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Influence of bearing coefficient in cold-formed stainless steel bolted connection

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Abstract

The connections play an important role in the overall behaviour of the structures. Therefore an adequate structural design taking into account both safe and economic criterion is necessary. The structural design of stainless steel bolted connections using actual codes can provide inadequate design capacity mainly due to the use of similar rules based on analogies from mild carbon structures. Thus, the purpose of this paper is to evaluate the structural response of stainless bolted connections considering the steel grade austenitic 304. Experimental and numerical analyses have been carried out considering bolted connection under bearing failure. In details, the study cases were subjected to two shear planes with thin-plate and thick-plate. In these cases, the occurrence of curling failures is possible. A detailed study involving the geometric parameters adopted by design equations of bolted stainless steel connections was made. The outcomes showed a reduction of the ultimate capacity characterised by out-plane deformation. In addition, the current codes led to significant difference when compared to both experimental and numerical results.

Keywords

Stainless Steel, bolted connection, curling, bearing failure.

1 Introduction

It is possible to observe a significant increase in the use of stainless steel in civil structures, mainly in structural members. For instance, Figure 1 illustrates the Helix Bridge located in Singapore that contains a double spiral structure to reduce the steel volume in which duplex stainless steel grade was utilised in all structural elements. Stainless steels can provide excellent properties when compared to carbon steel, such as improvement in corrosion resistance, durability, fire resistance and high sustainable value. On the other hand, their high-costs issue can be surpassed when a life-cost analysis is considered [1].

Although this advance in the use of stainless steel can be observed, the current structural codes still have prescriptions that are similar to carbon steel. The use of these requirements can lead to inefficient structural designs, especially in economic terms, as they may be neglecting a considerable structural capacity of these elements. One of the major parts that influence their costs is the connections that have a fundamental role in the behaviour of the steel structures, as they are responsible for transmitting loads among their members.

In the current codes, the bolted connection design under shear is based on their ultimate capacity without taking into account deformation criteria. In general, the process is performed considering different failure modes that may occur where the weakest limit state controls the design. The following failure modes should be considered for bolted connection under shear: gross section yield, bearing and net-section rupture.

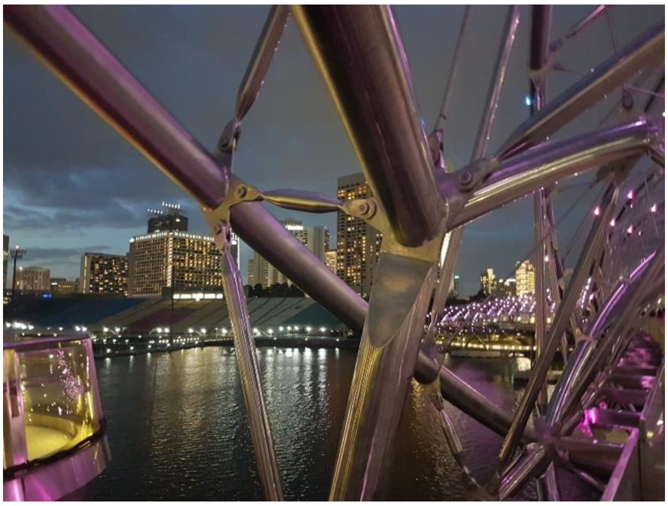


Figure 1 Helix bridge. Source: Lima, L (Author)

In addition, the evaluation also needs to address the bolts rupture (shear or tension), punching shear and combined shear and tension [2][3]. On the other hand, a recent design manual [4] reposted on a different approach to address stainless steel bolted connection where the needed to include deformation criteria in the structural design was prescribed.

In fact, in stainless steel connections, the large deformation capacity can provide a complex structural behaviour, especially for connections with thin-plate where there is a phenomenon characterised by out-plane deformation, i.e. curling [5]. This phenomenon is more likely in connections with long hole to end-plate distances. Kim & Kuwamura [6] concluded that the curling effect could reduce the ultimate capacity, especially in high ductility stainless steel connections.

This paper aimed to evaluate the influence of the curling effect in stainless steel bolted connection with double shear planes. Austenitic stainless steel 304 connections were investigated in two arrangements: with and without the occurrence of the curling effect. The present study involved both numerical and experimental modelling culminating in a parametric study varying geometric parameters to create a database for evaluating current codes

2 Literature review

Kim et al. [5] performed numerical and experimental studies with aiming to evaluate the behaviour of bolted connections with four bolts (2 rows and 2 columns) of 12 mm in diameter under single shear. The connection 3.2 mm thick plates were made of SS400 carbon steel. Characterisation test determined the 1.44 stress ratio ($f_u/f_{0,2\%}$) for the adopted stainless steel. The hole to plate edge distance (e_1), was studied with these connections presenting a block shear failure. The connections with e_1/d equal to 2.0 and 2.5 did not exhibit the curling effect, but for ratios equal to 3.0, 4.0 and 5.0 this phenomenon was observed. The parametric analysis was carried out in Abaqus program, and by restricting the deformation out of the plane (curling), the authors evaluated the influence of the curling effect on the ultimate connection resistance. In these joints, a reduction in their ultimate load was observed, ranging from 4% up to 17% for the models with e_1/d from 3.5 to 5.0, respectively. For lower values of e_1/d, the phenomenon did not occur or was not able to influence the ultimate load of the connection.

