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Experimental investigation on the instability phenomenon in stainless steel connections—plate curling

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ABSTRACT: The overlap bolted steel connection with thin-plates can be subjected to the occurrence of the phenomenon known as curling effect, which is able to influence the global behavior and decrease its ultimate strength. For stainless steel joints, the mechanism is even more important, because it is a material with high deformation capacity. Therefore, both experimental tests and numerical analyses are presented in this paper in order to investigate the influence of curling effect in overlap bolted connection. In addition, the lips were also studied because they increase the stiffness for the out-plane displacement. The outcomes shown that the curling effect reduced the ultimate bearing resistance. Comparing the actual codes, the design load provided by they are lower than those are obtained in both experimental and numerical tests. In addition, it can be reported the efficiency from the lips for the ferritic overlap connection.

1 INTRODUCTION

The connection plays a very important role in structure in order to transfer the forces among the structural members and contribute in the global structural behavior. In nowadays, the most commonly used types of connections are welded and bolted. The rivet connections also were very common in the past. In details, the overlap bolted connections have been observed in several civil constructions due to easy applicability. In structural design of these connections type, it is important to define the possible failure modes associated to applied load type, geometric proprieties and material employed. It is recognized that these connection types can present the following failure modes corresponding to net rupture, bearing, bolted shear and yielding gross section. In addition, in thin-plates, there is another failure mode associated to high compression stress in near hole known as curling. In fact, the curling effect can occur due to compression deformation in the end-region of the connection, where the end-plate is fixed by both nut and bolt, and at the other there is no restriction resulting in out-plane deformation. This phenomenon has superior relevance in bolted connections with high distance between the hole and edge plate, as well as, in materials with high deformation capacity, such as, stainless steel (Henriques et al, 2018).

In fact, the stainless steel provides large deformation capacity in comparison with the carbon one. Although there is still a limited examples of civil structures with stainless steel members, the application of stainless steel for structural has been used more frequently in recent years, mainly due to the increase of research on its use. This steel grade is recognized by the presence of the chromium and nickel, and may contain molybdenum, iron and other elements. In special, stainless steel should contain at least 10.5% chromium. The interesting in this steel grade from engineer and researcher is associated to excellent proprieties in comparison with traditional mild carbon steels, such as high corrosion resistance, durability, fire resistance and high aesthetic value. On the other hand, the material cost of the stainless profiles is very higher complicating the use in large scale in civil constructions. Recently, this idea was overcome through of the study performed by Silva et al (2016) when the structural design is addressed to assessment of the maintenance cost to be spent over the life of power transmission tower when there is comparison of mild carbon against stainless steel grades. Therefore, stainless steel can provide several advantages related to carbon steel, which over time can become a more economical solution, such as corrosion resistance, better behavior at high temperatures when compared to carbon steel, higher reuse capacity, ductility and impact resistance (Baddoo, 2008).

Considering the promising use of stainless steel in civil structures, this paper aims to investigate the influence of this steel type in overlap shear connection using thin-plates when it is possible to observe the curling effect. Several studies can be found in literature about the structural behavior of stainless bolted connections. In details, Kim et al (2009) observed that in the bolted connections, the ultimate resistance increases in proportion to distance between hole and edge-plate until the appearance of the curling effect. The occurrence and magnitude of the influence of the curling effected the ultimate resistance being associated to thickness plate and distance from hole and edge-plate. For the described arrangements, this phenomenon reduced the connection ultimate resistance by 11%, 16% and 14% for the plates with 1.5 mm, 3.0 mm and 6.0 mm, respectively. In order to reduce the influence of the curling effect, Yancheng & Young (2014) investigated through experimental tests the behavior of the stainless bolted connections using lips. The idea was to assess the bolted connections capacity without the influence of the curling effect since the lips increase the stiffness for the out-plane displacement. The results shown that the nominal resistance obtained from actual design codes are generally conservative for both single and double shear bolted connections. On the other hand, the failure modes observed in experimental tests are close to those predicted by European code (EN 1993-1-4, 2006). Hence, the purpose of the present investigation is to contribute with further experimental and numerical analyses in order to investigate the curling effect in bolted stainless steel connections using lips. Hereafter, experimental tests are presented where it was carried out two stainless steel grades: Austenitic and Ferritic. In addition, a numerical model has been developed on basis of the experimental tests and the results are compared in terms load-displacement curves and failure modes.

