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Investigations on the bearing strength of stainless steel bolted plates under in-plane tension

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Abstract. This paper presents a study on the behavior and design of bolted stainless steel plates under in-plane tension. Using an experimentally validated finite element (FE) program strength of stainless steel bolted plates under tension is examined with an emphasis on plate bearing mode of failure. A numerical parametric study was carried out which includes examining the behavior of stainless steel plate models with various proportions, bolt locations and in two different material grades. The models were designed to fail particularly in bolt tear-out and material piling-up modes. In the numerical simulation of the models, non-linear stress-strain material behavior of stainless steel was considered by using expressions which represent the full range of strains up to the ultimate tensile strain. Using the results of the parametric study, the effect of variations in bolt positions, such as end and edge distance and bolt pitch distance on bearing resistance of stainless steel bolted plates under in-plane tension has been investigated. Finally, the results obtained are critically examined using design estimations of the currently available international design guidance.

Keywords: stainless steel; finite element analysis; bolted connection; bearing failure mode; strength reduction.

1. Introduction

Behavior of a bolted steel tension member connection as in many other steel connection types with various configurations is generally governed by a significant interaction between bolts and the connected plates or members. In the very general case of a single bolted steel plate in tension, having overcome any possible friction at the interface of plate surfaces, the bolts will slip into bearing against the steel plates followed by a linear connection behavior until yielding occurs at one of the regions namely, the net section, the bolt shear plane, in bearing between the side of the bolt hole and the bolt or at a position which would be a combination of these possible yielding regions (mixed failure). At which region or regions yielding would initiate depends on the proportions of the connected parts, positions of bolts and the relative material strengths of bolts and connected parts. The post-elastic response is a more non-linear response as a result of the spread of plasticity within the connection in the presence of strain hardening. The non-linear behavior continues until the connection finally fails at one of the regions mentioned above (Owens and Cheal 1989).

Among the modes of failures mentioned above, bearing mode of failure usually occurs in connections which are composed of large-diameter bolts connecting relatively thin plates. In connections which are used in practice in which proportions of bolts and plates are close, plate bearing is generally the governing mode of failure unless a very high-strength grade plate is used in the connection in which

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case the failure would be expected to be a bolt bearing type of failure.

As a result of a single bolt or a group of bolts bearing against a plate, different modes of bearing type failure could be observed namely bolt tear-out or end failure, pure bearing or material piling up in front of the bolt in the loading direction, block tear-out failure in a multi-bolt situation and plate bending in the case of a single lap joint accompanied by a plate net section yielding.

In connections in which plate bearing is critical the behavior is ductile compared with bolt shear or net-section fracture modes of failure. Substantial amounts of deformations are observed which, in some cases, may lead to as much as the bolt diameter before connection failure occurs. Bearing strength is influenced mostly by the proximity of the plate hole to the plate boundaries since the material around the bolt provides restraint to the bearing zone. An additional restraint provided by the nut and bolt head, which is a through-thickness restraint, alongside the restraint due to the material around the bearing zone results in a tri-axial containment of this region. Owing to this high restraint it is possible to achieve high bearing stresses. However, the ductile nature of the bearing failure mode makes the stresses achieved unpractical due to concerns regarding serviceability. Therefore, the hole elongations at service loads need to be limited. This is particularly more significant for stainless steel bolted connections. As well known, the mechanical behavior of stainless steel differs from carbon steel in that the stress-strain curve departs from linearity at much lower stress levels than that for carbon steel. Considering, therefore, higher ductility of stainless steel plates, serviceability criteria are more important for bolted connections in stainless steel than in carbon steel.

In this study strength of stainless steel bolted plates under in-plane tension is examined with an emphasis on the above mentioned plate bearing mode of failure. An experimentally validated finite element (FE) program was used for this purpose. A numerical parametric study was organized which includes examining the behavior of stainless steel plate models with various proportions, bolt locations and in two different material grades. The models were designed to fail particularly in bolt tear-out and material piling-up modes. In the numerical simulation of the models, non-linear stress-strain material behavior of stainless steel was considered by using expressions which represent the full range of strains up to the ultimate tensile strain. Using the results of the parametric study, the effect of variations in bolt positions, such as end and edge distance and bolt pitch distance on bearing resistance of stainless steel bolted plates under in-plane tension has been investigated. Finally, the results obtained are critically examined using design estimations of the currently available international design guidance.

2. Design of bolted stainless steel connections against bearing

Excluding net-section yielding and bolt shear failure modes, bearing resistance of a bolted connection is governed by one of the bearing failure types as mentioned earlier. Below the treatment of the European Euro Inox (2006) Design Manual for Structural Stainless Steel and the American ASCE Specification for the Design of Cold-Formed Stainless Steel Structural Members, SEI / ASCE (2002) for bearing resistance of stainless steel bolted connections is summarized;

2.1. Treatment of Euro Inox (2006)

Minimum strength to prevent end tear out failure in Euro Inox is given by,

$$F_{b,Rd} = k_1\left(\frac{e_1}{3d_0}\right)f_{u,red}dt \tag{1}$$

where e_1 is the end distance which is the distance from the center of a bolt hole to the end of the plate in the direction in which the bolts bear. d is the bolt diameter, t is the thickness of the plate for which bearing resistance is considered. $f_{u,red}$ is the reduced material ultimate tensile strength given as;

$$f_{u,red} = 0.5f_y + 0.6f_u \leq f_u \tag{2}$$

A reduced value for the ultimate tensile strength of the material is used to limit the hole elongations at serviceability loads. This expression is based on a 3 mm deformation limit (SCI-RT157 1990).

If end-tear out type of bearing failure mode is not critical, the next probable critical mode of bearing failure would be one of the other modes namely, material piling up (pure bearing), block tear out (for multi-bolt cases) or plate curling. For pure bearing the resistance is given as;

$$F_{b,Rd} = k_1 f_{u,red} dt \tag{3}$$

The transition from end tear out failure mode to pure bearing mode occurs for $e_1 = 3d_0$ (in Eq. (1) for $e_1 = 3d_0$ yields Eq. (3)). In other words, end failure occurs for end distances less than 3 times the bolt hole diameter since the free end boundary reduces the in-plane containment as mentioned above.