Kim & Kuwamura [6] performed a numerical investigation on connections using stainless steel thin-plates with single shear planes. A parametric analysis was performed in Abaqus, where the authors concluded that curling could reduce from 19 to 39 % of the joints ultimate load. The authors also evaluated the minimum geometry requirements that could induce the curling effect, i.e., plates with thickness (t) equal to 1.5 mm with end distance (e_1) higher than 1.5 times the bolt diameter (d) and edge distance (e_2) higher than 1.5d; for t equal to 3 mm, e_1 greater than 2.5d and e_2 higher than 2.0d; in 6mm connections, the curling effect did not occur.

Mahmood and Elaminb et al. [7] evaluated the ultimate resistance and failure modes of four-bolt carbon steel connections with single shear planes. The authors proposed equations to predict five failure modes present in this connection type, including the curling effect. The equations presented a better approximation to the results obtained experimentally, and in the numerical parametric study carried out for comparing the current design codes. The authors concluded that the curling effect could influence their ultimate capacity up to 12%, and the geometrical parameter e_1 could lead to an increase in resistance to up to the 50 mm limit value.

3 Design rules

This section presents the design equations for failure modes related to bearing included in design codes. This paper is limited to joint failing by bearing, inhibiting other failure modes. The idea was to compare the different approaches present in the current stainless steel bolted connection design codes. Thus, the investigated design codes were: EN1993-1-4 [3], AS/NZS 4673 [8], ASCE 8-02 [9] and the recent SCI design manual SCI 413 [4]. The equations are presented in Table 1 without the partial safety coefficients.

Table 1 Equation from different structural codes

Design	Bearing failure	Coefficient
EC3-1.4	$2.5^{1)} \cdot \alpha_b \cdot d \cdot t \cdot f_{u,red}$	$f_{u,red} = 0.5f_y + 0.6f_u \leq f_u$ $\alpha_b = \frac{e_1}{3d_0} \leq 1$ *and* $\leq f_{ub}/f_u$
AS/NZS ASCE	$e_1 \cdot t \cdot f_{ut}$	for tear-out failure
	$2.75 \cdot d \cdot t \cdot f_u$	for bearing failure
SCI	$2.5 \cdot k_t \cdot \alpha_b \cdot d \cdot t \cdot f_u$	$\alpha_b = \min\left[1.0, \frac{e_1}{3d_0}\right]$ $\alpha_b = \min\left[1.0, \frac{e_1}{2d_0}\right]^{2),3)}$ $k_t = 1.0$ for $\frac{e_2}{d_0} > 1.5$ $k_t = 0.8$ for $\frac{e_2}{d_0} \leq 1.5$ $k_t = 0.5^{2)}$ $k_t = 0.64^{3)}$
1) equal to 2.5 for $\frac{e_2}{d_0} \geq \mathbf{1.5}$ 2) for deformation criteria 3) Thin plate in outer sheet		

For a better comparison of the equations shown in Table 1, Figure 2 shows the evolution of the connection capacity for the bearing failure mode, where the load ratio recommended by the code, concerning the e_1/d_0 parameter was evaluated. The value of, e_1 corresponding to the distance between the hole and the edge parallel to the load application while d_0 is the hole diameter. In this graph, the bolt diameter was kept constant and equal to 12 mm since this was the value adopted n the investigated connections. The other parameters were the same used in the analyzed connections, which will be discussed in more details in the next sections.

In this graph, as SCI 413 [4] uses different equations depending on the plate thickness and its arrangement, two hypotheses were considered. The first with the external plates controlling the design (SCI1) and the other with the central plate it (SCI2). SCI 413 [4] uses the same criteria for thick plates (t> 4 mm). It could also be observed the limit of resistance increase associated with each code, where SCI 413 [4] uses when external thin plates control the design. The limit of resistance increase due to the bearing coefficient in the load direction is given by $e_1/d_0 \geq 2.5$. For the equation used for thick and thin plates with the central plate controlling the design, this limit becomes $e_1/d_0 \geq 3.5$. The same is used by EN1993-1-4 [3]. AS/NZS 4673 [8] and ASCE 8-02 [9] codes separate the plate tearing failure mode from the bearing mode, where the second failure mode is valid for $e_1/d_0 \geq 3.0$, which is constant for higher values of e_1.