2 STRUCTURAL DESIGN OF OVERLAP BOLTED CONNECTIONS

2.1 *Eurocode*

According to EN 1993-1-4 (2006), the structural design of overlap bolted connections is addressed to verification of the plastic resistance of the both gross and net cross-section, bearing and limitation of the geometries on basis of the ultimate capacity. Considering the particular stainless behavior for gross cross-section, based on the yield stress, this criterion can control the structural design and limit the connection resistance. The gross cross-section resistance should be determined using the following equation:

$$N_{pl,Rd} = \frac{A \times f_y}{\gamma_{M0}} \tag{1}$$

where, A corresponds to gross cross-section area, fy is the yield strength obtained from the stress-strain curve. The partial safety factor γ_{M0} is equal to 1.1. On the other hand, if this expression is employed for the carbon steel connections with a distinct value equals to 1.0 is adopted.

The net cross-section resistance of a plate with holes is prescribed in EN 1993-1-4 (2006) on basis of the following equation:

$$N_{u,Rd} = \frac{k_r \times A_{net} \times f_u}{\gamma_{M2}} \tag{2}$$

where, A_{net} is associated to net cross-section area, f_u is the ultimate tensile strength of the material and γ_{M2} is a partial safety factor equal to 1.25. In this case, there is no difference between the carbon or stainless steel connections for this partial safety factor. In contrast, the value of the k_r is equal to 0.9 for the carbon steel.

The bearing resistance is given in EN 1993-1-8 (2005) using a similar curve for carbon steel:

$$F_{b,Rd} = \frac{k_1 \times \alpha_b \times f_u \times d \times t}{\gamma_{M2}} \tag{3}$$

where, d is the nominal bolt diameter, t corresponds to plate thickness, k_1 depends on the edge distance and inner bolts and α_b is minimum value of the following based in geometric relationships. For stainless steel connection, EN 1993-1-4 (2006) establishes that the ultimate strength, f_u, should be reduced due to a hole elongation limitation under serviceability loads. This reduction is defined by combination of the yielding and ultimate strength of the material:

$$f_{u,\mathrm{Red}} = 0,5f_y + 0.6f_u \tag{4}$$

Recently, it was published a new version of the Design Manual for Structural Stainless Steel developed by The Steel Construction Institute (SCI) of for stainless steel structures in which there is an important contribution in the bearing resistance of bolted connections. The SCI P413 (2017) establishes that the use of the reduced ultimate strength to be applied in bearing capacity is replaced by ultimate strength. In addition, this manual determinates that bolted connection design needs to be verified based on two limit states: serviceability and ultimate. This design strategy has been investigated in other study (Salih et al, 2011).

3 STUDY CASES

3.1 *Experimental program*

In this section, it is presented the experimental program carried out, which consists of eight tests with and without lips being divided by stainless steel grades. For the first, two connections with two shear planes were investigated where the external plates are controlling the structural design. Here, the use of lips aim to mitigate the curling influence on the global behavior due to stiffness increasing for out-plane displacements. For the second one, tests were carried out on two shear planes with the central plate controlling the connection capacity. In these models, the main objective is to analyze the behavior of the central plate, which is prevented from occurring the curling effect. Therefore, with the tests carried out, it was possible to evaluate the influence of the curling effect on austenitic and ferritic bolted connections steels.

A schematic drawing of the tests with and without lips is shown in Figure 1 where the nominal value of the length of the stiffener L_2 is equal to twice the value of e_1, and its height, h, equal to 10 mm. The plates have 3 mm thickness where the value of e_1 is equal to 32 mm, w corresponding to 50 mm, hole diameter equal to 13 mm and total length is 40 mm. In addition, the bolted connections with lips are composed by mild carbon steel with 15 mm thickness being designed in order to avoid a premature failure.

