Structural analyses of reinforced tubular T-joints

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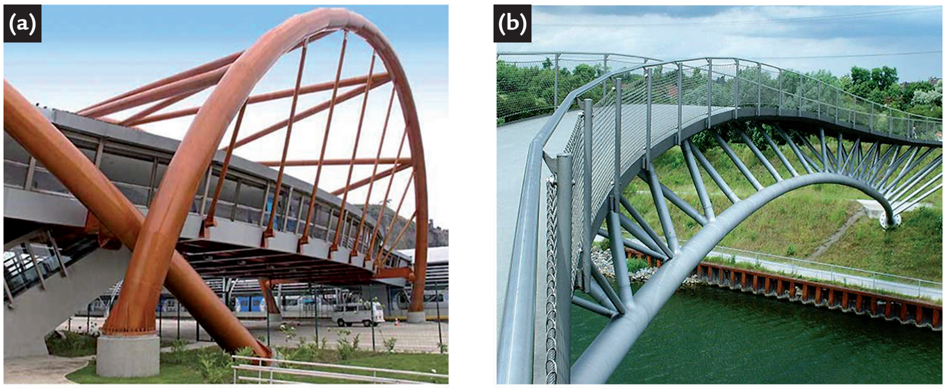
Abstract

The use of rolled hollow sections has been substantially boosted mainly due to the advantages associated with structural behavior and aesthetics, leading to an intense use in Europe, Southeast Asia, North America, Australia, and now, in Brazil due to the wider supply of these profiles. Therefore, it is important to investigate the structural behavior in order to provide an adequate structural design for the civil engineering community. Thus, this paper presents a parametric analysis of a reinforced T-joint focused on NBR 16239 provisions. Two types of reinforcement plates: Collar and Double were investigated. A wide set of numerical models has been defined varying the thickness of the reinforcing plate, chord and brace members and axial loads applied in the brace. The numerical models have been developed using ANSYS 12.0 software considering both geometrical and material non-linearity. Concerning the results, there was a slight gain of resistance when a double plate reinforcement was used, mainly for small displacement, due to large stiffness provided and a linear response up to the serviceability limit. In addition, Von Mises stress distribution confirmed the type A failure with chord yielding beginning at the upper chord surface. Comparing the numerical results with NBR 16239 provisions, an excessive conservatism was noted for this code. In fact, the Brazilian code only takes into account the reinforcement thickness in joint resistance. However, when the results provided by the new proposal where both thicknesses (chord and reinforcement) are considered, a more realistic assessment of the joint capacity is obtained.

Keywords: reinforced T-joint, rolled hollow sections, nonlinear numerical analyses.

1. Introduction

The pressing needs to obtain solutions for the various structural problems in engineering associated with the large growth of steel construction have given rise to the adoption of tubular profiles around the 1960s. Therefore, these are considered one of the most recent structural groups of steel profiles. The appearance and diffusion of the tubular profiles motivated the foundation of CIDECT (International Committee for the Development and Study of Tubular Structures) in 1962, which is the largest international organization of tubular profile manufacturers. Figure 1 shows examples of various structures using tubular cross-sections in structural members.



Bridgefoot, Rio de Janeiro
Ripshorster Bridge, Germany

Figure 1
Tubular structures examples.

It is largely recognized that the situation in the Brazilian market has changed due to the supply of structural hot rolled hollow sections from the year 2000 on. This trend boosted the dissemination and implementation of this new profile type for the civil engineering community, and consequently led to an increase in the number of research papers to understand its structural behavior. Consequently, this paper reports on a study of the static performance of reinforced T tubular joints. The behavior of this type of joint has been investigated in the last years, due to lack of test evidence needed to enable the development of a reliable and accurate design approach (Choo et al. 2005, Vegte et al. 2005, Shao *et al.* 2011, Brasil, 2013). These studies revealed that the use of a reinforcing plate significantly enhances the ultimate resistance of the T-joints. The RHS profiles have been employed in the chord while the CHS ones have been used in the brace. The adopted reinforcement consists of thin-plates, of which two typologies are evaluated in this paper: Collar and Double plate. The reinforced joints have been designed in accordance with NBR 16239 (2013). The T-joint is predominantly subjected to static loading with both compression and tension axial forces applied to the brace (Brasil, 2013). The study was conducted in two distinct phases. The analyses were based on the numerical models calibrated against design recommendations present in NBR 16239 (2013). It is important to observe that the NBR 16239 (2013) is almost entirely based on the EN1993-1-8 (2005). Additionally, the influence of employed reinforcement type and the axial load applied on the brace was investigated.