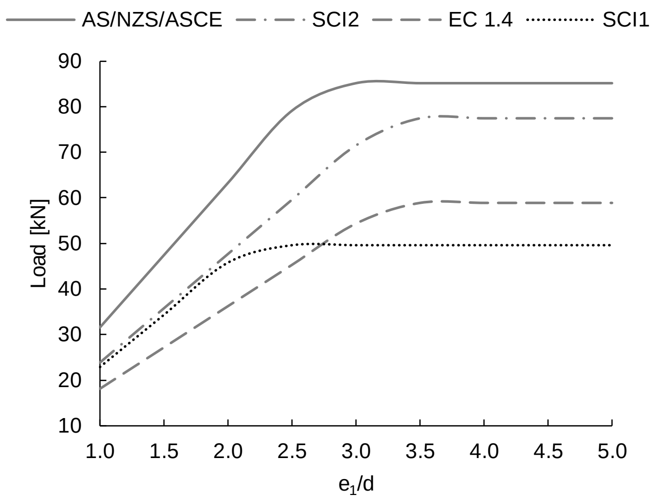


Figure 2 Load versus e_1/d curves for the same hole diameter

4 Experimental programme

The experimental program consisted of four austenitic 304 stainless steel bolted connections with two different arrangements. The test arrangements are shown in Figure 3. The investigated connections have two shear planes, however, in a), a connection with the external stainless steel plates controlling the structural design, a thick carbon steel central plate was used; in b), a connection with three equal thickness stainless steel plates the middle plate controlled the joint design. The bolts used in all tests were M12 steel, class 12.9.

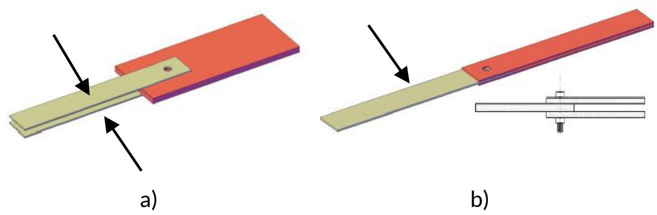


Figure 3 Arrangement developed - a) outer plate critical, b) inner plate critical

The experiments were performed focusing on the e_1 variation, where the values of 22 mm and 32 mm were used in each arrangement shown in Figure 3. A sketch with the geometric parameters of the stainless steel plates is shown in Figure 4. The plates had a nominal value of 50x400x3 mm. The actual dimensions of the stainless steel plates are reported in Table 2.

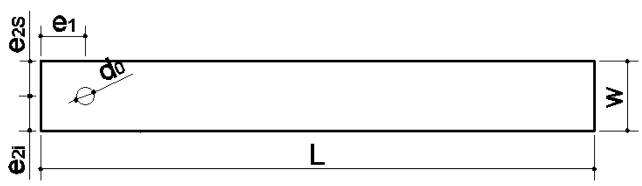


Figure 4 Stainless steel plate geometry

A nomenclature was proposed based on the three parameters investigated to identify the case studies: the first represents the type of arrangement used where the (O) corresponds to the connection that has the external or the middle plate controlling the (I); the second and third parameters represent the nominal value of the plate geometry, the distance e_1 (EXX) and thickness (TX), respectively.

Table 2 Tested geometry

Specimen		Thickness	End distance	Edge distance	Hole diameter
		t (mm)	e_1 (mm)	e_2 (mm)	d_0 (mm)
O-E22-T3	a	3.10	22.07	25.12	13.02
	b	3.08	21.98	25.15	13.00
O-E32-T3	a	3.10	31.98	25.05	13.00
	b	3.10	31.80	25.15	13.00
I-E22-T3		3.08	22.04	25.15	13.00
I-E32-T3		3.08	32.30	25.13	13.00

4.1 Tensile coupons tests

Tensile tests were carried out considering the Huang & Young [10] criteria. The stainless steel coupon tests had very complex behaviour in comparison with traditional carbon steel. These tests provided the material stress-strain curves. Coupon tests were performed considering the plates rolling direction where the loading direction (A00) and in the transversal direction (A90), with repetition was performed for each model totalling four tests. The average of the main results found are presented in Table 3 and the stress versus strain curves in Figure 5, which also contains a photograph of the deformed and undeformed specimens.

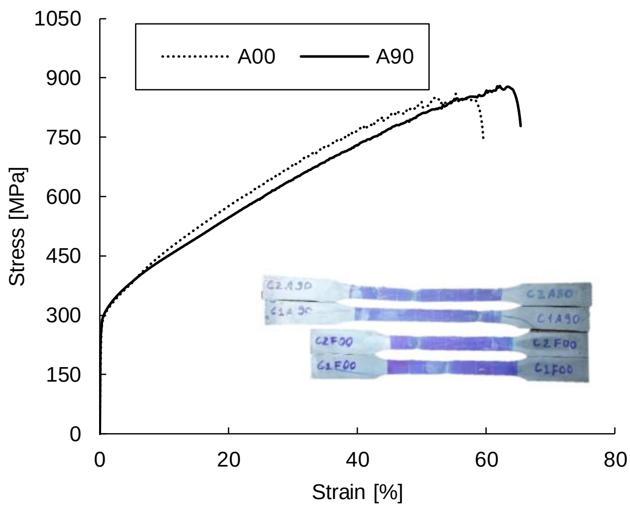


Figure 5 Stress-strain curves of Austenitic 304

With these results, a small degree of anisotropy was observed, and the large deformation capacity stands out when compared to the results obtained by Kim and Kim et al. [5] for the carbon steel (1.44).