In order to identify the study cases, a nomenclature has been used being composed of a code with two parameters. The first represents if the bolted connection is composed by outer plates (OP) or inner plate (IN) to be considered as controlling member. The outer plates have lips in order to increasing the stiffness against out-plane displacement. Thus, the aim is

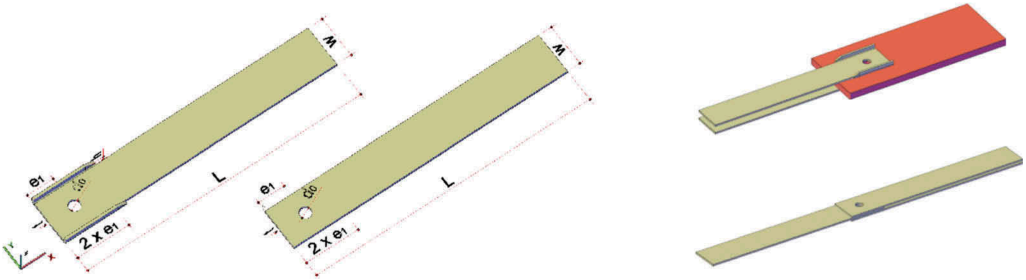


Figure 1. Geometries properties of the plates investigated.

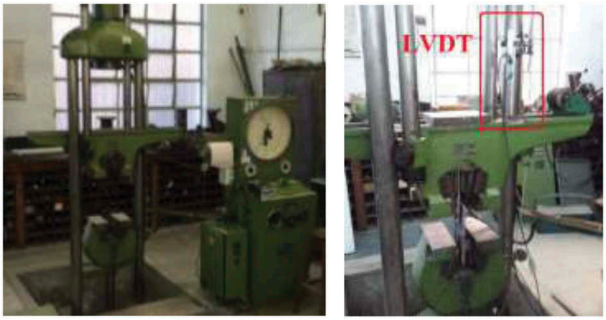


Figure 2. Universal machine and LVDT position used in experimental tests.

avoiding the influence of the curling effect on bolted connection behavior, which may influence its maximum resistance (Sobrinho et al, 2018). The last parameter of the code represents whether the bolted connections is with Austenitic (A) or Ferritic steel grades. The bolt used for all tests was M12 class 12.9 type.

In order to perform the tests, the Losenhausen machine of 600kN was used, as shown in Figure 2. The tests were instrumented with a linear differential transformer (LVDT) for measuring the axial displacement of the tests and the curling displacement in the region between the hole and the end of the plate. All the instruments were connected to the system Quantum X-MX1615B universal data acquisition from HBM Test and Measurement.

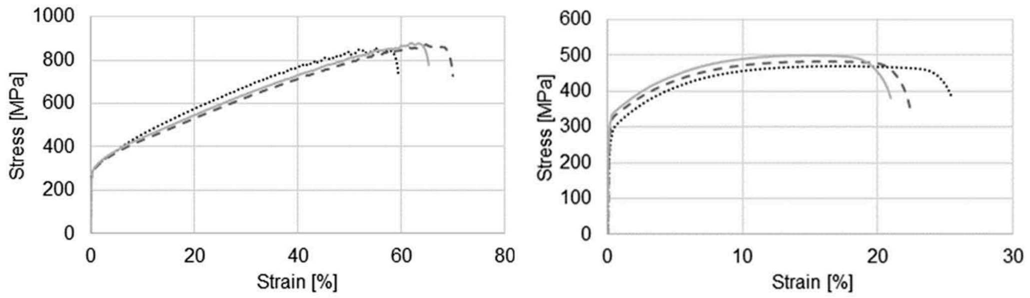
3.2 *Material characterization*

The stress-strain curves were obtained for both ferritic and austenitic stainless steel grades using the longitudinal tensile tests. The coupons tests were extracted considering the orientation of the batch of stainless steel plate. In detail, it was fabricated twelve coupons tests being considered the load axis for parallel, perpendicular and one direction corresponding to forty-five degrees of batch of the plate. Figure 3 illustrates the three stress-strain curves found in tensile coupon tests.