In the strength equations, k_1 is the smaller of 2.5 or $(2.8\frac{e_2}{d_0} - 1.7)$ for edge bolts perpendicular to load transfer direction and for inner bolts perpendicular to load transfer direction it is the smaller of 2.5 or $(1.4\frac{p_2}{d_0} - 1.7)$. The parameter k_1 controls the effect of edge distance (e_2) or bolt pitch in the direction perpendicular to the load direction (p_2) on the bearing resistance. For edge distances e_2 smaller than $1.5d_0$ and/or for p_2 smaller than $3.0d_0$ the resistance is reduced due to closer proximities of the bolts or bolt hole to plate edge, i.e. $F_{b.Rd} < 2.5f_{u,red}dt$. According to the specification, the minimum value of the end distance, e_1, and that of the edge distance, e_2, should be taken as, $1.2d_0$ where d_0 is the diameter of the bolt hole. On the other hand, the minimum value for p_2 is given as $2.4d_0$. In between these limiting values of e_2 and p_2, interpolation is made for bearing resistance calculations. No guidance is given for $e_2 < 1.2d_0$ or for $p_2 < 2.4d_0$.

Assuming $k_1 = 1.5$ a resistance value which is 40 % lower than the above pure bearing resistance ($F_{b.Rd} = 1.5f_{u,red}dt$) is used for plate bending mode and for block tear-out mode the resistance is given by;

$$F_{b,Rd} = 2.5\left(\frac{p_1}{3d_0} - 0.25\right)f_{u,red}dt \tag{4}$$

A separate check is needed in relation to bolt bearing, i.e. plate bearing against the bolt. According to the specification bolt bearing will not be critical provided that the ultimate tensile strength of the bolt (f_{ub}) is greater than that of the steel plate ($f_{u,red}$). For all cases explained above, a partial safety factor of $\gamma_M = 1.25$ is used for design strength calculations.

2.2 Treatment of SEI/ASCE 8-02

The provisions given in SEI/ASCE (2002) for bearing resistance of bolted stainless steel connections are generally based on the test results presented in Errera *et al.* (1974). In this specification, end tear-out strength is given as;

$$P_n = teF_u \tag{5}$$

where e is the distance measured in line of force from center of hole to end of connected part, t is thickness of the thinnest connected part and F_u is ultimate tensile strength of connected part.

On the other hand, bearing strength is determined as follows;

$$P_n = F_p dt \tag{6}$$

where $F_p = 2.00F_u$ for single shear connection and $F_p = 2.75F_u$for double shear connections. Therefore the bearing resistance becomes, e.g. for single shear connection,

$$P_n = 2.00F_u dt \tag{7}$$

Design bearing strength is given as $P_n = \phi F_p dt$ where $\phi = 0.65$.

In the American Institute of Steel Construction (AISC) (2005) specification the bearing resistance for a carbon steel bearing-type connection is given as $P_n = 2.4F_u dt$ which is 20% higher than the resistance specified for stainless steel connection. The specification of a lower bearing resistance for stainless steel is again, as in the Euro Inox approach in which material tensile strength is reduced, due to the need to limit hole deformations at serviceability loads.

Minimum distance between centers of bolt holes allowed in SEI/ASCE (2002) is 3 times the bolt diameter. On the other hand the minimum value specified for the distance from the center of hole to the end or other boundary (e.g. edge) of the connecting member is 1.5 times the bolt diameter.

Table 1 presents a summary of the minimum values stipulated by both Euro Inox (2006) and SEI/ASCE (2002) for bolt spacing, end and edge distances for stainless steel bolted connections. Comparing both standards, it is observed that SEI/ASCE (2002) is more stringent whereas Euro Inox (2006) specifies lower minimum values.

3. Finite element simulation of previous experiments

For the numerical finite element (FE) analysis of models investigated in this study, ABAQUS (2007), a general-purpose finite element program, is used. A validation study has been carried out to assess how various ABAQUS models compare with available experimental results. The program is then used to carry out analysis of stainless steel bolted plates within a parametric study. To validate the FE models produced by using ABAQUS, test data that was produced by three different studies on behavior and design of steel bolted shear connections (Rex and Easterling. 2003, Puthli and Fleischer 2001 , Freitas *et al.* 2005) were used in the finite element simulations. A total of 15 tests selected from these studies for which the failure loads are known were analyzed. Properties of the analyzed specimens (material and

Table 1 Minimum bolt spacing, end and edge distances for stainless steel bolted connections

Standard	End distance, e_1	Edge distance, e_2	p_1	p_2
Euro Inox(2006)	$1.2d_0$	$1.2d_0$	$2.2d_0$	$2.4d_0$
SEI/ASCE (2002)	1.5d	1.5d	3.0d	3.0d

d : bolt diameter

d_0 : hole diameter

geometrical) are given in Table 2. In general, these 15 tests deal with studying the behavior and design of bolted steel plates under in-plane tension for a variety of connection geometry which includes the plate dimensions, bolt diameter and bolt positions. In these tests, one and two bolt connections were considered.

Finite element analyses of the plate models were carried out using three-dimensional, hexahedral eight-node linear brick, reduced integration with hourglass control solid elements (ABAQUS C3D8R). The bolts were modeled as 3D analytical rigid shell. A rigid body reference node having both translational and rotational degrees of freedom was defined for the bolts. The reference node was placed at the center of mass of bolts. Bolt bearing on the side of the plate was simulated by defining interaction between the outer surface of the rigid bolts in contact with the surface of the steel plate in the bolt hole region. Contact between the bolt and the plate was modeled by the surface-based contact feature available in ABAQUS (2007). The contact surfaces of the rigid bolt and the deformable plate hole were first defined and the surfaces which interact with one another were specified. In order to achieve a full transfer of load to the plate by bolt bearing against the bolt hole, a frictionless contact property model was defined to simulate the behavior of the surfaces when they are in contact (Aceti *et al.* 2004).

Fig. 1 shows a typical FE model adopted in the study. Load was applied as concentrated point load in the longitudinal x axis of the plate at the reference nodes described above. At the reference node (or nodes for two bolt cases) only the translation in the load application direction was released and all other five degrees of freedom were restrained in order to prevent bolt tilting. On the other hand, translation of the far end plate edge surface was restrained in all three orthogonal directions (u_1, u_2 and u_3 as defined in ABAQUS).