Table 3 Coupon tests results

CP	E [GPa]	$\sigma_{0.2}$ [MPa]	$\varepsilon_{0.2}$ [%]	f_u [MPa]	ε_u [%]	f_u / f_y
A00	202	275	0.336	860	55.279	3.13
A90	258	279	0.308	879	62.092	3.15

4.2 Experimental results

In this section, the results obtained in the experiments are presented and summarized in Table 4. The connections with the distance e_1 equal to 22 mm did not present the curling effect, or at least it was not significant. In both cases analysed, the connections failed due to the plate tearing failure mode (T). For the connections with e_1 equal to 32 mm, the curling effect occurred; however, for the connection with external plates (O-E32), there was an unexpected bolt rupture. Thus, it was not possible to obtain the ultimate load. For the I-E32connection, the bearing plate failure mode (B) was observed.

Table 4 Ultimate load and failure modes obtained in the experiments

Specimen		Thickness t (mm)	End distance e1 (mm)	Failure mode	P_{ue} (kN)
O-E22-T3	a	3.10	22.07	T	56.47
	b	3.08	21.98		
O-E32-T3	a	3.10	31.98	S + curling	54.35
	b	3.10	31.80		
I-E22-T3		3.08	22.04	T	53.38
I-E32-T3		3.08	32.30	B + Curling	70.11

5 Finite element modelling

The numerical models were developed in Abaqus [11]. Static analyses were carried out with both physical and geometric nonlinearities using C3D8 solid elements. General contact type was used where the friction coefficient, equal to 0.25, was employed together with the standard type "hard" contact. The boundary conditions are similar to the ones observed in the experiments. In Figure 6, the reference model with e_1 equal to 60 mm is illustrated.

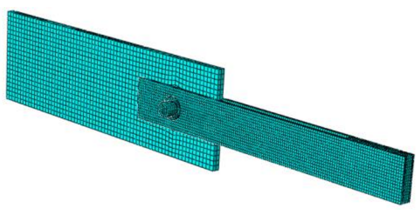


Figure 6 Adopted finite element mesh O-E60-T3

Data obtained in the characterization tests were considered as the model materials properties using true stress- true strain curves.

5.1 Validation of FE models

In general, the numerical models were able to represent the bolted connections actual behaviour, both in terms of ultimate loads and failure modes. Figure 7 contains a comparison of experiments and numerical models in term of load versus axial displacement curves. It also presents the predictions given by each code. Figure 8 depicts the deformed of the tests with external plates controlling the design with their respective numerical models.

With the results shown in Figure 7, it is possible to observe the dispersion between the results provided by the codes. SCI 413 [4] showed a good correlation with the results obtained experimentally and numerically. AS/NZS 4673 [8] and ASCE 8-02 [9] codes for cases where ($e_1/d<3$) proved to be unsafe. EN1993-1-4 [3] led to the most conservative forecasts.

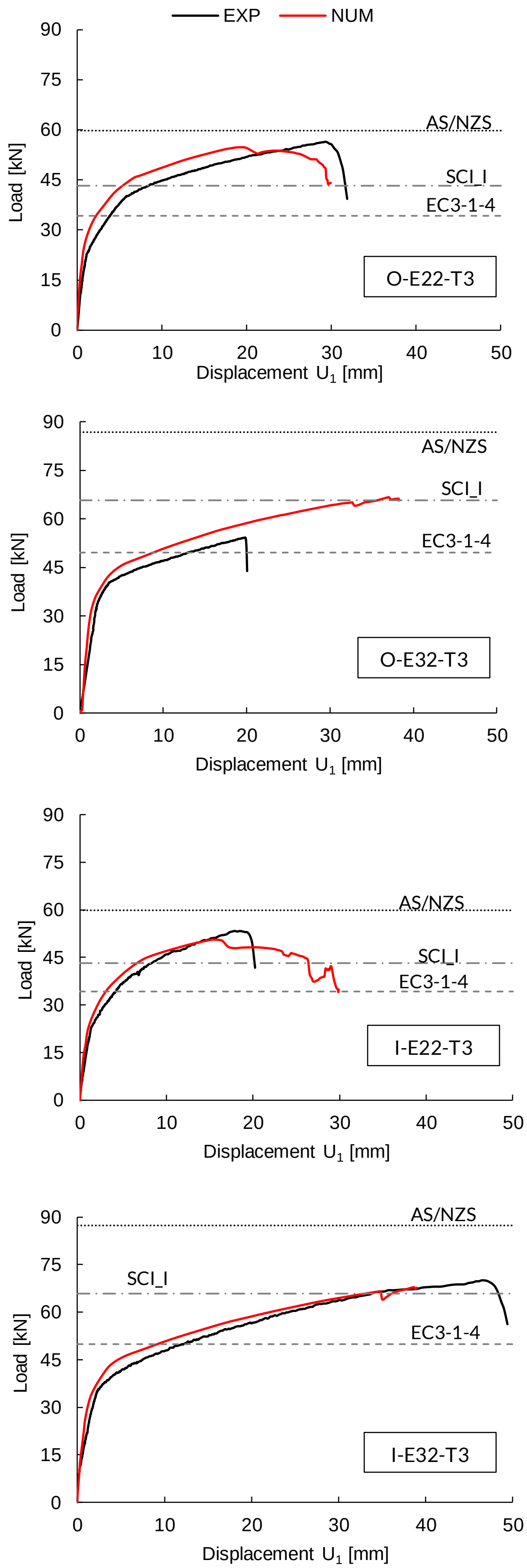


Figure 7 Experimental and numerical and current design codes comparison.