In addition, the Table 1 reports the summary of main proprieties obtained from these curves. As can observed, there is a notorious difference observed in structural behavior from the both austenitic and ferritic stainless grades. The batch orientation has more influence for the ferritic plates in comparison with the austenitic. Comparing the outcomes with the EN 1994-1-4 (2006), it can be observed a good correlation in terms of $\sigma_{0.2\%}$. On the other hand, the ultimate strength from the Austenitic plate presented an higher difference. In general, the values found in longitudinal tensile tests are superior to reported in EN 1993-1-4 (2006).

3.3 *Numerical modelling*

The finite element model used in this paper to investigate the tension capacity of overlap bolted connections was developed by of software Abaqus 6.14 (2014). This element finite



a) Austenitic b) Ferritic

Figure 3. Stress-strain curves reported in tensile coupons tests.

Table 1. Main proprieties of coupon tests.

						EN 1993-1.4 (2006)	
CP	E [GPa]	$\sigma_{0,2\%}$ [MPa]	$\varepsilon_{0,2\%}$ [%]	σ_u [MPa]	ε_u [%]	$\sigma_{0,2\%}$ [MPa]	σ_u [Mpa]
A00	202	275	0.336	860	55.2	230	540
A45	245	276	0.313	873	64.7		
A90	258	279	0.308	879	62.0		
F00	271	281	0.260	472	17.2	260	450
F45	254	322	0.286	484	15.6		
F90	219	325	0.291	500	15.0		

program is recognized by powerful tool that can incorporate material, geometric and boundary non-linearity cause by nonlinear elasticity, plasticity, large displacement, contact problem, etc. The numerical models were implemented using solid elements C3D8R defined by eight nodes with three degrees of freedom per node: translations in the nodal x, y and z directions.

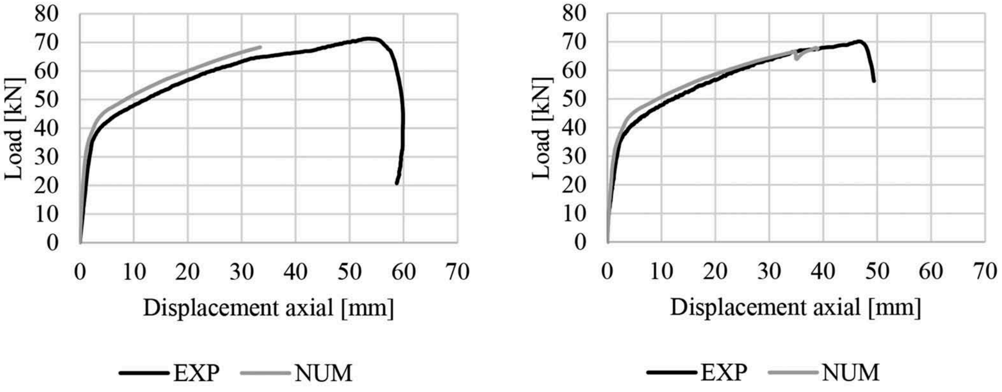
Concerning to adopted mesh, it was chosen a distribution which the proportions and size to be adopted had the aim of avoid the numerical problems. In special, the mesh was refined locally near the bolt hole for improved resolution of stress and strain due to be a region with recognized high stress concentration. Contact surfaces were considered in bolt and plates to better fit the adopted mesh distribution. The load was applied by means of axial load plate displacements in reference node of the lateral face. In addition, all nodes of this face were constrained to reference node through of MCP-Tie.