To represent the entire non-linear response of the tested specimens, geometric and material nonlinearities were included in the analysis modes. This is particularly of importance to be able to capture the necking and tear-out types of behaviour observed over the plate regions around the bolt locations. Also in order

Table 2 Properties of the analyzed specimens for FE validation

Specimen number	f_y (MPa)	f_u (MPa)	Plate Width (mm)	Plate Length (mm)	Plate Thickness (mm)	Bolt diameter, d_0 (mm)	e_1/d_0	e_2/d_0	p_2/d_0	Test Maximum Load (kN)	FE Maximum Load (kN)	FE/Test
[a] 1	524.00	645.00	144.00	400.00	17.50	30.00	1.20	1.20	2.40	817.00	750.00	0.92
[a] 2	524.00	645.00	162.00	400.00	17.50	30.00	1.20	1.35	2.70	772.00	736.00	0.95
[a] 3	524.00	645.00	108.00	400.00	17.50	30.00	1.20	0.90	1.80	568.00	575.00	1.01
[a] 4	524.00	645.00	144.00	400.00	17.50	30.00	1.20	1.50	1.80	662.00	649.00	0.98
[a] 5	524.00	645.00	153.00	450.00	17.50	30.00	1.20	1.50	2.10	783.00	723.00	0.92
[a] 6	524.00	645.00	135.00	400.00	17.50	30.00	1.20	1.35	1.80	643.00	635.00	0.99
[b] 7	301.00	439.00	127.00	600.00	9.50	25.00	1.52	2.54	NA	144.60	142.80	0.99
[b] 8	414.00	690.00	114.00	600.00	6.50	25.00	1.00	2.28	NA	108.10	98.37	0.91
[b] 9	299.00	441.00	127.00	600.00	9.50	25.00	1.76	2.54	NA	157.50	167.18	1.06
[b] 10	307.00	452.00	127.00	600.00	6.50	25.00	1.52	2.54	NA	114.30	102.80	0.90
[c] 11	769.00	821.00	96.00	300.00	10.00	25.00	2.00	2.00	NA	390.80	367.12	0.94
[c] 12	769.00	821.00	48.00	300.00	10.00	25.00	1.00	1.00	NA	178.10	168.50	0.95
[c] 13	769.00	821.00	96.00	300.00	10.00	25.00	1.20	2.00	NA	240.60	229.60	0.95
[c] 14	769.00	821.00	48.00	300.00	10.00	25.00	1.20	1.00	NA	209.00	204.50	0.98
[c] 15	769.00	821.00	72.00	300.00	10.00	25.00	1.20	1.50	NA	228.20	220.70	0.97
											Mean	**0.96**
											Standart deviation	**0.04**

[a] Rex and Easterling 2003, [b] Puthli and Fleischer 2001, [c] Freitas *et al.* 2005

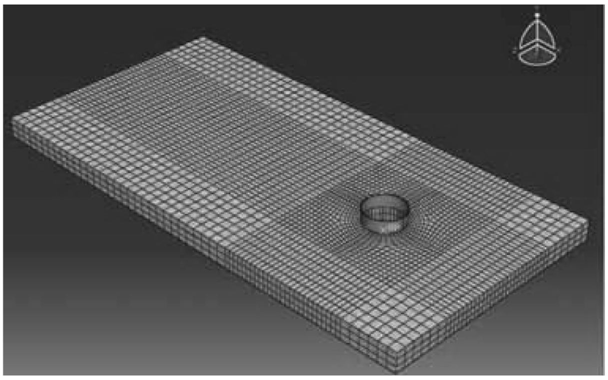

Fig. 1 Typical finite element (FE) analysis model

to improve the accuracy of the analysis, mesh refinement was implemented over such regions. The nonlinear stress-strain behavior of steel is modeled using the Von Mises yield criterion with isotropic hardening. Yield stress, ultimate stress and elongation values presented in the material property descriptions for the selected tests were used for material modeling of the analyzed models.

The non-linear response and ultimate strength of steel plate models as described above is examined through finite element analysis. The FE program used in this study (ABAQUS) uses Newton's method to solve the nonlinear equilibrium equations. In this method, the solution is obtained as a series of increments, with iterations to obtain equilibrium within each increment. Using the output variable identifiers as outlined in ABAQUS (2007), output data were requested for the generation of load-displacement curves. Load output was obtained by extracting the incremental point load values applied at the reference node defined at the centre of the rigid bolt. Corresponding nodal displacements were extracted from the same node in the direction of loading.

Besides the properties of the analyzed specimens, Table 2 also presents the ultimate load predictions achieved through finite element (FE) analysis together with test ultimate loads for the 15 tests. The test ultimate loads are also compared in Fig. 2 with the predictions of the present finite element program. It is shown that numerical ultimate load predictions agree well with the test ultimate loads. On average, ultimate load was predicted within 4%. In addition to the comparisons made in terms of the ultimate load, Fig. 3 shows non-linear response curve obtained from one of the above mentioned 15 experiments (specimen 10 in Table 2) compared with the load-displacement prediction of the present finite element program (ABAQUS). Using the aforementioned finite element modeling assumptions, FE predictions of important performance measures, such as the form of load-displacement response and ultimate strength, were found to be in close agreement with test. Deformed shape for one of the models at ultimate load is shown in Fig. 4. This deformed shape is typical of a plate end tear-out mode of failure.

4. Numerical parametric study

Following the satisfactory agreement between the FE model behaviour and experiments, a parametric study was carried out to investigate the strength of stainless steel bolted plates in tension with varying plate dimensions and bolt positions and associated with the aforementioned bearing type failure modes. Modeling assumptions used for the simulation of the previous experimental work as described above

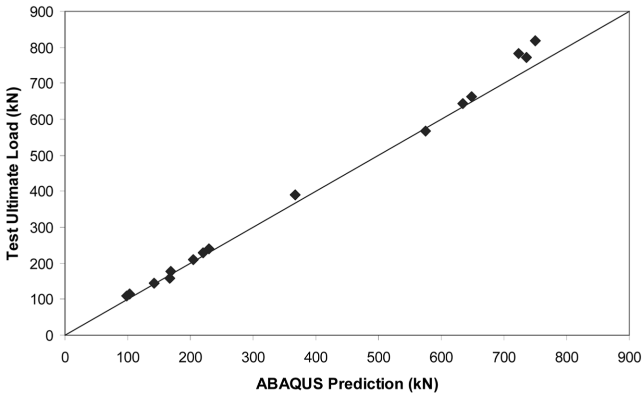

Fig. 2 Comparison of finite element analysis predictions with experimental findings