2. Design of t tubular joints

In order to design a typical reinforcement for a T-joint, it is necessary to establish an initial criteria. In this case, the next sections present the equations to be used in the joint design as well as their validity limits for the T-joints studied in this paper in accordance to NBR 16239 (2013) and also EN1993-1-8 (2005).

Tensioned brace

NBR 16239 (2013) recommends that the maximum tension load ($N_{t,Rd}$) to be applied on the brace of the T-joint is determined with the use of the following equations (their associated nomenclature is depicted in Figure 2).

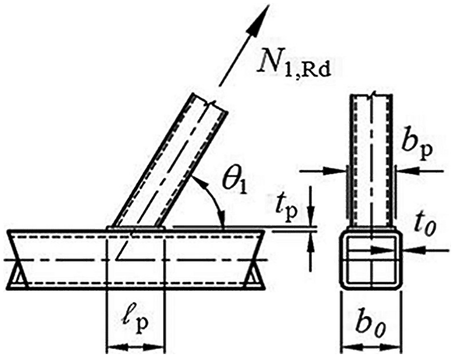


Figure 2
Reinforced T-joint geometry (NBR 16239, 2013).

$$N_{t,Rd} = \left(\frac{1{,}1 f_{yp} t_p^2}{\left(1 - \frac{b_1}{b_p}\right) sen\ \theta_1} \left(\frac{2\frac{h_1}{b_p}}{sen\ \theta_1} + 4\sqrt{1 - \frac{b_1}{b_p}} \right) / \gamma_{a1} \right) \times \frac{\pi}{4} \quad (1)$$

Fulfilling the following conditions:

$$l_p \geq \begin{cases} \frac{h_1}{sen\ \theta_1} + \sqrt{b_p(b_p - b_1)} \\ 1{,}5 \frac{h_1}{sen\ \theta_1} \end{cases} \quad \text{where: } b_p \leq b_0 - 2t_0 \quad (2)$$

Compressed brace

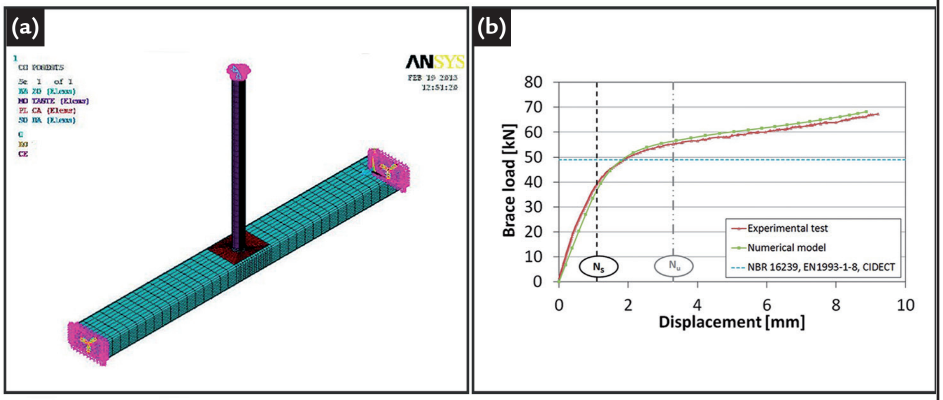
In this case, the NBR 16239 (2013) that determines that the maximum compression load (N_c,R_d) is defined by applying Equation 3 below, being the same expression used for joints without reinforcement only changing t_p (reinforcement plate thickness) by t_0 (chord thickness).

$$N_{c,Rd} = \left(\frac{k_n f_{yp} t_p^2}{(1-\beta) sen\ \theta_1} \left(\frac{2{,}2\beta}{sen\ \theta_1} + 4{,}4\sqrt{1-\beta} \right) / \gamma_{a1} \right) \times \frac{\pi}{4} \quad (3)$$

Once again, it is important to observe that the same restriction imposed by equation 2 should be fulfilled.

