Bearing strength of stainless steel bolted plates in tension

G. KIYMAZ[1]
[1]*Department of Civil Engineering, Istanbul Kultur University, Ataköy Campus, Bakırköy, Istanbul, Turkey*

ABSTRACT: A study on the behavior and design of bolted stainless steel plates under in-plane tension is presented. An experimentally validated finite element program was used to examine the strength of stainless steel bolted plates under in-plane tension. Emphasis was given on plate bearing mode of failure. The behavior of stainless steel plate models with various proportions and bolt locations was investigated within the framework of a numerical parametric study. 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.

1 INTRODUCTION

The failure of a steel bolted connection is generally governed by a significant interaction between the bolts and other components of the connection usually in the form of flat steel plates. In practical structural steel bolted connections, failure which may occur as a result of this interaction manifests itself as either bolt shear, plate net-section fracture or bolts bearing against the plate in the direction of loading. Among these modes of failure, 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 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. 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. 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. Design rules for bearing resistance for bolted stainless steel connections are given in 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).
In Euro Inox Minimum strength to prevent end tear out failure is given by,

$$F_{b.Rd} = k_1 \left(\frac{e_1}{3d_0}\right) f_{u,red}\, d\, t \qquad (1)$$

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;

$$f_{u,red} = 0.5 f_y + 0.6 f_u \;\; \leq \;\; f_u \qquad (2)$$

A reduced value for the ultimate tensile strength of the material is used to limit the hole elongations at serviceability loads. This expression, which is based on test results of mainly single-bolted stainless steel shear connections (SCI-RT157, 1990), has been derived by examining the loads at which the deformation is 3mm. 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;

$$F_{b.Rd} = k_1\, f_{u,red}\, d\, t \qquad (3)$$

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 ($2.8(e_2/d_0) - 1.7$) 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 ($1.4(p_2/d_0) - 1.7$). 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. $F_{b.Rd} < 2.5 f_{u,red}\, d\, t$. 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 $p_2 < 2.4d_0$.
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;

$$P_n = t\, e\, F_u \qquad (5)$$

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;

$$P_n = F_p\, d\, t \qquad (6)$$

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

$$P_n = 2.00\, F_u\, d\, t \qquad (7)$$

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.

3 NUMERICAL PARAMETRIC STUDY

3.1 *FE validation study*

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 *et al.* 2003, Puthli *et al.* 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. The 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). Figure 1 shows a typical FE model adopted in the study and a typical deformed shape. 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).

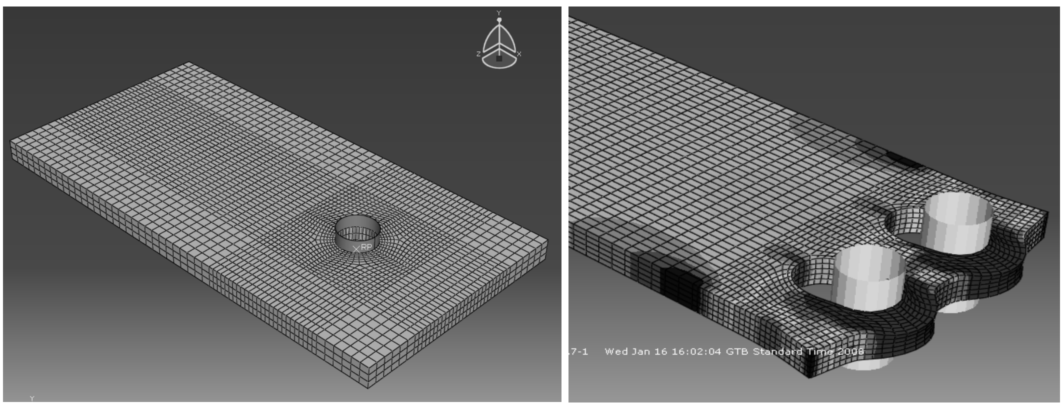

Figure 1. Typical finite element (FE) analysis model and deformed shape of a two-bolt model

The test ultimate loads are compared in Figure 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, Figure 3 shows non-linear response curve obtained from one of the above mentioned 15 experiments 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.

