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NUMERICAL MODEL OF STAINLESS STEEL PLATES WITH STAGGERED BOLTS SUBJECTED TO TENSION

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ABSTRACT
Changes of attitudes associated to the building construction industry and a global transition for a sustainability development reduction in environmental impacts has been causing a boost in the stainless steel use. Despite this fact the current stainless steel design codes, Eurocode 3, part 1.4, 2003 [1] are still largely based in carbon steel structural behaviour analogies. However, considering that these codes represented a first attempt to produce specific stainless steel structural design rules, the idea of using similar rules to the ones adopted for carbon steel, enabled engineers to perform a smooth transition for the stainless steel design. The present paper presents an experimental investigation aiming to evaluate the tension capacity of stainless steel bolted structural elements. The results are discussed in terms of the stress distribution (that detects, among other structural parameters, first yield), and force-displacement curves. The numerical results are compared to tests and to Eurocode 3 design provisions. A significant conclusion from the present study was that, due to the large strain observed in these structures, additional criteria based on deformation limits, similar to the one used in tubular joints, should also be used in stainless steel design.

1. INTRODUCTION

Changes of attitudes associated to the building construction industry and a global transition for a sustainability development reduction in environmental impacts has been causing an increase in the stainless steel use. Despite this fact the current stainless steel design codes like the Eurocode 3, pt. 1.4 are still largely based in analogies to carbon steel structural behaviour. It is widely known that the stainless steel presents four nonlinear tension vs. deformation curves (tension & compression, parallel & perpendicular to the rolling direction) without a defined yielding stress and a strain hardening region, significantly modifying their global structural response. The present paper presents a finite element numerical model developed, using the Ansys [2] program, to evaluate the tension capacity of stainless steel bolted elements. The numerical results were calibrated and compared to previously performed tests in terms of load vs. deformation curves, stress distributions & failure modes.

2. EUROCODE 3 PROVISIONS

The current investigation uses the European design code for stainless steel elements - Eurocode 3, part 1.4 [1]. In this design standard , the failure modes of a plate with holes under tension axial forces is governed by two ultimate limit states: the gross area yield and the net area tension rupture. The presence of staggered holes in the transversal section as presented in Figure 1, complicates an immediate identification of the plate critical net section. This process is not new since in 1922 Crochrane [3], performed one of the first attempts to characterize staggered bolted connection failure modes by the use of the well known, eq. (1). This expression adds a term to the original net width to obtain the final net section area and is still present in major steel design codes all over the world.

$$b_n = b - d_b + \frac{s^2}{4p} \tag{1}$$

In the previous equation b is the plate width, d_b is the bolt diameter, s and p represent the staggered centre to centre hole distances measured parallel and perpendicular to the member axis. The Eurocode 3, part 1.4 (2003) [1], establishes the guidelines for the stainless steel plate design submitted to axial tension forces. The structure failure is associated to the smallest tension axial force obtained considering two limit states: gross cross-section plastic resistance given by eq. (2), or the ultimate net cross-section tension rupture expressed by eq. (3).

$$N_{pl,Rd} = \frac{A_g \cdot f_y}{\gamma_{M0}} \tag{2}$$

where, $N_{pl,Rd}$ is the tension design plastic resistance, A_g is the plate gross area, f_y is the steel yielding stress and γ_{M0} is the partial safety factor, in this case equal to 1.

$$N_{u,Rd} = \frac{k_r \, . \, \mathrm{A_n} \, . \, f_u}{\gamma_{M2}} \qquad \text{where} \qquad k_r = \left(1 + 3r\left(d_0 / u - 0.3\right)\right) \tag{3}$$

where A_n is the net cross-section plate area, f_u is the steel tension rupture stress, k_r is obtained from eq. (4) and γ_{M2} is the partial safety factor, in this case equal to 1.25, r is the ratio between the number of bolts at the cross-section and the total number of joint bolts, d_0 is the hole diameter, u = 2.e_2 but u ≤ p_2 where e_2 is the edge distance from the centre of the bolt hole to its adjacent edge, in the direction perpendicular to the direction of load transfer and p_2 is the hole centre-to-centre distance measured perpendicular to the load axis.