3. Numerical model

A numerical model has been developed using the ANSYS 12.0 (2010) software in order to carry out a parametric analysis (see Figure 3). The finite element (SHELL 181) was used for all members and welds and contains four nodes per element with six degrees of freedom per node. This element is adequate for various analyses associated with the development of bending moments, shear and membrane effects. In order to obtain the global behavior in terms of stiffness, resistance and deformability, a nonlinear material and geometric analysis was carried out. The adopted material's constitutive law was associated with a bilinear elastic-perfect plastic behavior. The geometrical nonlinearity was considered by using the updated Lagrange algorithm. The numerical model developed is shown in Figure 3. The adopted boundary conditions are illustrated in Figure 3(a) where the end chord's rigid response, and the pinned support present at the top of the brace allowing the displacement in the axial direction, is depicted. The calibration was performed based on experimental results found in Mendes (2008). The studied joint was characterized by a chord made of a RHS 110x60x4.8 with a 456MPa yield stress and a CHS 38.1x3.2 with a 350MPa yield stress for the brace more details can be found in Brasil (2013). Figure 3(b) depicts the model calibration, where it is possible to observe the excellent match between the numerical and experimental results.



Numerical model

Calibration of the numerical model

Figure 3
Numerical model
developed in the ANSYS 12.0 (2010).

In particular, three different materials were defined in the analyses for the chord, brace and welds. Both chord and reinforcing plate thicknesses were added ($t_0 + t_p$) in the same area. Figure 4 presents the developed numerical model T-joints containing Collar and/or Double plate reinforcements.

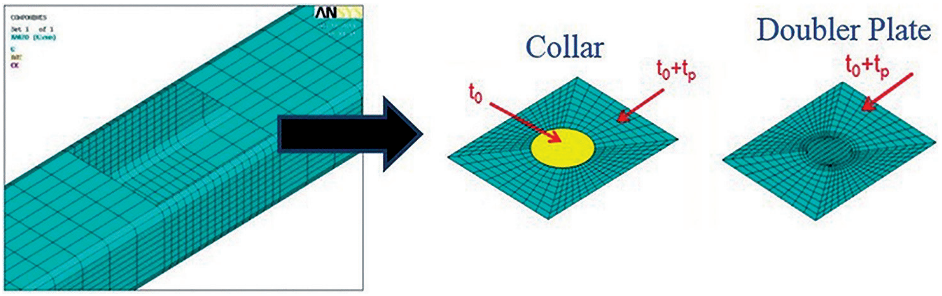


Figure 4
Mesh details for Collar and Double
plate reinforcement typologies(t_0+t_p).

3.1. Phase 1

In this step, the parametric analyzes included the development of twenty numerical models divided as follows: ten models varying the thickness of the reinforcing plate, five presenting compression axial loads and another five with tensile axial loads applied to the brace; finally, ten models were made varying the reinforcement typology for each thickness (five collar and five double plate reinforcement with brace compression loads). In detail, an RHS 110x60x4.8 with a yielding stress of 456MPa has been employed in the chord, while a CHS 38.1x3.2 with a yielding stress of 350MPa was used in the brace. It is important to observe that reinforcement plate thicknesses of: 1.0, 2.0, 3.0, 4.0 and 4.8 were investigated in this phase. Figure 5 points out the results obtained by numerical analyses, Nansys, their associate NBR 16239 (2013), $N_{1,rd\ ref}$ design prediction, and an alternative design proposal, $N_{1,rd\ ref} + N_{1,rd\ s/ref}$. At this point, it is important to emphasize that according to NBR16239 (2013), for joints with braces in compression, the joint resistance is evaluated using, in Equation 3, the reinforcement plate thickness (t_p) instead of chord thickness (t_0). It can be observed in Figure 5(a) that there is a reduced joint capacity enhancement with the adoption of the reinforcement when the value recommended by Brazilian code was considered. In fact, the formulation incorporated in this code only considers the contribution of the reinforcement plate.

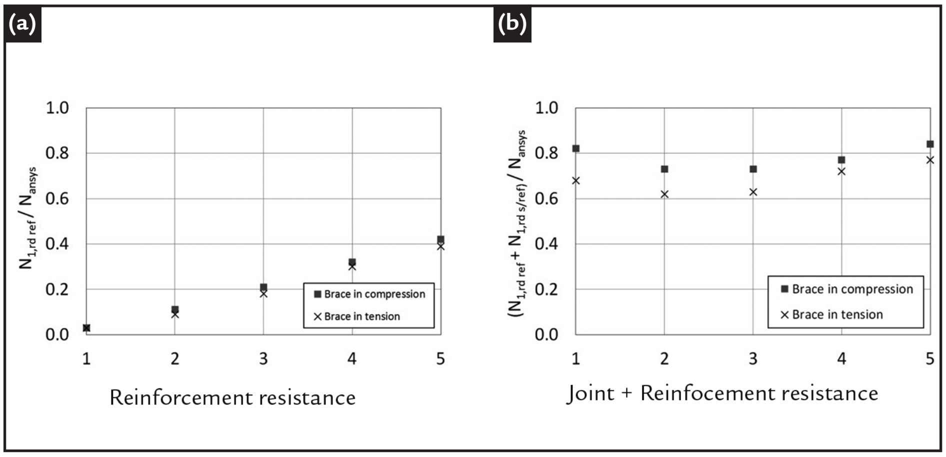
On the other hand, when both thicknesses are considered for the joint resistance enhancement, these results reach values closer to that obtained in the numerical analyses - see Figure 5(b). Therefore, in these cases, the reinforcement provides a significant increase to the joint load carrying capacity but still does not reach the estimated numerical capacity.