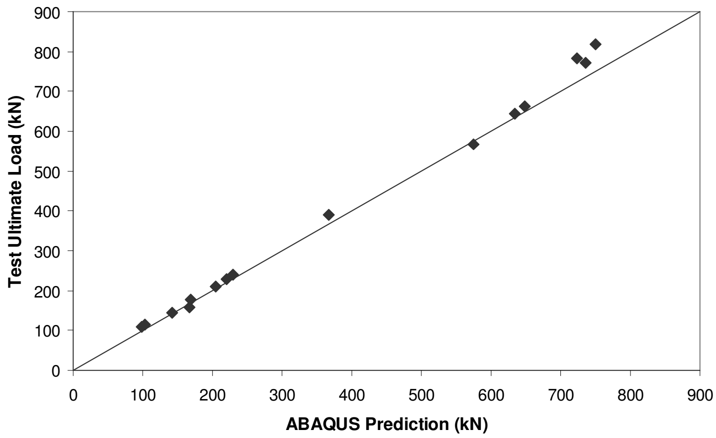

Figure 2. Comparison of finite element analysis predictions with experimental findings

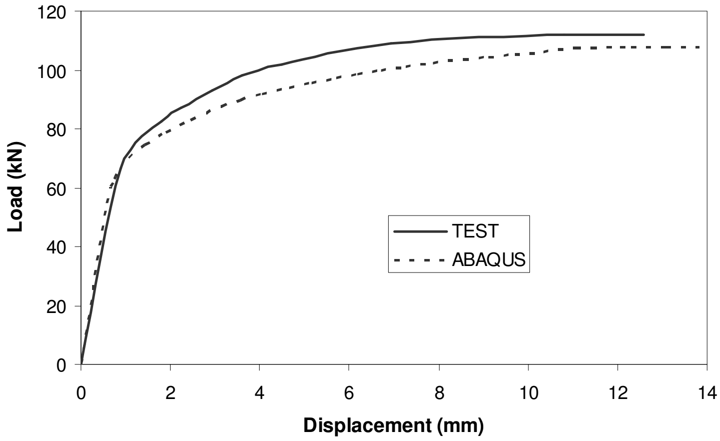

Figure 3. Test versus finite element analysis prediction for load-displacement history

3.2 *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 were also considered for the models in the parametric study.

More realistic material behavior is assumed for material modeling of stainless steel plates. 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 as proposed by Rasmussen (2003). In the study, stainless steel was considered in two common grades; Grade 1.4301 (AISI 304) and Grade 1.4462 (Duplex 2205). 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).

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.

A constant plate thickness of 13.5mm (current maximum production thickness for hot rolled strip as given in Euro Inox Table 3.1) and a constant hole diameter of 25mm 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. In total 32 different FE model geometry were developed half of which are one-bolt and the rest are the two-bolt cases. Each group is also divided into two cases as being either Grade 304 steel or Duplex steel. In other words, a particular model geometry was analyzed for two different steel grades making 64 analysis runs in total. 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.

4 RESULTS OF THE PARAMETRIC STUDY

In Figure 4 and Figure 5 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). 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) formulation. Therefore, the FE ultimate strength results 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. Also, the partial factors were set to unity.

Considering the average values for the ultimate strength ratios between FE and code predictions 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.

It is observed in Figure 4 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 Figure 5 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 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.

As explained earlier the bearing resistance in Euro Inox (2006) is given as a function of parameter k_1 which is a parameter that mainly controls the effect of edge distance (e_2) on the bearing resistance. For edge distances e_2 smaller than $1.5d_0$ the resistance is reduced due to closer proximities of the bolts to plate edges. In Figure 6 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 compared against the current Euro-Inox (2006) k_1- e_2 relationship. For this 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 values smaller than the code limits; e_2=1.5 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 values smaller than the above code limits may not need to be that much. Finally, it is noted that in the relationships k_1- e_2 similar amounts of increase are observed for both grades of stainless steel.