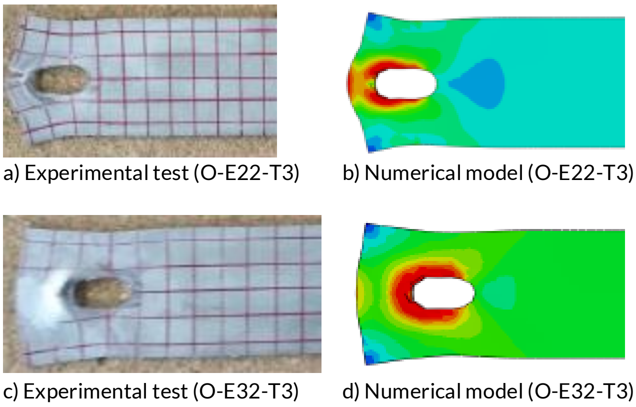


Figure 8 Comparison between deformed experimental tests and numerical models

Table 5 presents a summary of the results obtained, showing a good correlation between the ultimate loads obtained between the experiments and the numerical model, except for the O-32-T3 test, which had an unforeseen bolt failure. Excluding this test from the analysis, a P_{NUM}/P_{EXP} average of 0.96 could be obtained, with a small standard deviation of 1.2%. These numbers validated the numerical model enabling a parametric study to be performed.

Table 5 Validation of results

Specimen	FE analysis		Experiment		P_{NUM}/P_{EXP}
	P_{NUM} (kN)	Failure mode	P_{EXP}	Failure mode	
O-E22-T3	54.82	E	56.47	T	0.97
O-E32-T3	66.68	B + curling	54.35*	S + curling	1.23
I-E22-T3	50.58	E	53.38	T	0.95
I-E32-T3	67.89	B + curling	70.11	B + curling	0.97

* Bolt rupture before reaching the maximum load

5.2 Parametric study

The parametric study aimed to evaluate the influence of the curling effect on the behaviour of the connection. Thus, the geometric properties of the connections varied from, e_1 equal to 42 mm (e_1/d =3.5) to a value of 60 mm (e_1/d =5.0). The analyzed cases were expected to be in the constant load regime provided by design codes (see Figure 2). In addition to the variation of parameter e_1/d, different thickness values were also analyzed: 2 mm, 3 mm and 5 mm, including thin and thick plates. Two layouts were studied with inner and outer as the critical plate, totalling 12 models. Table 6 presents the parametric study models evaluated with their main geometric parameters.

The bearing failure mode observed in all connections. The difference between the connections ultimate loads with curling presented a reduction in their load capacity. Figure 9 presents a comparison between the two investigated joints layout with a 3 mm plate where it can be observed that the model without curling reached a higher ultimate load (about 8%).

Figure 10 shows the deformation of each investigated connection when it reaches the load predicted by EN1993-1-4 [3]. It can be mentioned that the out of the plane displacement is much higher for cases with higher e_1 values, and even for thinner plates.

Table 6 Numerical models investigated in the parametric study

	Models	e_1 (mm)	t (mm)	d_0 (mm)	w (mm)	L (mm)
1	**O-E42-T2**	42	2	13	50	400
2	**O-E42-T3**	42	3	13	50	400
3	**O-E42-T5**	42	5	13	50	400
4	**O-E60-T2**	60	2	13	50	400
5	**O-E60-T3**	60	3	13	50	400
6	**O-E60-T5**	60	5	13	50	400
7	**I-E42-T2**	42	2	13	50	400
8	**I-E42-T3**	42	3	13	50	400
9	**I-E42-T5**	42	5	13	50	400
10	**I-E60-T2**	60	2	13	50	400
11	**I-E60-T3**	60	3	13	50	400
12	**I-E60-T5**	60	5	13	50	400

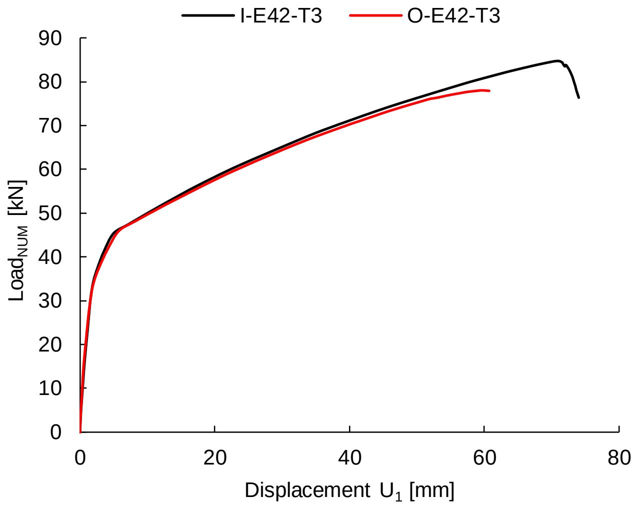


Figure 9 $Load_{NUM}$ versus axial displacement curves for the X-E42-T3 model.