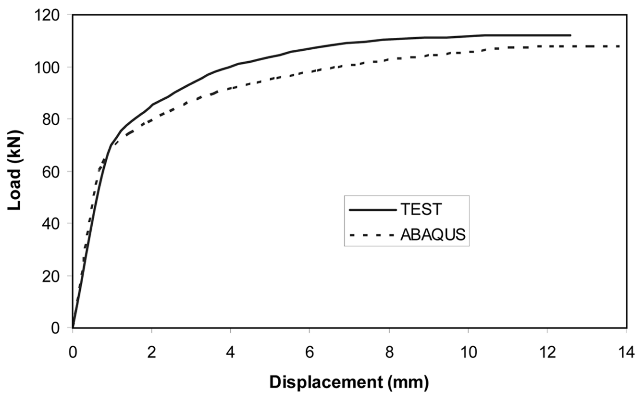

Fig. 3 Test versus finite element analysis prediction for load-displacement history for specimen number 10 in Table 2

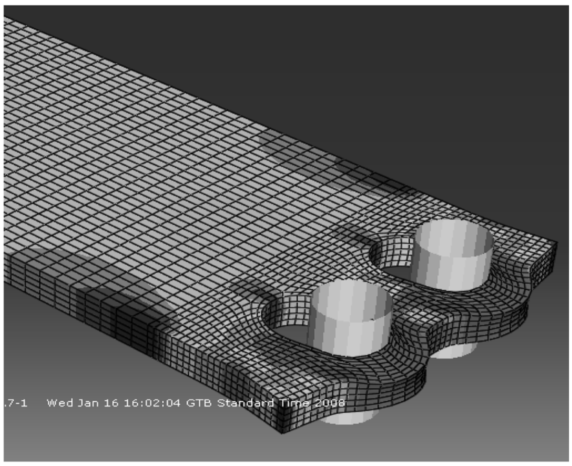

Fig. 4 Deformed shape for a typical finite element model

were also considered for the models in the parametric study. More realistic material behavior, as explained below, is assumed for material modeling of stainless steel plates.

The numerical study incorporates mainly a parametric non-linear finite element analysis of bolted plates of stainless steel with varying dimensions and bolt positions in single and two-bolt cases. With this respect, dimensional variables which were considered in the study are end distance (e_1), edge distance (e_2) and bolt pitch distance (p_2). A constant hole diameter and a constant plate thickness was assumed for all the models. The models in the parametric study cover a practical range of stainless steel plate models with various bolt locations for which the expected mode of failure is in general plate bearing.

In the study, stainless steel was considered in two common grades; Grade 1.4301 (AISI 304) and Grade 1.4462 (Duplex 2205). Grade 304 is one of the most commonly used stainless steel grades and referred to as the standard austenitic grade which provides a good combination of corrosion resistance, forming and fabrication. Duplex stainless steels have high strength and wear resistance. Duplex 2205 is a UK designation and the corresponding US designation for this grade is UNS S31803. These grades are both included in both the aforementioned European Euro Inox (2006) and the American SEI-ASCE (2002) design guidance for the design of structural stainless steel.

Stainless steels exhibit a rounded (non-linear) stress-strain curve, with no sharp yield point whereas carbon steel typically exhibits linear elastic behavior up to yield stress and a plateau before strain hardening. Yield stress for stainless steel is generally quoted in terms of a proof stress ($\sigma_{0.2}$) defined at 0.2% permanent strain while the limit of proportionality is generally defined as the stress at 0.01% plastic strain.

Non-linear relationship between stress and strain for stainless steel is generally represented by the Ramberg and Osgood (1943) equation as given below;

$$\varepsilon = \frac{\sigma}{E_0} + 0.002\left(\frac{\sigma}{\sigma_{0.2}}\right)^n \tag{8}$$

In Eq. (8), n is a hardening measure for the non-linearity of the stress-strain behavior, lower n values implying a greater degree of non-linearity. The degree of non-linearity varies among different grades of stainless steel. As the value of n increases the material behavior tends to converge to the elasto-plastic behavior of carbon steel (elastic- perfectly plastic behavior for $n = \infty$). Grades of low n values exhibit higher hardening behavior and for a given stress level benefits of strain hardening comparatively becomes more apparent.

Eq. (8) is known to give excellent agreement with experimental stress-strain data up to the 0.2% proof stress, however, for higher strains the formulation generally over estimates the corresponding stresses. Therefore two-stage versions of expressing the full-range stress-strain material behavior of stainless steel were developed. In this respect, Rasmussen (2003), proposed the use of an expression for the complete stress-strain curve for stainless steel alloys. The expression (Eq. (9)) involves the conventional Ramberg-Osgood parameters (n, E_0, $\sigma_{0.2}$) as well as the ultimate tensile strength (σ_u) and strain (ε_u). The expressions have been shown to produce stress-strain curves which are in good agreement with tests over the full range of strains up to the ultimate tensile strain.

$$\varepsilon = \begin{cases} \dfrac{\sigma}{E_0} + 0.002\left(\dfrac{\sigma}{\sigma_{0.2}}\right)^n & for\ \sigma \le \sigma_{0.2} \\[2ex] \dfrac{\sigma - \sigma_{0.2}}{E_{0.2}} + \varepsilon_u\left(\dfrac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}}\right)^m + \varepsilon_{0.2} & for\ \sigma > \sigma_{0.2} \end{cases} \tag{9}$$

In the equations, E_0 is the initial modulus of elasticity (e.g. 200000 MPa), $E_{0.2}$ is the tangent modulus of the stress-strain curve at the 0.2% proof stress and given as;

$$E_{0.2} = \frac{E_0}{1 + 0.002n/e} \tag{10}$$

in which e is the non-dimensional proof stress given as $e = \sigma_{0.2}/E_0$.

In this study, in the FE material modeling for stainless steel (for Grade 1.4301 (AISI 304) and Grade 1.4462 (Duplex 2205)) the formulations proposed by Rasmussen (2003) were used. Stress-strain curves were produced using minimum values specified in Euro Inox (2006) Table C. 3.1 for the 0.2% proof stress and the non-linearity index n for the grades considered (for Grade 304 n = 8, $f_{y,0.2}$ = 230 MPa, f_u = 540 MPa, for Duplex n = 5, $f_{y,0.2}$ = 500 MPa, f_u = 700 MPa). Curves obtained using these values through Eq. (9) for Grade 304 and Duplex 2205 are given in Fig. 5. Additionally for the purpose of viewing trends in behavior, different values of $\sigma_{0.2}$ and n were also considered and corresponding curves are also plotted in Fig. 5 alongside the curves for Grade 304 and Duplex 2205. It is observed that stainless steels of higher proof stress values display a greater degree of non-linearity than lower proof-stress stainless steels, as indicated by the lower n values.