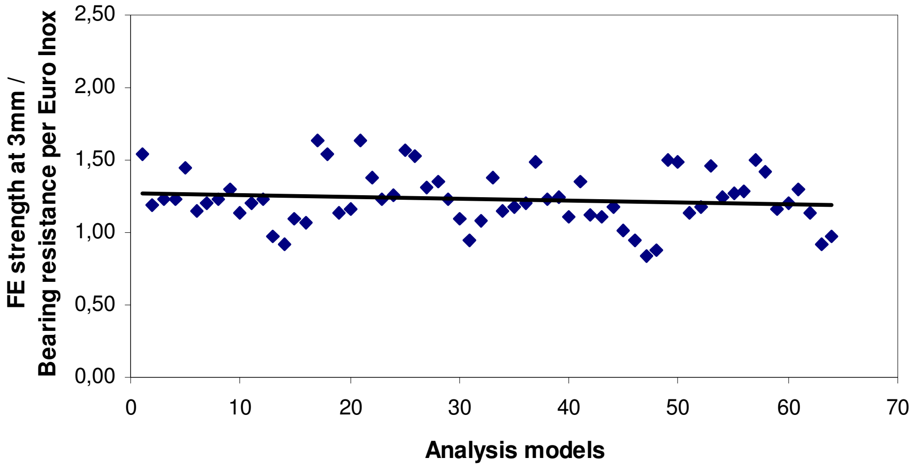

Figure 4 Distribution of the FE maximum strength-to-Euro Inox (2006) estimation ratios for the models analyzed

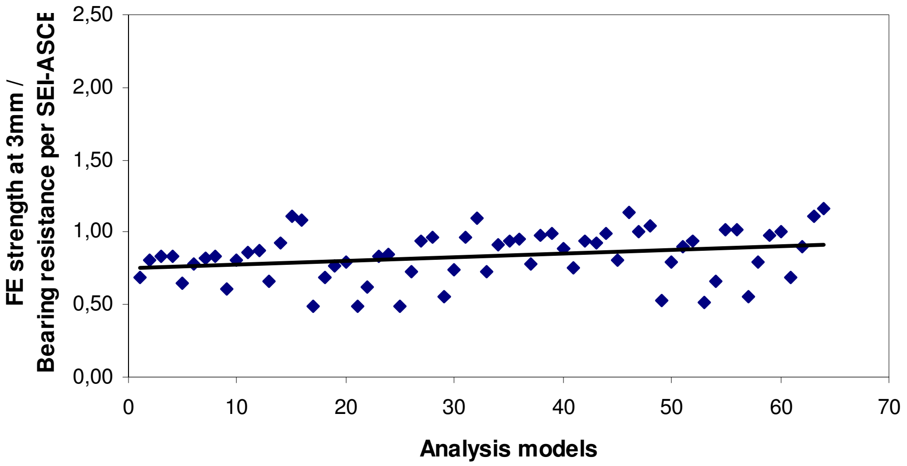

Figure 5 Distribution of the FE maximum strength-to-SEI/ASCE (2002) estimation ratios for the models analyzed

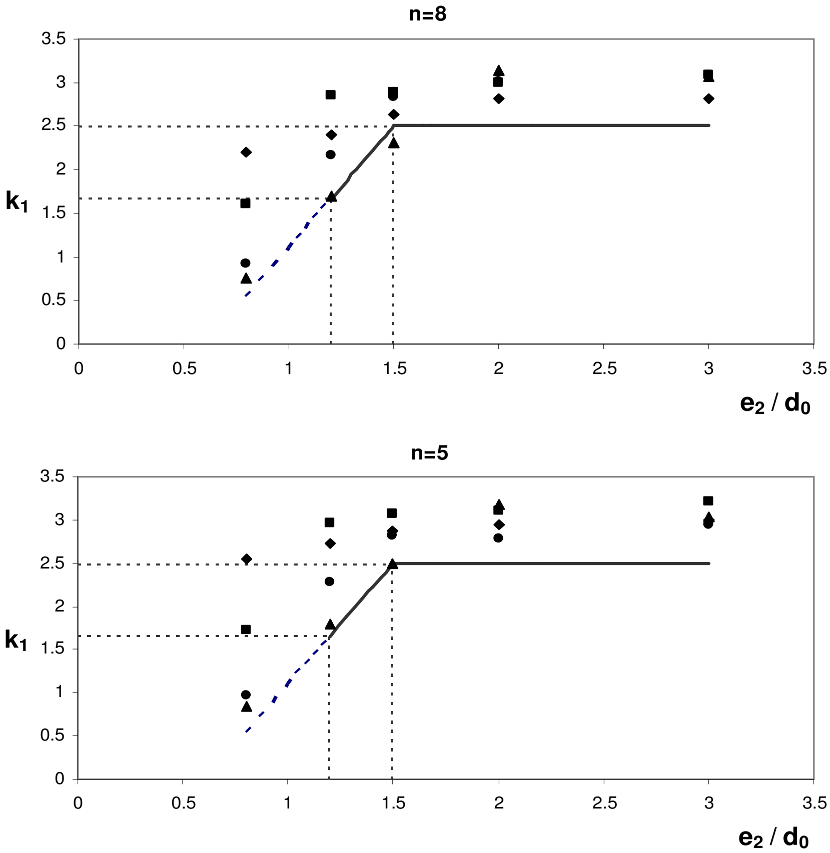

Figure 6 Comparison of FE predicted k_1 parameter as a function of edge distance e_2 with the Euro-Inox k_1 - e_2 relationship