A curve was traced relating the load normalized ($P_{NUM}/P_{EC3-1-4}$) with the out of the plane displacement (curling), measured on the axis of the end of the stainless steel plate is shown in Figure 11. From this curve, it was possible to observe that regardless of the connection thickness, the curling effect starts at the same load level, equal to 0.4, which is very close to the value determined by SCI 413 [4] for connections with deformation control, identified as SCI_ELS. After this limit, the phenomenon begins to be influenced by the connection geometric parameters, t and e_1. Connections with upper e_1 and lower t presented a lower load level for the same level of out of the plane displacement.

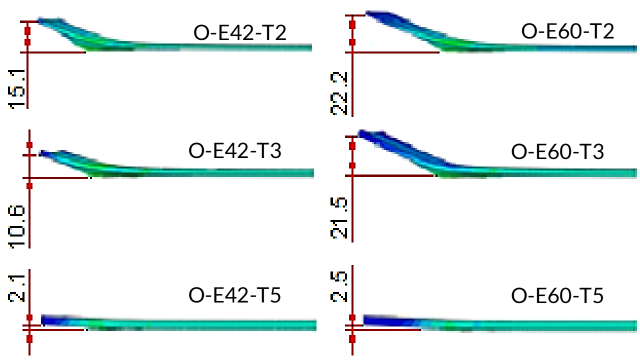


Figure 10 Out-plane deformation (values in mm)

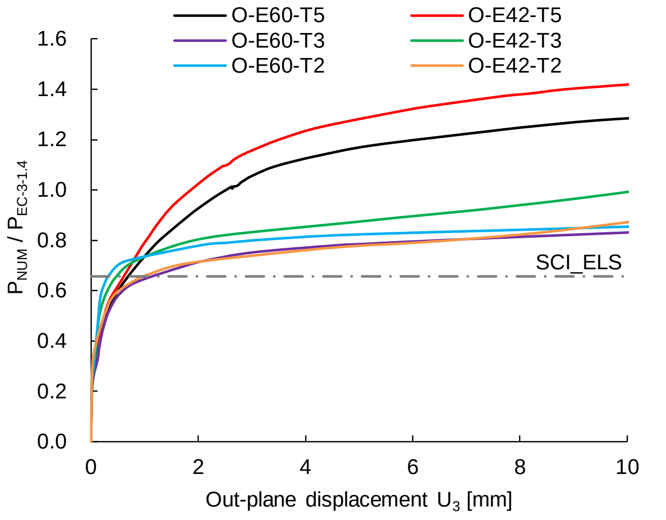


Figure 11 Curves comparing the ratio $P_{NUM}/P_{EC3\text{-}1.4}$ with the out-plane deformation

Figure 11, 12 and 13 show curves with the numerical normalised load ($P_{NUM}/P_{EC3\text{-}1\text{-}4}$) versus the bearing measured at the displacement associated with the hole elongation.

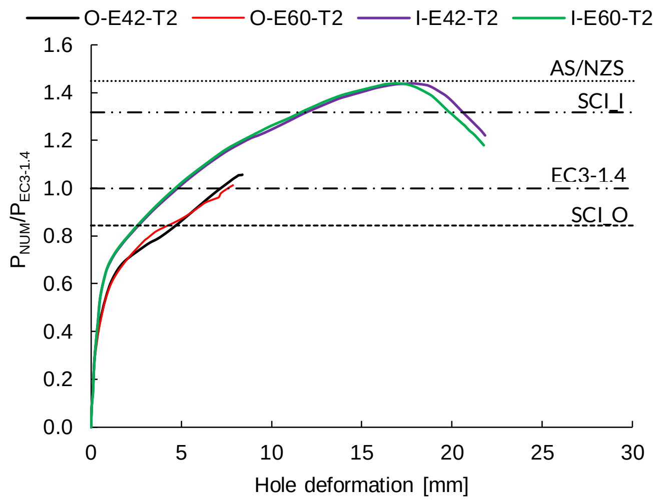


Figure 12 $P_{NUM}/P_{EC3\text{-}1\text{-}4}$ versus bearing for connection with t equal to 2 mm

From these curves, it was possible to observe a drop in stiffness generated by the curling effect, which was slightly more pronounced in thickness, t equal to 2 mm, which are more susceptible to the phenomenon. For connections with t equal to 5 mm, considered thick by SCI 413 [4], the phenomenon was not relevant, being similar to connections where the inner plate controlled the design.

Despite the difficulty in determining the connections ultimate load in the influenced by the curling effect through a static analysis, it was possible to verify how conservative the codes are in this aspect except for AS/NZS 4673 [8] and ASCE 8-02 [9], which reached excellent approximations for connections without the curling effect, or in which the phenomenon did not influence their behaviour. Alternatively, connections that presented the curling effect or tear out failures led to unsafe value when using AS/NZS 4673 [8] and ASCE 8-02 [9]. Therefore, for connections with the e_1/d ratio lower than 3, SCI 413 [4] led to the most efficient predictions. For connections with higher e_1 values where the phenomenon occurs, the code presents a high reduction of resistance with the adoption of the bearing coefficient α_b Therefore, for these connections, EN1993-1-4 [3] proved to be more suitable, although the Eurocode uses a reduced ultimate strength that would lead to more economical designs.