For the plate models considered in the parametric study, a constant plate thickness of 13.5 mm (current maximum production thickness for hot rolled strip as given in Euro Inox Table 3.1) and a constant hole diameter of 25 mm was assumed. For two different values of the nonlinearity index, n (n = 5 and n = 8) and four different values of end distance-to-hole diameter ratio, e_1 / d_0 (0.80, 1.20, 2.10 and 3.00), models were analyzed for varying values of edge distance, e_2 and bolt pitch, p_2. For two-bolt cases the alignment of the bolts were considered to be transverse to the loading direction. In the models, the geometric dimensions were selected on the basis of the Euro Inox (2006) limits for end, edge and pitch distances. The values for these distances are varied not only within the allowable limits of Euro Inox (2006), but also outside them. Table 3 presents a summary of the analysis models considered within the parametric study. In total 32 different FE model geometry were developed half of which are one-bolt (O1 through O16) and the rest are the two-bolt cases (T1 through T16). Each group is also divided into two cases as being either Grade 304 steel with n = 8 or Duplex steel with n = 5. In other words, a particular model geometry was analyzed for two different steel grades making 64 analysis runs in total.

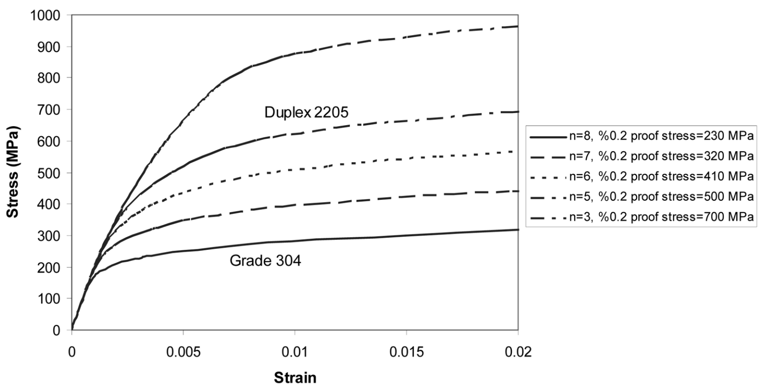

Fig. 5 Stress-strain curves for various grades of stainless steel obtained using Eq. (9)

Table 3 Properties of the analyzed specimens within the parametric study

Model no	Plate	End distance (mm)		Edge distance (mm)		Pitch (mm)	
	Width (mm)	e_1	e_1/d_0	e_2	e_2/d_0	p_2	p_2/d_0
O1	60,00	20,00	0,80	30,00	1,20	0,00	0,00
O2	75,00	20,00	0,80	37,50	1,50	0,00	0,00
O3	100,00	20,00	0,80	50,00	2,00	0,00	0,00
O4	150,00	20,00	0,80	75,00	3,00	0,00	0,00
O5	60,00	30,00	1,20	30,00	1,20	0,00	0,00
O6	75,00	30,00	1,20	37,50	1,50	0,00	0,00
O7	100,00	30,00	1,20	50,00	2,00	0,00	0,00
O8	150,00	30,00	1,20	75,00	3,00	0,00	0,00
O9	60,00	52,50	2,10	30,00	1,20	0,00	0,00
O10	75,00	52,50	2,10	37,50	1,50	0,00	0,00
O11	100,00	52,50	2,10	50,00	2,00	0,00	0,00
O12	150,00	52,50	2,10	75,00	3,00	0,00	0,00
O13	60,00	75,00	3,00	30,00	1,20	0,00	0,00
O14	75,00	75,00	3,00	37,50	1,50	0,00	0,00
O15	100,00	75,00	3,00	50,00	2,00	0,00	0,00
O16	150,00	75,00	3,00	75,00	3,00	0,00	0,00
T1	110,00	20,00	0,80	30,00	1,20	50,00	2,00
T2	135,00	20,00	0,80	37,50	1,50	60,00	2,40
T3	175,00	20,00	0,80	50,00	2,00	75,00	3,00
T4	250,00	20,00	0,80	75,00	3,00	100,00	4,00
T5	110,00	30,00	1,20	30,00	1,20	50,00	2,00
T6	135,00	30,00	1,20	37,50	1,50	60,00	2,40
T7	175,00	30,00	1,20	50,00	2,00	75,00	3,00
T8	250,00	30,00	1,20	75,00	3,00	100,00	4,00
T9	110,00	52,50	2,10	30,00	1,20	50,00	2,00
T10	135,00	52,50	2,10	37,50	1,50	60,00	2,40
T11	175,00	52,50	2,10	50,00	2,00	75,00	3,00
T12	250,00	52,50	2,10	75,00	3,00	100,00	4,00
T13	110,00	75,00	3,00	30,00	1,20	50,00	2,00
T14	135,00	75,00	3,00	37,50	1,50	60,00	2,40
T15	175,00	75,00	3,00	50,00	2,00	75,00	3,00
T16	250,00	75,00	3,00	75,00	3,00	100,00	4,00

Grade 304 ($n = 8$; $f_{y,0.2} = 230$ MPa; $f_u = 540$ MPa) / Duplex ($n = 5$; $f_{y,0.2} = 500$ MPa; $f_u = 700$ MPa)
Bolt diameter: $d_0 = 25$ mm (constant)
Plate thickness: $t = 13.5$ mm (constant)

The following section presents a discussion of the results obtained from the parametric study. The FE ultimate strength predictions for the models considered are used in the assessment of the current design recommendations.

5. Results of the parametric study

Ultimate strengths achieved through FE are compared in Table 4 with predictions of the design specifications. Results are given separately for two different grades of steel as designated in this study by the non-linearity index n (n = 5 and n = 8).

As stated earlier, limited account can be taken of the high ductility of stainless steel and therefore a deformation limit is generally set to safeguard any unfavorable conditions at working loads. With this respect, in this study ultimate strength of the FE models was assumed to be reached at 3mm elongation of the hole center (the reference node) which is also the limit deformation value used in the Euro Inox (2006)

Table 4 Comparison of FE and code predicted ultimate strengths (kN)