3. EXPERIMENTAL TESTS

An innovative experimental program was used to calibrate the numerical model presented in the present paper. The experiments involved bolted cover plate joints made of stainless steel A304 denominated E5_INOX_S50, E7_INOX_S30 and E9_INOX_S23 [4] with vertical gaps equal to: 50, 30 and 23 mm. The bolted joints were made of two 3 mm thick stainless steel plates and two 15 mm thick carbon steel plates with a 5 mm gap. The horizontal bolt pitch, p were 55 mm, Figure 1. The strains measurements were made using linear strain gauges located in both stainless steel plates named SG as it can be seen in Figure 1. The curves obtained in tensile coupons tests are presented in the Figure 2 where a nonlinear behaviour can be observed. The stainless steel yield stress was determined using a straight line parallel to the initial stiffness at a 0.2% strain, Figure 2, leading to a value equal to 350.6 MPa while the ultimate tension stress was 960 MPa. Figure 2 also present the results of a true stress, $\sigma_t = f_y(1+\varepsilon_n)$, versus true strain, $\varepsilon_t = \ln(1+\varepsilon_n)$, curve. This curve was used in the finite element modelling due to the large strain and stresses associated to the investigated problem where σ_t , ε_t , f_y ,and ,ε_n represent the true stress, the true strain, the yield stress and original measured strain, respectively.

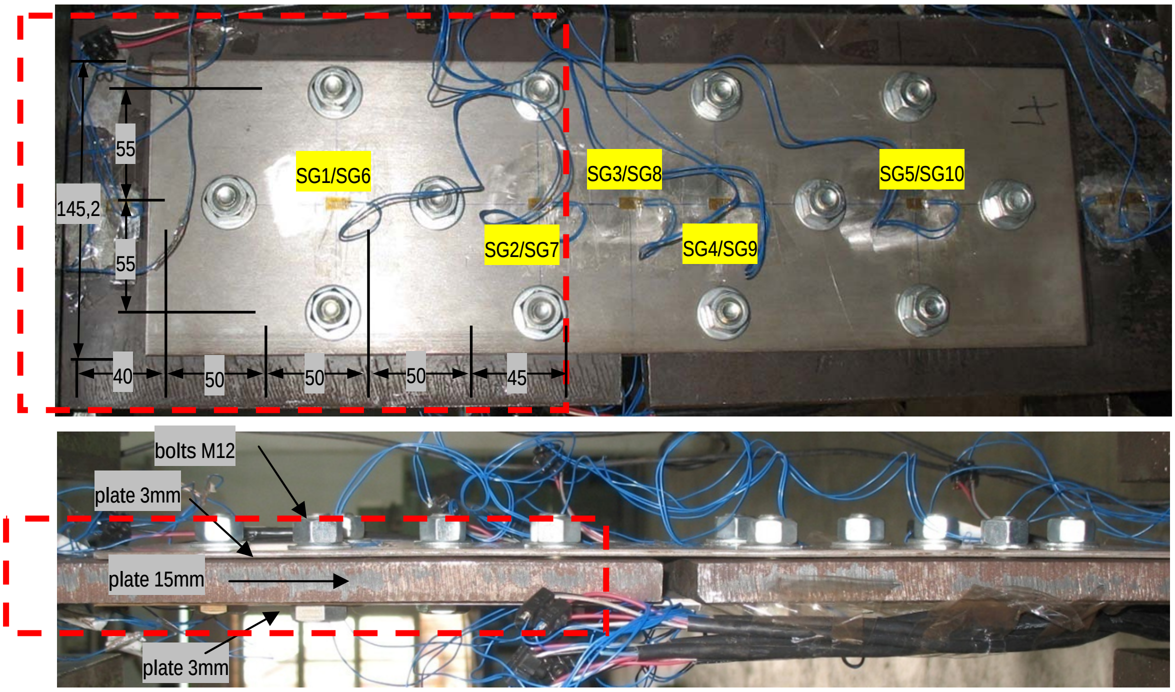
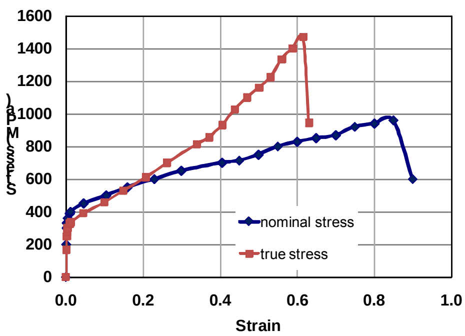