3.1.1 Comparison between Collar and Double plates reinforcement

A nonlinear behavior of the T-joint based on load versus displacement curves shown in Figure 6(a) for both typologies can be observed. The joint capacity presented in this figure corresponds to the applied brace axial load. In addition, the values for the serviceability and ultimate limit states according to deformation limit criterion proposed by Lu *et al.* (1994) are also plotted. It can also be observed that there is a slight gain of resistance when a double reinforcement was used, mainly for small displacement, due to the great stiffness provided. Due to this difference in initial stiffness, the reinforced T-joint with double plate presents a linear range up to serviceability limit. On the other hand, the ultimate resistance for both typologies is obtained for similar displacements.

3.1.2 Comparison between compression and tensile axial loads applied on the brace

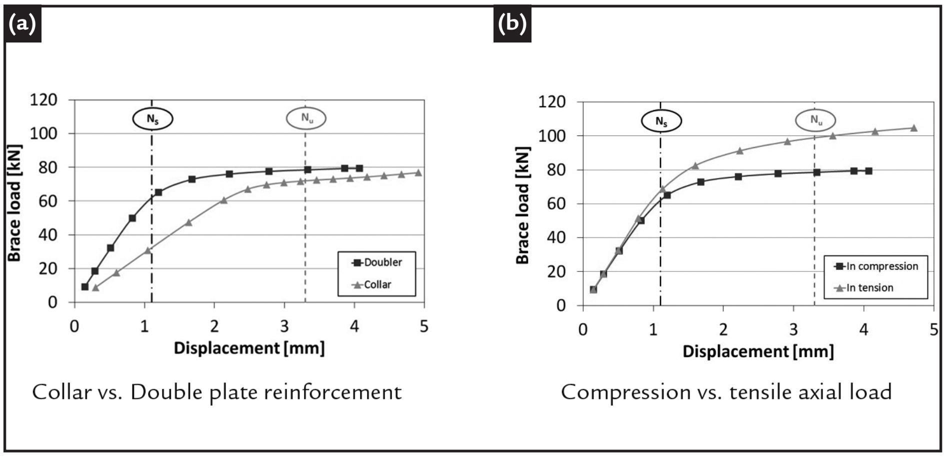
Figure 6(b) shows the comparison between compression and tensile axial brace loads. As can be observed, there is a similar behavior for both loads up to the serviceability limit state. After this point, the reinforced T-joint with tensile axial brace load presents a higher resistance than a similar T-joint with compressive axial brace loads. This behavior was also observed for numerical models varying the reinforcement plate thickness.



Reinforcement resistance

Joint + Reinfocement resistance

Figure 5
Comparison between NBR 16239 (2013) versus numerical model results.



Collar vs. Double plate reinforcement

Compression vs. tensile axial load

Figure 6
T-joint structural response considering the studied reinforcement typologies and the brace axial loads (for a 3.0mm thick reinforcement plate).

3.2 Phase 2

In the second phase, one hundred and sixty numerical models were developed varying the profile chord, brace profile, and reinforcing plate thickness. Forty models were associated with compressive axial loads and forty with tensile axial loads applied to the brace. In addition, eighty numerical models were used, varying the reinforcement type for each thickness; in other words where forty models for each reinforcement type (Collar or Doubler). The various types of hollow sections used in this study are commercially available in Brazil through the product catalog of Vallourec Brazil (2014). Table 1 reports on the geometric and material proprieties investigated in this phase. In particular, Figure 7 depicts the results obtained varying both chord and brace structural members as well as the reinforcement thickness. It is important to observe the similar behavior when the comparison is towards the design resistance recommended by NBR 16239 (2013). The numerical results provided resistances higher than the formulation proposed by the code, mainly, when the comparison was performed only considering the reinforcement contribution. Figure 8 shows the results of the loads associated to 3.35mm and 4.72mm displacements, i.e.: 110kN and 131kN.