Model	n = 8 (Grade 304)					n = 5 (Duplex)				
	FE	Euro Inox	SEI-ASCE	FE/ Euro Inox	FE/ SEI-ASCE	FE	Euro Inox	SEI-ASCE	FE/ Euro Inox	FE/ SEI-ASCE
O1	101,00	65,59	145,80	1,54	0,69	138,00	100,10	189,00	1,38	0,73
O2	117,00	98,78	145,80	1,18	0,80	172,80	150,75	189,00	1,15	0,91
O3	121,00	98,78	145,80	1,23	0,83	177,30	150,75	189,00	1,18	0,94
O4	121,00	98,78	145,80	1,23	0,83	181,00	150,75	189,00	1,20	0,96
O5	142,00	98,38	218,70	1,44	0,65	223,01	150,15	283,50	1,49	0,79
O6	171,00	148,16	218,70	1,15	0,78	277,00	226,13	283,50	1,22	0,98
O7	178,00	148,16	218,70	1,20	0,81	281,00	226,13	283,50	1,24	0,99
O8	183,00	148,16	218,70	1,24	0,84	249,48	226,13	283,50	1,10	0,88
O9	224,00	172,16	364,50	1,30	0,61	355,00	262,76	472,50	1,35	0,75
O10	293,40	259,28	364,50	1,13	0,80	446,00	395,72	472,50	1,13	0,94
O11	312,00	259,28	364,50	1,20	0,86	440,00	395,72	472,50	1,11	0,93
O12	320,00	259,28	364,50	1,23	0,88	467,00	395,72	472,50	1,18	0,99
O13	219,00	245,95	364,50	0,89	0,60	380,00	375,37	472,50	1,01	0,80
O14	298,00	370,41	364,50	0,80	0,82	500,00	565,31	472,50	0,88	1,06
O15	404,00	370,41	364,50	1,09	1,11	426,00	565,31	472,50	0,75	0,90
O16	395,00	370,41	364,50	1,07	1,08	440,00	565,31	472,50	0,78	0,93
T1	142,60	86,92	291,60	1,64	0,49	198,60	132,66	378,00	1,50	0,53
T2	201,50	131,17	291,60	1,54	0,69	298,40	200,20	378,00	1,49	0,79
T3	224,00	197,55	291,60	1,13	0,77	342,00	301,50	378,00	1,13	0,90
T4	230,00	197,55	291,60	1,16	0,79	355,00	301,50	378,00	1,18	0,94
T5	213,80	130,38	437,40	1,64	0,49	289,50	198,99	567,00	1,45	0,51
T6	271,53	196,76	437,40	1,38	0,62	375,36	300,29	567,00	1,25	0,66
T7	363,00	296,33	437,40	1,23	0,83	576,00	452,25	567,00	1,27	1,02
T8	373,00	296,33	437,40	1,26	0,85	580,00	452,25	567,00	1,28	1,02
T9	358,30	228,17	729,00	1,57	0,49	521,40	348,23	945,00	1,50	0,55
T10	527,00	344,33	729,00	1,53	0,72	743,80	525,51	945,00	1,42	0,79
T11	682,00	518,57	729,00	1,32	0,94	920,00	791,44	945,00	1,16	0,97
T12	700,00	518,57	729,00	1,35	0,96	952,00	791,44	945,00	1,20	1,01
T13	401,00	325,96	729,00	1,23	0,55	647,00	497,48	945,00	1,30	0,68
T14	539,00	491,90	729,00	1,10	0,74	850,00	750,74	945,00	1,13	0,90
T15	700,00	740,81	729,00	0,94	0,96	978,85	1130,63	945,00	0,87	1,04
T16	800,00	740,81	729,00	1,08	1,10	1101,15	1130,63	945,00	0,97	1,17
		Average		**1,25**	**0,80**		Average		**1,20**	**0,87**

formulation. Therefore, the FE ultimate strength results presented in Table 4 correspond to strengths obtained at 3mm hole center elongation.

The design strength calculations have employed the dimensions and material properties as assumed in the FE parametric study (Table 3). Also, the partial factors were set to unity.

Average values for the ultimate strength ratios between FE and code predictions are also given in Table 4. For both standard (n = 8) and high strength Duplex (n = 5) grades the numerically achieved ultimate strengths are 25% and 20% higher than Euro Inox (2006) predictions, respectively, while on the other hand they are observed to be 20% and 13% lower than SEI-ASCE (2002) predictions, respectively. These may be regarded as indications of Euro Inox (2006) rules for bearing resistance being conservative and SEI-ASCE (2002) rules being un-conservative. However, as stated above, in the strength calculations per design specifications the partial factors were set to unity. Therefore, considering these factors ($\gamma_M = 1.25$ for Euro Inox and $\phi = 0.65$ for SEI-ASCE) in the calculations more conservative results are obtained for Euro Inox and conservative results for SEI-ASCE estimations. For an overall average discrepancy of 20% between FE and Euro Inox (FE > Euro Inox) a 50% average discrepancy is obtained if $\gamma_M = 1.25$ is used. Similarly, for an overall average discrepancy of 15% between FE and SEI-ASCE (FE < SEI-ASCE) a 31% average discrepancy is obtained if $\phi = 0.65$ is used in which case FE predictions, in average, become smaller than SEI-ASCE design strength estimations.

In Fig. 6 and Fig. 7 ratios of FE predicted strength at 3mm elongation over the design bearing resistance calculated according to Euro Inox (2006) and SEI/ASCE (2002) rules are plotted for all the models analyzed within the parametric study. In the figures, data presented include all 64 analysis runs with one-bolt and two-bolt cases in both 304 and Duplex material grades (the first 32 being 304 and the last Duplex steel). It is observed in Fig.6 that FE predictions for resistance accumulate around the 1.20 region for Euro Inox (2006). In other words, for the range of model geometries considered FE predicts an average value of around 20% higher than what Euro Inox (2006) predicts. On the other hand, in Fig. 7 where the distribution of the FE predicted strength-to-SEI/ASCE (2002) estimation ratios are given, the average value for the ratio is around 0.85. As discussed above, these levels are achieved when partial resistance factors are set to unity and they become higher if the factors are used in the strength calculations. One important observation made in these figures is that a nearly horizontal trend is noted for all the models analyzed including one and two-bolt cases in both material grades. In other words, a nearly constant level of discrepancy is obtained between FE and code given strengths regardless of the material

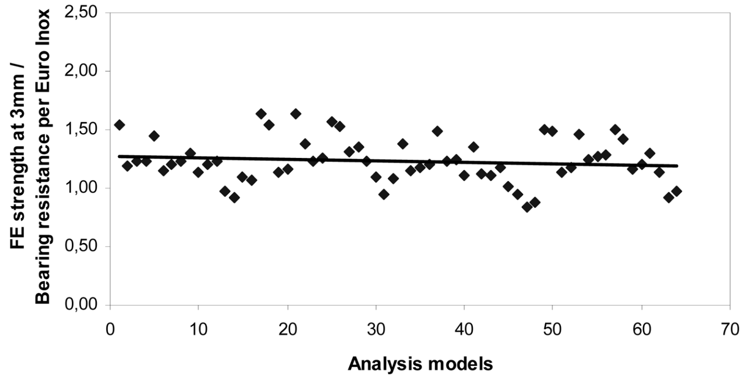

Fig. 6 Distribution of the FE maximum strength-to-Euro Inox (2006) estimation ratios for the models analyzed