The bolt material was idealized as linear elastic with Young modulus of 210 GPa and 0.3 Poisson coefficient. This strategy was also used in the mild carbon steel plate. On the other hand, the stainless materials were modelled considering the stress-strain curves obtained in longitudinal tensile coupons tests for the same direction of the batch with load. Due to high strain capacity from stainless steel plates, the stress-strain curves were converted to true stress versus true strain where it is considered the large deformation observed in tensile coupons tests.

Therefore, a full nonlinear analysis was performed in all numerical models. The material non-linearity was considered using a Von Mises yield criteria associated to a multi-linear stress-strain relationship. The geometrical non-linearity was introduced in the model by using an updated Lagrangean formulation.

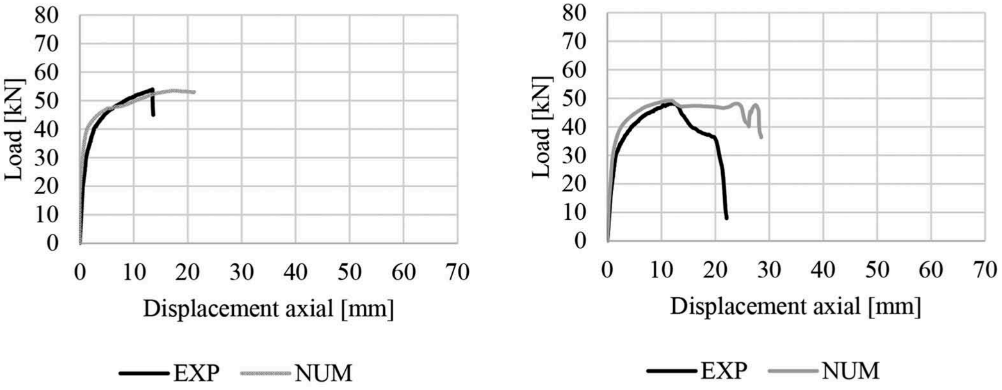
4 RESULTS

Figure 4 illustrates the load-displacement curves for the four experimental tests together with the numerical response. In addition, Table 2 reports the maximum load observed in both



(a) OP-A

(b) IP-A



(c) OP-F

(d) IP-F

Figure 4. Load-displacement curves from both experimental and numerical tests.

Table 2. Maximum load observed in both experimental and numerical tests.

Test	Code	$Load_{EXP}$ [kN]	$Load_{NUM}$ [kN]	EXP/NUM
1	OP-A	71,33	68,31	1,04
2	IP-A	70,11	67,89	1,03
3	OP-F	53,93	53,5	1,01
4	IP-F	48,15	49,15	0,98
Média				1,02
C.O.V				0,03

experimental and numerical tests. As can be observed, it was possible to obtain a similar behavior for the numerical analyses in comparison with the outcomes observed in experimental tests. Thus, it is possible to conclude that finite element analysis can consistently represent the behavior of overlap bolted stainless steel connection submitted to shear.

Another important observation is related to maximum resistance observed for Austenitic study cases. In fact, the ultimate strength observed in tensile coupon tests provided a significant increasing of the bolted connection capacity. This issue resulted in bearing resistance higher in compliance with the design code. In addition, the Austenitic bolted connection reported an high axial deformation. In this case, a possible design on basis of the serviceability or ultimate limit state should be taking into account this important difference reaching a value five times higher for the Austenitic study cases.

Analyzing the maximum load obtained for the connection with lips, it can be mentioned that this system is more efficiency for case with ferritic stainless steel grade. There was a similar behavior comparing the bolted connection with and without lips for the study cases with Austenitic steel grade. There is no difference for the resistance observed in both experimental and numerical analyses. On the other hand, the case where the bolted connection with lips using Ferritic steel grade presented an increasing of the maximum resistance equal to 10%.

Figures 5 and 6 show the deformed obtained in both analyses. As can be noted, there is an out-plane displacement in study case with Ferritic steel grade. It is possible to note that there is high stress concentration in near hole due to high deformation capacity from the Austenitic one. In fact, the Ferritic study case provided a better stress distribution along the distance between the end-plate to near hole. This fact is very important because the actual codes using similar formulas in order to determine the bearing capacity of the overlap bolted stainless steel connections.

