforced joints tests, CR1 and CR2, considered a sidewall plate thickness of 6.35mm (t_p=t_0) cut from an identical section as thechord, provided a 37% increase in the joint resistance. At this point, it is worth observing that this reinforced joint does not meet the design codes requirements in terms of the reinforcement plate thickness (t_p>2t_1 but t_1=t_0).

The third reinforced joint CR3 was selected to investigate the influence of the reinforcement plate length (l_p), that increases from 165 mm (length used in tests CR1 and CR2 corresponding to the minimum value according to design codes) to 250 mm. Figure 4 and Table 3 show that this joint resistance was in this test with the increased plate length, equal to 1191.5 kN; only 0.4% greater than CR1 and CR2 tests. The failure mode of the test CR3 was characterised by a combination of sidewall failure and brace failure as may also be observed in

Figure 5.

Finally, the reinforced joint CR4 witha 9.6 mm thick sidewall reinforcement plate (tp=1.5t_0) exhibited the failure mode presented in Figure 5, involving the brace yielding followed by local buckling. This failure sequence is equal to the tests where only the braces in compression were evaluated (Gomes, 2017). In terms of joint resistance, the peak load was equal to 1261.7 kN with a sharp decrease of the applied load as observed in the respective load-lateral displacement curve presented in Figure 4. This value is smaller than 1361.5 kN corresponding to the average of the two stub column tests of the braces subjected to compression load. This phenomenon occurred due to different boundary conditions between the stub column tests and the T-joints tests.

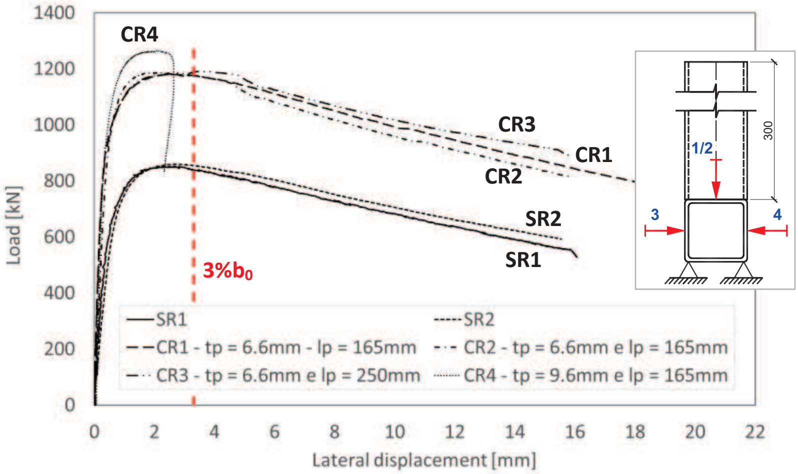


Figure 4.Load versus lateral displacement experimental curves

Table 3. Comparison of experimental and theoretical results

Test	Failure mode	N_{exp}^{peak} [kN]	$N_{exp}^{3\%b0}$ [kN]	N_{EC3} [kN]	N_{NBR} [kN]	N_{Zhang} [kN]	N_{Packer} [kN]	$\frac{N_{exp}}{N_{EC3}}$	$\frac{N_{exp}}{N_{NBR}}$	$\frac{N_{exp}}{N_{Zhang}}$	$\frac{N_{exp}}{N_{Packer}}$
SR1	SW	852.9	850.9	461.8	572.9	542.7	473.3	1.85	1.49	1.57	1.80
SR2	SW	860.4	857.1	461.8	572.9	542.7	473.3	1.86	1.50	1.59	1.82
CR1	SW+BY [a)]	1181.6	1176.1	1136.7	1410.1	1085.3	1537.8	1.04	0.84	1.09	0.77
CR2	SW+BY [a)]	1186.3	1176.4	1136.7	1410.1	1085.3	1537.8	1.04	0.84	1.09	0.77
CR3	SW+BY [a)]	1191.5	1191.5	1136.7	1410.1	1085.3	1537.8	1.05	0.84	1.10	0.77
CR4	BY	1261.7	-	-	-	-	-	-	-	-	-