Figure 1: Cover plate joint detail and strain gauges location



$$\sigma_t = f_y(1+\varepsilon_n)$$

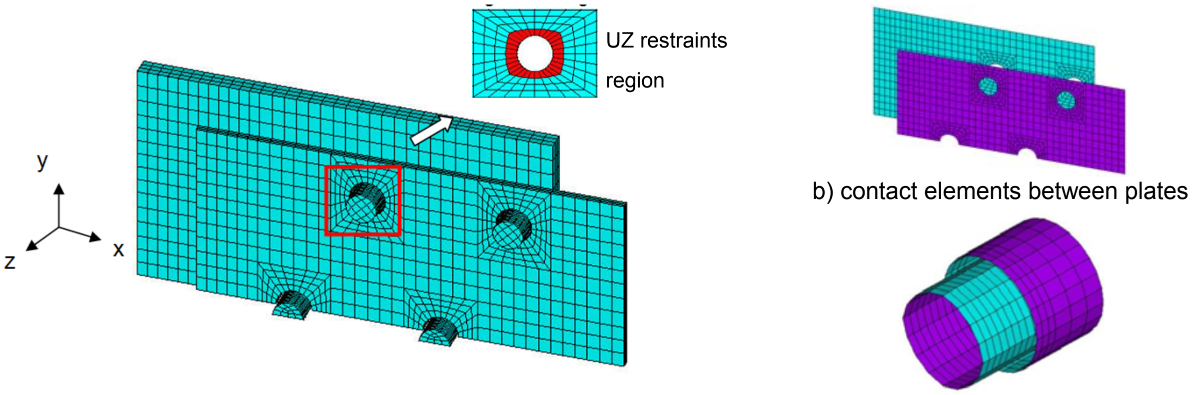
$$\varepsilon_t = ln(1+\varepsilon_n)$$

Figure 2: Stress versus strain curves for the stainless steel A304

4. NUMERICAL MODEL

The finite element model used in this paper to investigate the tension capacity of cover plate joints was developed with the aid of the Ansys 11 FE package [2]. The numerical model adopted solid elements (SOLID45) defined by eight nodes with three degrees of freedom per node: translations in the nodal x, y and z directions. The adopted mesh was chosen so that the elements had a proportion and size to avoid numerical problems. Figure 3 presents a typical mesh configuration of the complete model. Only half of the model was considered due to symmetry. Contact elements (CONTA174 and TARGE170) presented in the Ansys Elements Library [2] were considered between the plates and between the holes and the bolt shanks. The load was applied by means of axial load plate displacements (UX), Figure 3. In this figure, it is also possible to observe that the bolt head and nuts were simulated through UZ displacements restraints at the hole adjacent area. The adopted material properties were:

Young's modulus of 210 GPa (Figure 2) and a 0.3 Poisson's coefficient. As previously mentioned, stainless steel true stress vs. true strain curves with a nonlinear behaviour were adopted using data from the tensile coupons tests [4]. A full nonlinear analysis was performed for the developed numerical model. The material non-linearity was considered using a Von Mises yield criterion associated to a multi-linear stress-strain relationship and isotropic hardening response. The geometrical non-linearity was introduced in the model by using an Updated Lagrangean formulation. This procedure represents the full structural assessment of the analysed bolted joints, and may be summarized in several outputs, ie. the stress distribution or the force-displacement curve for any node within the joint [5].