In addition, there is a von Mises stress distribution in the chord for two different load steps. It is interesting to note that when the numerical model reaches a load of 110kN, a chord yielding failure can be observed corresponding to the failure mode A present in NBR16239 (2013). Later, at a load of 131kN, the numerical model already has the chord upper face, close to the joint, fully yielded while yielding regions in the lateral face can also be noted.

Models	Chord (RHS)				Brace (CHS)			Reinforcement				
	b	h	t	fy(MPa)	d	t	fy(MPa)	b	fy(MPa)	l	t_1	t_2
1.1	110	60	4.8	456	38.1	3.2	350	100.4	456	117	2	4
1.2					48.3	4.0	350	100.4	456	121	2	4
1.3					60.3	4.0	350	100.4	456	124	2	4
1.4					76.1	4.0	350	100.4	456	125	2	4
2.1	200	120	8.0	456	88.9	4.0	350	184	456	221	4	6
2.2					101.6	5.0	350	184	456	225	4	6
2.3					114.3	6.3	350	184	456	228	4	6
2.4					127	8.0	350	184	456	229	4	6
3.1	300	150	10.0	456	159	6.3	350	280	456	343	5	8
3.2					168.3	8.0	350	280	456	345	5	8
3.3					177.8	8.0	350	280	456	347	5	8
3.4					193.7	10.0	350	280	456	349	5	8
4.1	400	200	12.5	456	177.8	10.0	350	375	456	450	6	10
4.2					193.7	12.5	350	375	456	454	6	10
4.3					219.1	12.5	350	375	456	461	6	10
4.4					244.5	16.0	350	375	456	466	6	10
5.1	400	300	16.0	456	193.7	10.0	350	368	456	447	8	12
5.2					219.1	10.0	350	368	456	453	8	12
5.3					244.5	12.5	350	368	456	458	8	12
5.4					273	10.0	350	368	456	460	8	12

Table 1
Phase 2 reinforced
T-joint proprieties.

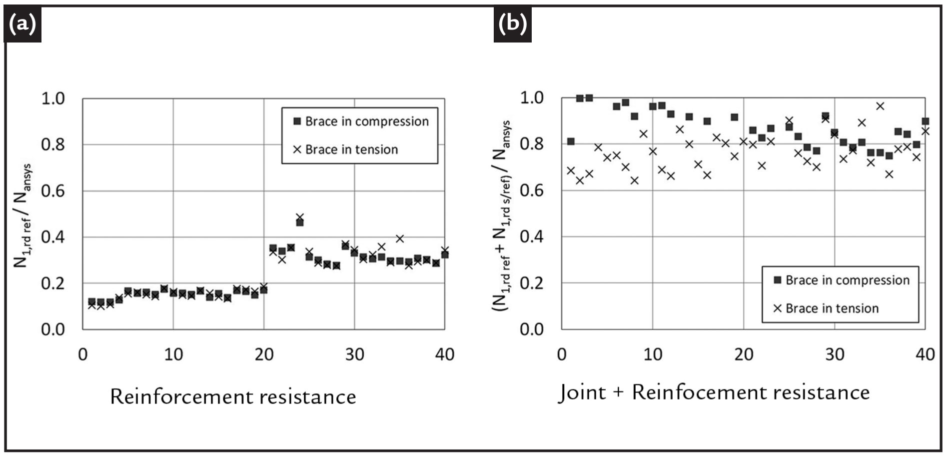


Figure 7
Comparison between NBR 16239 (2013) versus numerical model results.

3.2.1 Influence of the reinforcement type and applied axial load

Investigating the influence of the reinforcement type, as shown in Figure 9(a), it is easy to note the high stiffness provided by T-joint with double reinforcement. In an overview, this typology presents a linear behavior up to the serviceability limit state. On the other hand, the T-joint models with collar reinforcement exceed the ultimate limit state. From these observations, it was possible to conclude that the geometry of the reinforcing plate also influences on the joint resistance.