Comparing the outcomes with the expression given by EN 1993-1-4 (2006) and SCI P413 (2017), Table 3 reports the ratio experimental and code provisions. It can be noted that there is a better correlation in terms of maximum load capacity for the SCI P413 (2017). However, the value provided by both design code are very restrictive to provide an adequate safe level with economic aspects. In particular, EN 1993-1-4 (2006) does not distinguish for prediction of the maximum load of connections with two planes in shear with the central or end plate controlling the structural design. The EN 1993-1-4 resulted in maximum load equal to 48.26 kN and 31.29 kN for austenitic and ferritic steel, respectively. The SCI P413 (2017), which has an equation for each model, provides a load of 49.54 kN for the OP-A type connection and 63.51 kN for the IP-A. And for the ferritic study cases, values equal to 27.19 kN and 34.86 for OP-F and IP-F, respectively.

In general, the results reported in Table 3 show that the use of the reduced ultimate resistance provided a conservative safe level for the bearing resistance. This issue is not

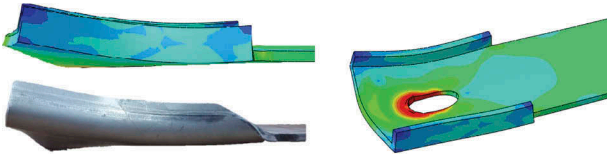


Figure 5. Comparing the experimental and numerical responses of Austenitic study case with lips.

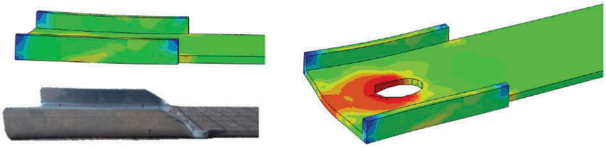


Figure 6. Comparing the experimental and numerical responses of Ferritic study case with lips.

Table 3. Comparison with code provisions.

EXP/EM 1993-1-4				EXP/SCI P413			
OP-A	IP-A	OP-F	IP-F	OP-A	IP-A	OP-F	IP-F
1,43	1,40	1,72	1,52	1,39	1,07	1,96	1,37

addressed to SCI P413 (20017) as was mentioned in previous sections. In contrast, this last code establishes a conservative value for the bolted connection when the outer plates are responsible by controlling of the structural design. In fact, the code is very conservative for the cases where stainless thin-plates can be susceptible to curling effect. Thus, the SCI P413 (2017) is not efficiency for the cases with Ferritic steel grade. Another issue is addressed to difference found among the Ferritic and Austenitic steel grades. In particular, the relation between the ultimate strength observed in tensile coupons tests is nor proportional to bearing resistance in experimental. This was confirmed in Table 3 where it is not linear correlation for both structural codes because the expression are proportional to ultimate strength from materials.

5 CONCLUSIONS

Experimental and numerical analyses have been studied in order to evaluate the influence of the curling effect, as well as, the use of the lips in bolted connection to mitigate this effect. Thus, a set of four study cases were selected modifying the structural scheme in order to investigate the bearing resistance comparing both Austenitic and Ferritic stainless steel grades. Concerning to outcomes observed, it was possible to reported that the performance of the lips was more evident for the cases where Ferritic steel grade is employed. This fact is related to high deformation capacity from the Austenitic steel grade. In fact, the deformed observed in both experimental and numerical analyses provided a reduced out-plane displacement for the Ferritic study cases minimizing the curling effects.

Comparing the outcomes with the expression given by design codes, it can be noted that the codes presented lower values for the determination of the bearing resistance. This is related to use of reduced ultimate strength from EN 1993-1-4 (2006) and a value very restricted for the overlap connection subjected to curling effect in SCI P413 (2017). Therefore, these issues should be investigated in further analyses with a large number of the variables.

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