SW – sidewall
BY – brace yielding followed by local buckling
[a)] small contribution of the brace yielding followed by local buckling

Table 3 shows a summary of the experimental results and the predicted values obtained using the equations presented in Table 1. As previously mentioned, it is crucial to observe that these equations were developed for T-joints with β = 1 without reinforcement. In the present study, these equations were used changing the chord thickness (t_0) by the sum of chord and reinforcement plate thickness (t_0+t_p). The equations from Eurocode 3 (2010) and NBR ABNT 16239 (2013) consider reinforced joints changing t_0 by t_0+t_p since $t_p \geq 2t_1$. It is essential to highlight that, in principle, the design codes equations cannot be used for the studied reinforced joints since $t_p \leq 2t_1$. It is also worth mentioning that, as observed in Table 3, for the reinforced joints considered in this work, the equations from Eurocode 3 (2010) and Zhang *et al.*(1989) presented a good agreement since the experimental to design formulation ratios were close to 1.0.The equations from ABNT NBR 16239 (2010) and Packer (1984) are not suitable for these reinforced joints. Moreover, these equations have led to conservative results when unreinforced T-joints, with $\beta = 1$, are considered.

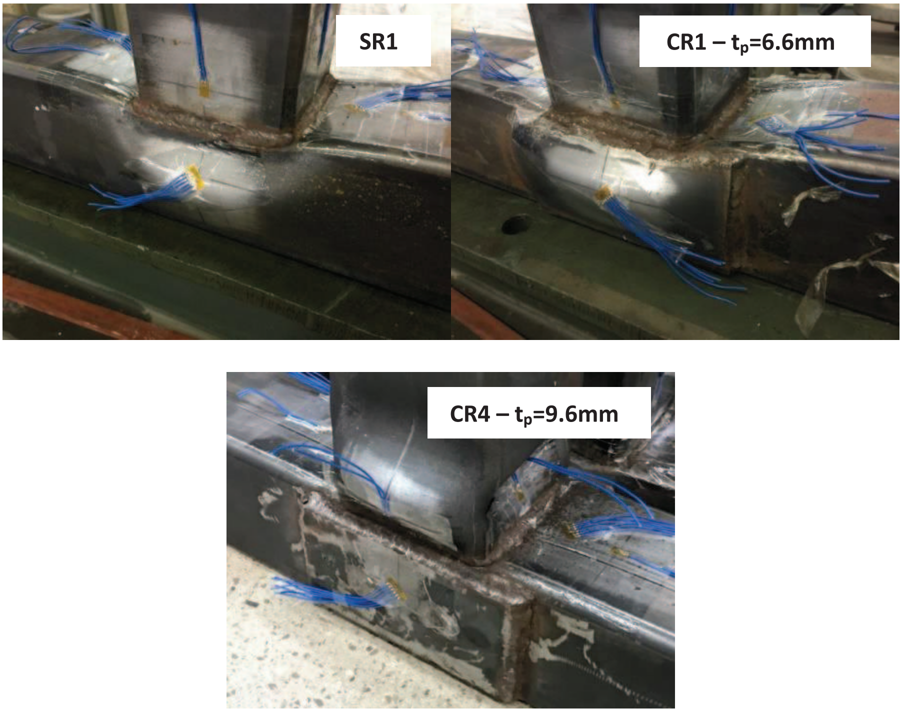


Figure 5.Deformed shapes – experimental tests

6 Final considerations

This paper presented an experimental investigation on the behaviour of tubular T joints using cold-formed SHS sections reinforced with a pair of sidewall plates at the joint, and where the braces were subjected to axial compressive forces. Also, reference tests without reinforcement were analysed to assess the influence of the reinforcement introduction and its size.All the results were compared to those delivered by the available formulations, based on the Eurocode 3 (2010), NBR 16239 (2013), ISO 14346 (2013) and the design recommendations proposed by Packer (1984) and Zhang *et al.*(1989).These comparisons indicated that the available methods for the design of the joints lead to scattered predictions, overestimating the resistance for reinforced joints with sidewall plates, namely with a similar thickness of the chord.

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