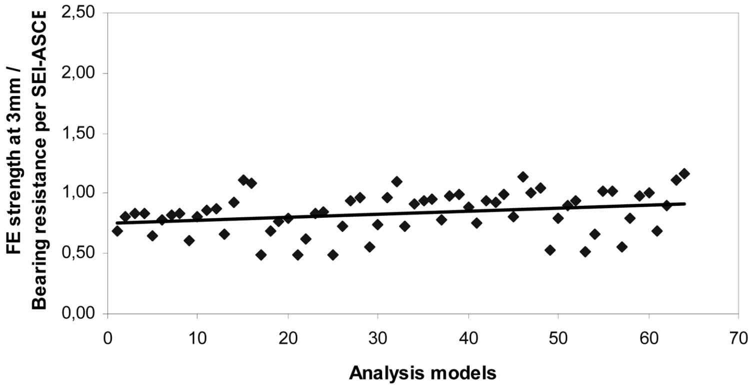

Fig. 7 Distribution of the FE maximum strength-to-SEI/ASCE (2002) estimation ratios for the models analyzed

grade. Therefore, it can be stated that, in agreement with both Euro Inox (2006) and SEI-ASCE (2002) specifications, same rules apply for the calculation of bearing resistance of bolted plates in both material grades. Regarding the scatter of the strength ratios in Figs. 6 and 7, although the models for which the ratios are plotted follow a systematic rule in terms of their geometry (Table 3) and the design predictions are expected to follow a systematic relationship, it should be noted that in both figures, the observed scatter is more of a random nature due to FE predictions being included in the calculations of the ratios.

Fig. 8 presents the ratios of the resistance of Duplex steel to that of Grade 304 steel bolted plates calculated per the design specifications and estimated by FE analysis for all the models analyzed within the parametric study. As explained earlier, design strength is directly proportional to ultimate tensile strength of material per SEI-ASCE (2002) whereas in Euro Inox (2006) strength is a function of a reduced material ultimate tensile strength, $f_{u,red}$. As expected, FE and design predicts ratios greater than 1 as Duplex is a higher grade steel with a higher material ultimate tensile strength. In Fig. 8, it is observed that in comparison to SEI/ASCE (2002) specification, the ratio of the resistance of Duplex steel to that of Grade 304 steel bolted plates per Euro Inox (2006) is higher and that FE follows a closer

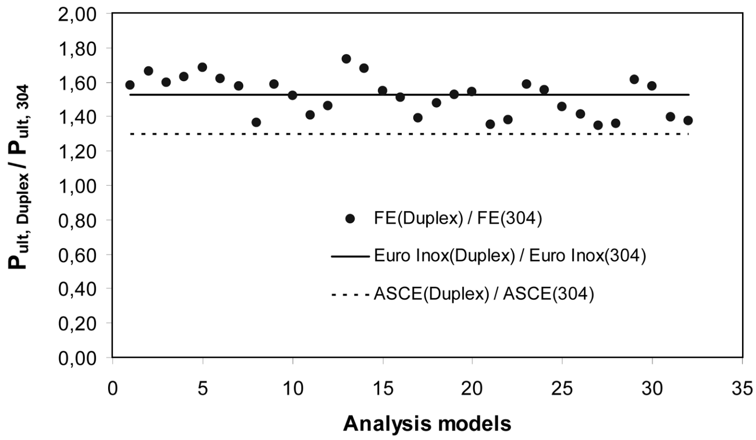

Fig. 8 Comparison of the ultimate strengths achived for Duplex steel with Grade 304 models per FE and design specifications

trend to what Euro Inox (2006) predicts.

As explained earlier the bearing resistance in Euro Inox (2006) is given as a function of parameter k_1 (Eq. (1)) which is a parameter that controls the effect of edge distance (e_2) or bolt pitch in the direction perpendicular to the load direction (p_2) on the bearing resistance. For edge distances e_2 smaller than $1.5d_0$ and/or for p_2 smaller than $3.0d_p$ the resistance is reduced due to closer proximities of the bolts to plate edges. In Fig. 9 and Fig. 10 k_1 values calculated using the FE strength results for the models considered for both material grades (n = 5 and n = 8) are plotted as a function of edge distance (e_2) and bolt pitch (p_2) and compared against the current Euro Inox (2006) k_1-e_2 and k_1-p_2 relationships. For both relationships it is observed that the FE predicted k_1 values are always higher than the code given values. This observation is more apparent for e_2 and p_2 values smaller than the code limits; e_2=1.5 d_0 and p_2 = 3 d_0. As k_1 is a direct indication of the level of bearing resistance these results indicate that the reduction in bearing resistance for e_2 and p_2 values smaller than the above code limits may not need to be that much. Finally, it is noted that for both relationships (k_1-e_2 and k_1-p_2) similar amounts of increase are observed for both grades of stainless steel.

Finally, regarding the deformed shapes of the models under increasing loads, for most of the models the numerically and code predicted deformation modes were in agreement both predicting a dominant bearing type of behaviour while some other exhibited mixed types of behaviour. For example, for model O14 for which code predicted net section and bearing failure loads are close a mixed type of failure was observed by FE analysis, i.e. bearing mode associated with necking of plate on both sides of the bolt hole (Fig. 11).