Finally, Figure 7 shows deformed shapes of analyzed models with various failure modes due to varying positions of bolts and also the plate dimensions. In this figure, the aforementioned failure modes such as net section yielding, plate bearing and plate edge tear-out types of bearing failures can be observed.

5 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 3mm 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.

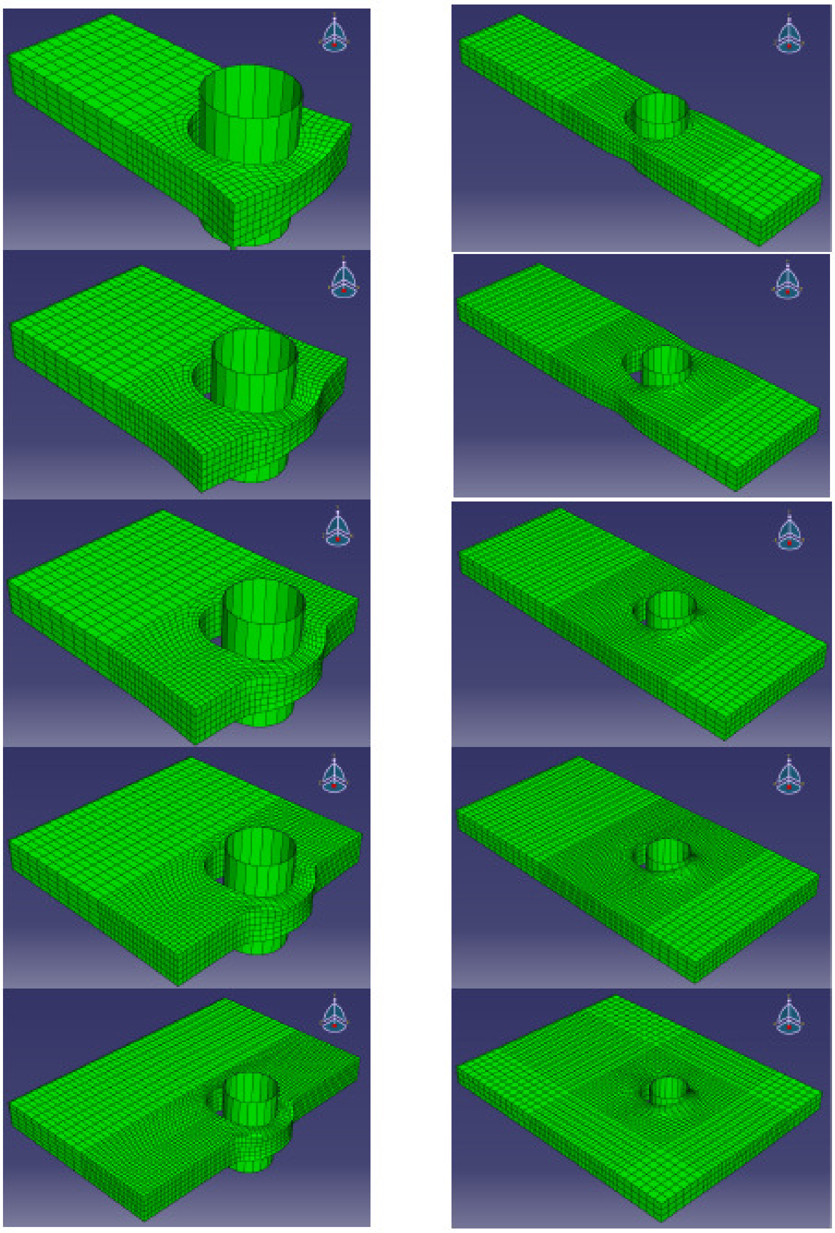

Figure 7 Deformed shapes of analyzed models with various failure modes

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) 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 values smaller than the code limits. With this respect, the study has provided evidence supporting the use of smaller limits for edge 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 distances were found to be valid and similar for both grades of stainless steel, namely Grade 304 and Duplex steels.

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