a) adopted mesh

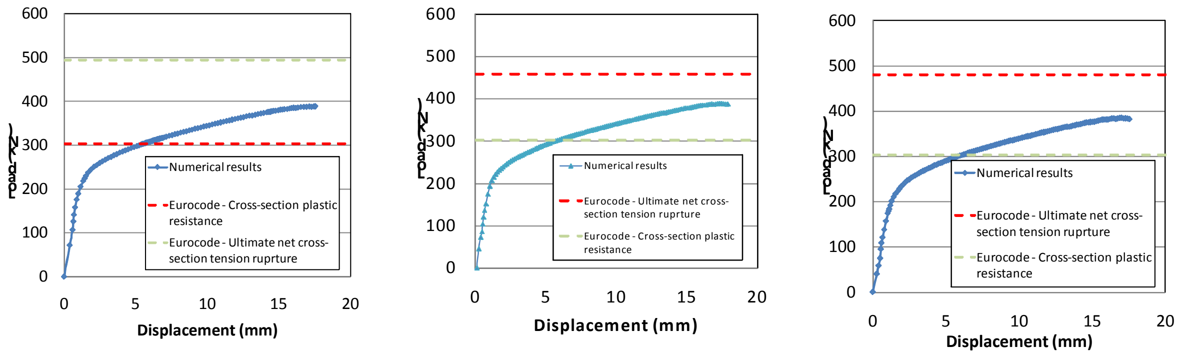
b) contact elements between plates

c) contact elements between plates

Figure 3: Finite element model and contact elements

5. RESULTS ANALYSIS

Figure 4 presents the numerical load-displacement curves for all the performed experiments where the peak loads related to specimens: E5_INOX_S50, E7_INOX_S30 & E9_INOX_S23 can be identified as: 389 kN, 389 kN & 385 kN, respectively. In all the performed simulations it was observed that the numerical peak loads were situated in an interval limited by their related experimental peak and Eurocode 3 pt. 1.4 design loads.



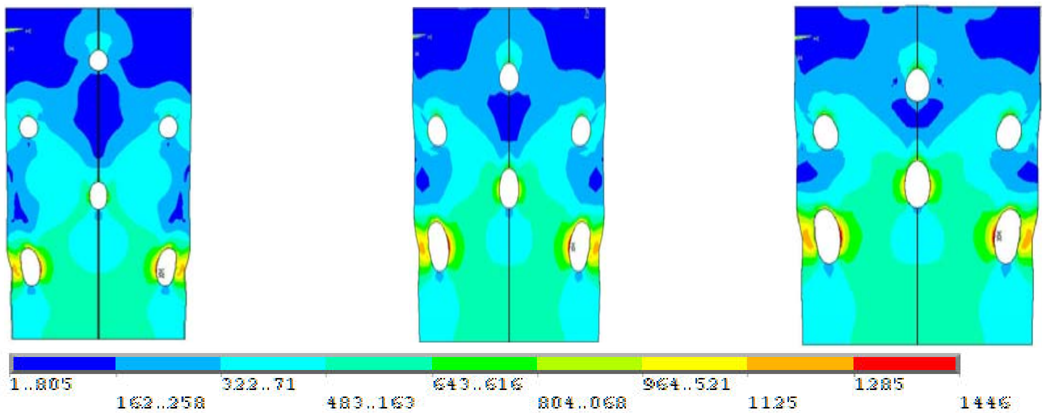
a) E5_INOX_S50

b) E7_INOX_S30

c) E9_INOX_S23

Figure 4: Load versus displacement curves - numerical results

Figure 5 depicts the Von Mises stress distribution for the investigated models where high stresses are observed, in all the models, in the region between the hole and the plate edge. In the E5_INOX_S50 numerical model the collapse mode can be identified in the net section passing through two holes. This collapse mode also occurred the associated experimental test. In the E7_INOX_S30 numerical model the collapse mode is not clearly identified since it could be related to a net section failure passing through two or three holes. Alternatively, in the E9_INOX_S23 numerical model the collapse mode can be identified in the net section passing through three holes, also confirmed by the experimental test counterparts.