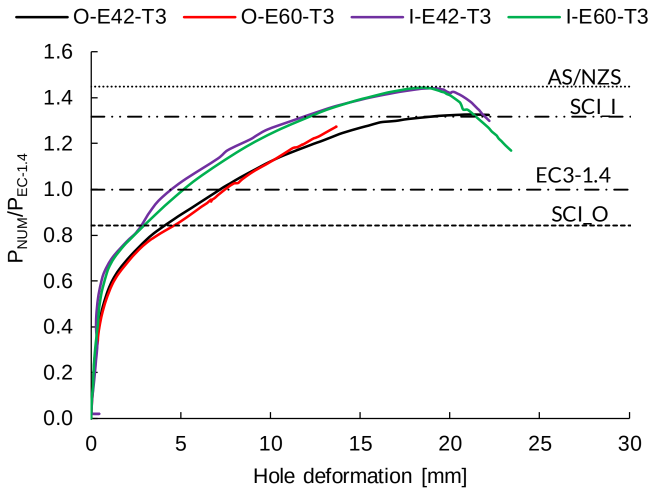


Figure 13 $P_{NUM}/P_{EC3\text{-}1\text{-}4}$ versus bearing for connection with t equal to 3 mm

On the other hand, SCI 413 [4] does not provide better precision in terms of the connections ultimate loads. For SCI 413 [4], as previously presented, the bolted connection design is divided into thin and thick plates. For the first, there is an equation for two shear planes connections where the inner plate control the design while another equation is used for connections with external plates controlling the design.

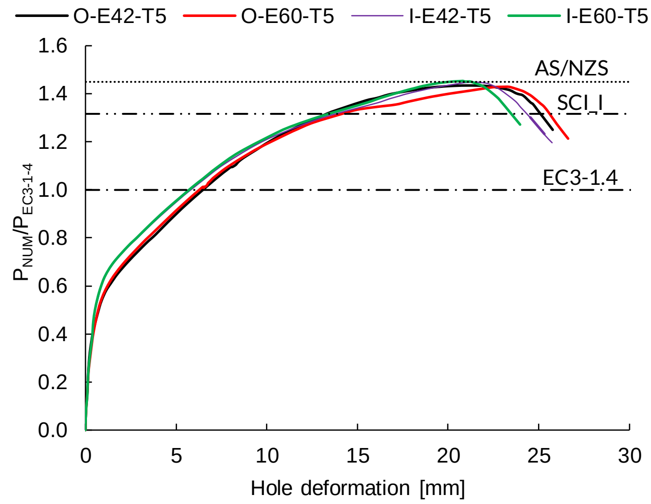
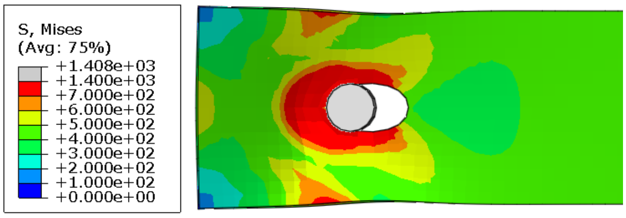


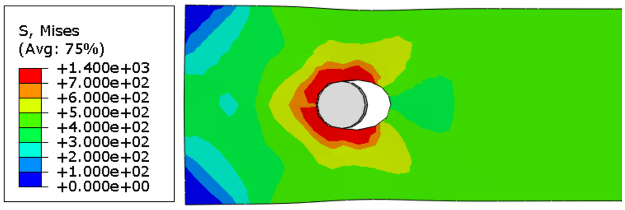
Figure 14 $P_{NUM}/P_{EC3\text{-}1\text{-}4}$ versus bearing for connection with t equal to 5 mm

Figure 15 shows the connection deformation with t equal to 3 mm and 5 mm and e_1 equal to 42 mm. This figure contains the von Mises stresses corresponding to the load predicted by EN1993-1-4 [3]. It is possible to notice that in connection with curling effect (O-E42-T3) there is higher stress level occurring in the bearing region, when compared to the connection of the same geometry (I -E42-T3) without curling. This observation explains the drop in rigidity in connections presenting the curling effect. For the 2 mm thick connection with e_1 equal to 60 mm the same conclusion could be drawn. For 5 mm thick connections, a similarity in the stress distribution between the connections with the inner or outter plate controlling the design could be observed.

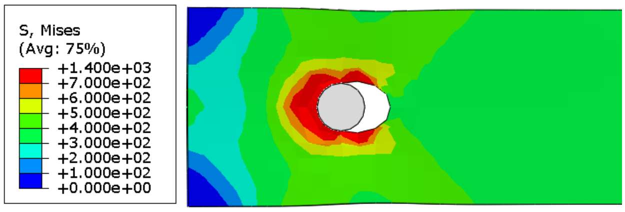
Figure 16 presents a ($P_{NUM}/P_{EC3\text{-}1\text{-}4}$) versus bearing curve where the magnitude of the curling effect (out-plane deformation in millimetres) was considered varying the loading levels. This curves made it possible to identify an out of plane displacement equal to 0.5 mm as the value corresponding to the design load predicted by SCI 413 [4] using the strain criterion. In addition, it was possible to confirm the connections ultimate load reduction due to the curling effect, i.e. 8%.