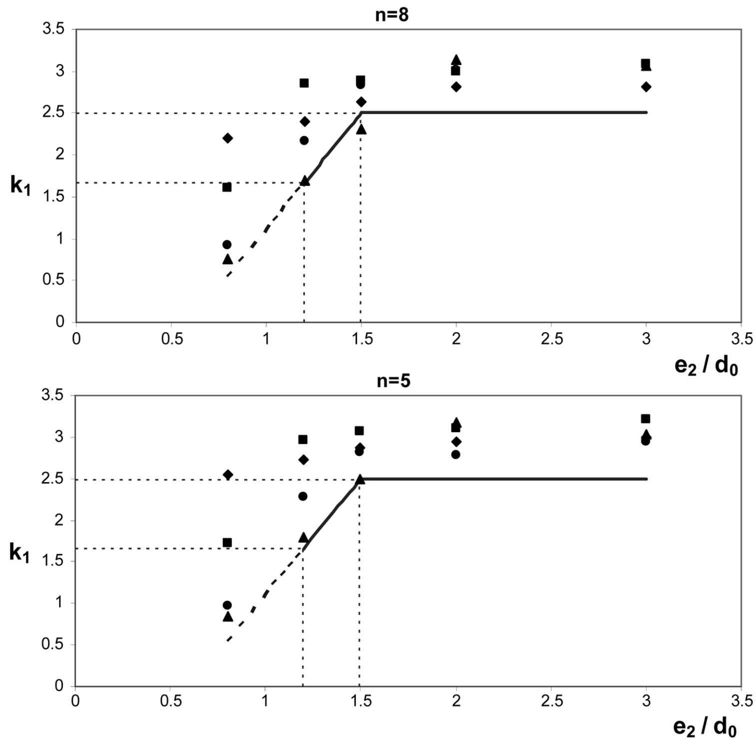

Fig. 9 Comparison of FE predicted k_1 parameter as a function of edge distance e_2 with the Euro Inox k_1 - e_2 relationship

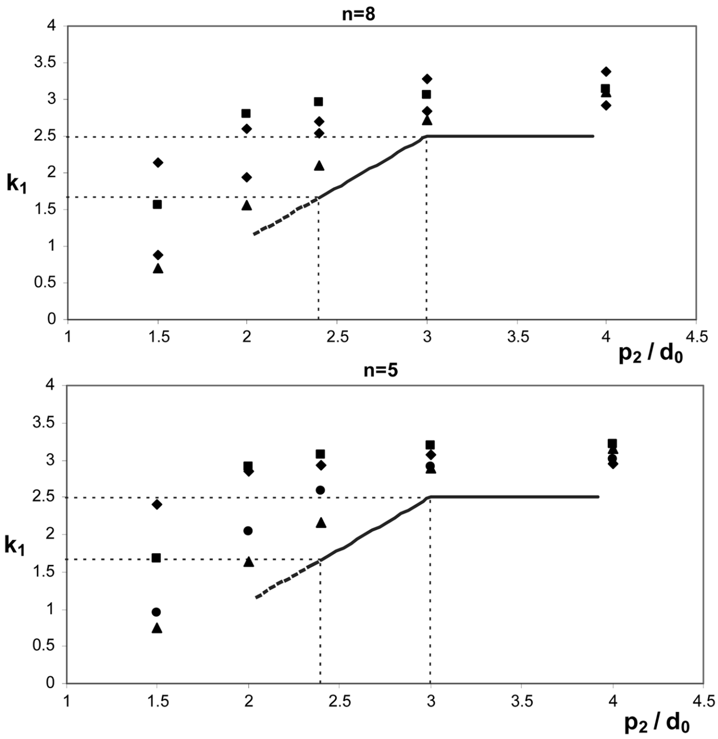

Fig. 10 Comparison of FE predicted k_1 parameter as a function of bolt pitch distance p_2 with the Euro Inox k_1-p_2 relationship

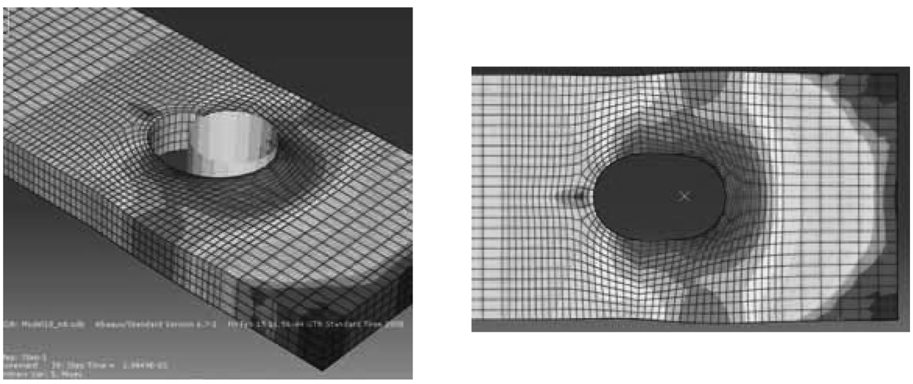

Fig. 11 Mixed-type failure mode

6. Conclusions

This paper reports the results of a numerical study on stainless steel bolted plates under in-plane uniform tension which were then critically examined and compared with currently available design guidance in terms of ultimate resistance in plate bearing. Experimental data provided by a number of relevant tests which were previously carried out on bolted steel plate specimens under in-plane tension were used to validate numerical models which could simulate closely the test behavior of the specimens. Finite element (FE) models were established for these test specimens accounting for the experimentally obtained material property and adopted boundary and loading conditions. Very close agreement was achieved between FE predictions and test in terms of important performance measures, such as the load-deformation curve and ultimate strength. On average, ultimate load was predicted within 4%. Following the numerical validation, a numerical parametric study was carried out on a family of bolted stainless steel plate models in two different material grades and which consider variations mainly in the positions of bolts. FE results generated in the parametric study were used for assessing the available criteria for bearing resistance of two specifications on structural stainless steel namely the European Euro Inox (2006) and the American SEI/ASCE (2002). FE predicted ultimate strength for a model was assumed to be the strength corresponding to a 3 mm hole center elongation. Bearing strength estimations of both specifications were compared with the FE predictions. It was found out that, regardless of the material grade, numerically obtained resistance values for all the models in the parametric study were higher than the resistance values obtained by Euro Inox (2006) rules. On the other hand, FE predictions were found to be lower (in average around 15%) than SEI-ASCE (2002) estimations. However, when partial factors are used in design bearing resistance calculations, a more pronounced conservativeness is obtained for Euro Inox (2006) and for SEI-ASCE(2002) the specification becomes conservative. Therefore, the guidance provided by both specifications for the estimation of design bearing strength seems to be conservative with Euro Inox (2006) rules giving strength estimations within a more additional safe strength reserve. In terms of strengths achieved for varying values of edge (e_2) and bolt pitch (p_2) distances, it was found out that the numerically obtained strength values for the models with small edge and bolt pitch distances are in general greater than what Euro Inox predicts particularly for e_2 and p_2 values smaller than the code limits. With this respect, the study has provided evidence supporting the use of smaller limits for edge and bolt pitch distances. Therefore, adjustments may be considered for these limits provided by the current specifications. Finally, the above observations made including the levels of conservativeness of the specifications in the estimation of design bearing resistance and the discrepancy between FE and design for smaller values of edge and bolt pitch distances were found to be valid and similar for both grades of stainless steel, namely Grade 304 and Duplex steels.

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