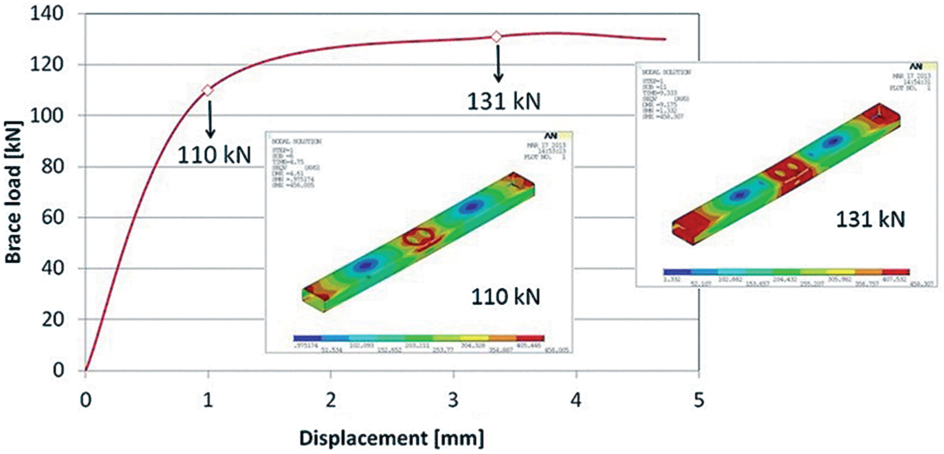
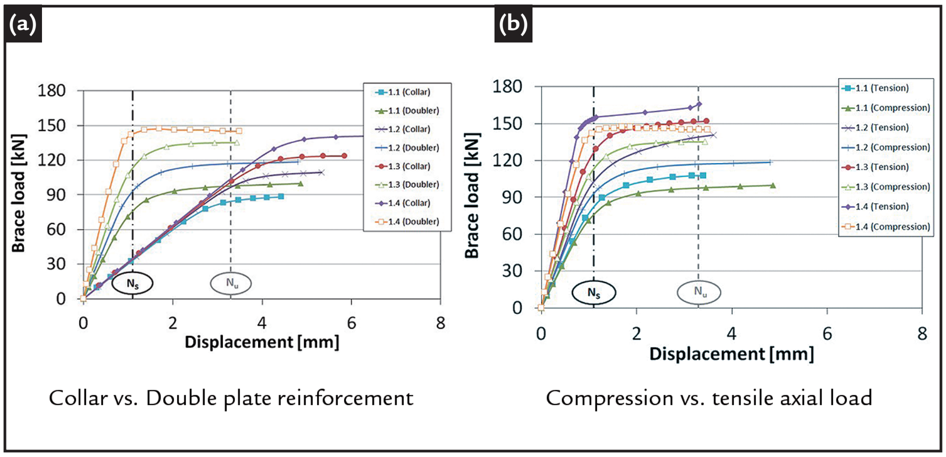


Figure 8
Numerical model results
for a 2.0 mm thick reinforcement plate.

Analyzing the cases where there is variation of the brace axial loads, present in Figure 9, a higher resistance for the reinforced T-joint subjected to tensile (compared to the ones with compression axial loads) could be observed. This difference becomes evident after the serviceability limit state.



Collar vs. Double plate reinforcement

Compression vs. tensile axial load

Figure 9
Numerical model results for a 4.0 mm thick reinforcement plate varying the reinforcement type and the brace axial loads.

4. Conclusions

In this paper, a numerical evaluation of T joints was carried out by varying the applied brace loads (compression and tension) while using two types of reinforcements: Collar and Double plates. The idea was to perform a structural joint reinforcement using a small thickness plate welded to the joint's upper chord region i.e.: a collar (where the weld was already present before the joint assembly), or double plates (where the weld was performed during the joint assembly). The aim of this plate was to increase the chord thickness at the joint region. The numerical models showed significant differences when the two reinforcement typologies were compared. There was a slight gain of resistance when a double plate reinforcement was used, mainly for small displacement, due to the great stiffness provided and a linear response up to the serviceability limit. This tendency was confirmed when other chords and braces were simulated. In terms of brace axial loads, the results showed a similar behavior. In special, there was a higher resistance for the reinforced T-joint subjected to tensile forces when compared to the ones with compression axial loads. The Von Mises stress distribution for the numerical models indicated that the chord yielding begins at the upper chord surface, close to joint region, being consistent with the type A failure mode predicted by design. Comparing the numerical results with NBR 16239 (2013), an excessive conservatism was noted for this code. In fact, the Brazilian code only takes into account the reinforcement thickness for evaluating the load carrying capacity. However, when the results provided by the new proposal where both thicknesses (chord and reinforcement) are considered, a more realistic assessment of the joint capacity is obtained. Even in this case, it is important to observe that the proposed formula results are still less than the numerical simulations showing a slight safety margin. Finally it must be said that there is an urge for the need of experiments to investigate and further calibrate the proposed change of the design method.

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