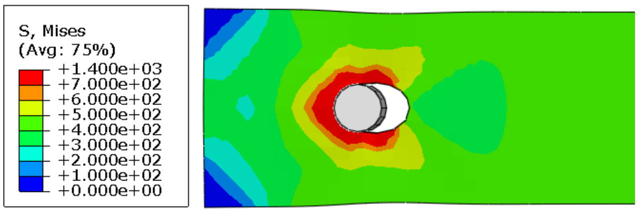
(a) O-E42-T3



(b) I-E42-T3



(c) O-E42-T5



(d) I-E60-T3

Figure 15 Von Mises stress distribution

6 Conclusion

The bearing coefficient Influence in cold-formed stainless steel bolted connection was evaluated in this paper through an assessment of the structural response of Austenitic 304 double shear plates with one bolt. Two joint layouts were studied considering the critical failure in the inner or outer plate. Both experimental and numerical analyses were performed, followed by a parametric study to investigate the curling effect in stainless steel bolted connections. This study indicated that curling reduces the joints ultimate loads and stiffness while in theses connections, a higher stress level in the plate crushing region was also observed.

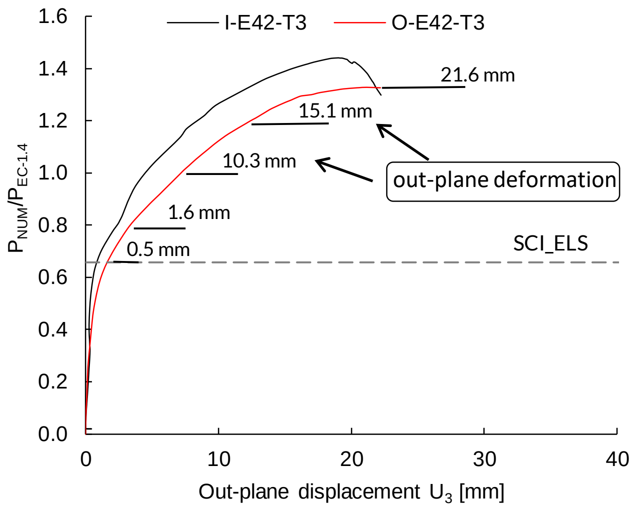


Figure 16 $P_{NUM}/P_{EC3-1-4}$ versus bearing deformation curves where the out-plane displacement are identified (e_1 = 42 mm and t = 3 mm).

SCI 413 [4] presented a good experimental and numerical accuracy associated with the adoption of the formulae used for connections design based on deformation control, where the maximum out of plane displacement reaches 0.5 mm. For connections without the curling effect or thick plates connections, AS/NZS 4673 [8] and ASCE 8-02 [9] provided an excellent prediction of their ultimate load-carrying capacities. However, for the other connections, it leads to unsafe design predictions. Therefore, the use of the SCI 413 [4]it is suggested for connections with e_1/d ratios less than 3. Although, the use of the European code reduced ultimate load led to more inconsistent values, more economical results were achieved while making the use of stainless steel in structural applications more competitive.

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References

[1] Silva, G.; Silva, A.T; Vellasco, P.C.G.S; Lima, L.R. (2016) *Avaliação técnica económica de torres de aço inoxidável para transmissão de energia*. Metálica 43, p10-16. (In Portuguese).

[2] EN1993-1-8 (2005) *Eurocode 3 - Design of steel structures: Part 1-8: Design of joints*. Brussels: European Committee for standardization, p. 133.

[3] EN1993-1-4 (2006) Eurocode 3 - Design of steel structures: Part 1-4: General rules - Supplementary rules for stainless steels. Brussels: European Committee for standardization, p. 35.

[4] SCI P413 (2018) *Design Manual For Structural Stainless Steel – 4th Edition*. The Steel Construction Institute - SCI. [S.l.], p. 284.

[5] Kim, T.S.; Yoo, J.H.; Roeder, C.W. (2015) *Experimental investigation on strength and curling influence of bolted connections in thin-walled carbon steel*. Thin-Walled Structures, 91, p. 1-12.

[6] Kim, T.S.; Kuwamura, H. (2011) *Numerical investigation on strength design and curling effect of mechanically fastened joints in*

cold-formed austenitic stainless steel. Materials and Design 32, 3942–3956.

[7] Mahmood, M., Elamin, A., Tizani, W. (2020) *Ultimate strength and fracture sequence of bolted connections to thin-walled carbon steel*. Structures 23, S 646–659.

[8] AS/NZS 4673 (2001) *Cold-formed stainless steel structures*. Sydney/Wellington, p. 130.

[9] SEI/ASCE-8-02 (2002) *Specification for the design of cold-formed stainless steel structural*. American Society of Civil Engineers.

[10] Huang, Y., & Young, B. (2014) *The art of coupon tests*. Journal of Constructional Steel Research 96, p. 159-175.

[11] ABAQUS/CAE 6.14-5 (2014). Theory Reference. SIMULIA - Inc. [S.l.].