a) E5_INOX_S50 b) E7_INOX_S30 c) E9_INOX_S23

Figure 5: Von Mises stress distribution (in MPa) for ultimate load

A comparison of load-displacement curves for test and numerical models was made to validate the numerical model. Figures 6(a) and 6(c) presents some of these comparisons for the E5_INOX_S50 & E9_INOX_S23 specimens measured at points located in sections between bolt closer to the joint centre line. A similar response was observed in the test and numerical models for the strain gauges 2(4) and 3(8). Despite this fact all the numerical model points in the inelastic range presented a more flexible structural response when compared to the experimental counterparts. Figure 6(b) presents some of these comparisons for the E7_INOX_S30 specimens measured at points located in sections between bolt closer to the joint centre line. The response was observed in the test and numerical models were not as good as the previous specimen due to the fact that the numerical model presented a more flexible structural response with more associated deformation for all the load levels when compared to the experimental counterpart.

6. CONCLUDING REMARKS

Table 1 presents a comparison of the numerical, experimental and Eurocode 3 pt. 1.4 results for the evaluated bolted stainless steel elements under tension loads. When the Eurocode 3 pt. 1.4 and the numerical results were compared differences in the order of 28% were observed. On the other hand differences ranging from 12% to 19% were found when the numerical and the experimental results were compared. The authors partially credit the observed difference due to the material modelling strategy adopted in the finite element simulations and to the implicit conservatism of the Eurocode 3 pt. 1.4 design standard. This implicit conservatism is largely due to the very few stainless steel tests available in the literature. Despite these fact all the numerical peak loads were less than the experiments peak loads. A possible reason for this discrepancy can be related to the fact that the simulations are an idealised model of the real joints and, at the present stage, did not presented any imperfection. Finally another possible reason for the observed differences in structural response can be related to the fact that the load-deformation curve used in the numerical model was associated to a coupon test that was extracted perpendicular to the load direction but in the tests the load direction was parallel to the stainless steel plate rolling direction.

7. ACKNOWLEDGMENTS

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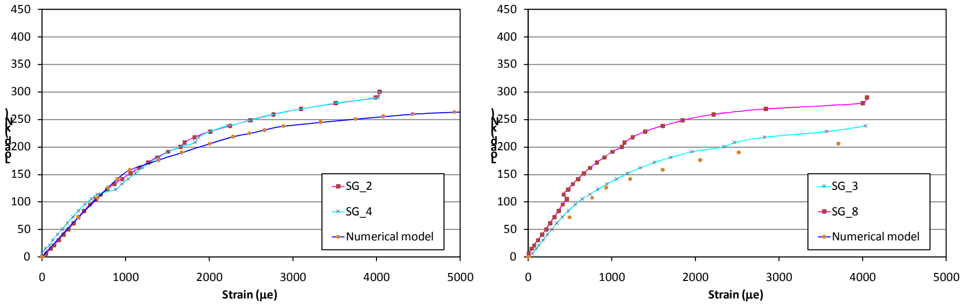
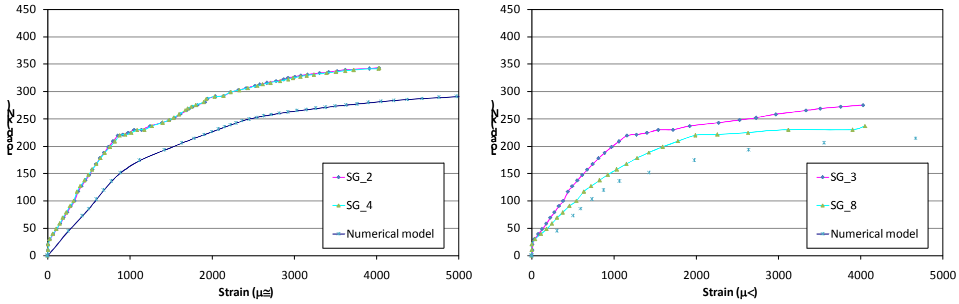
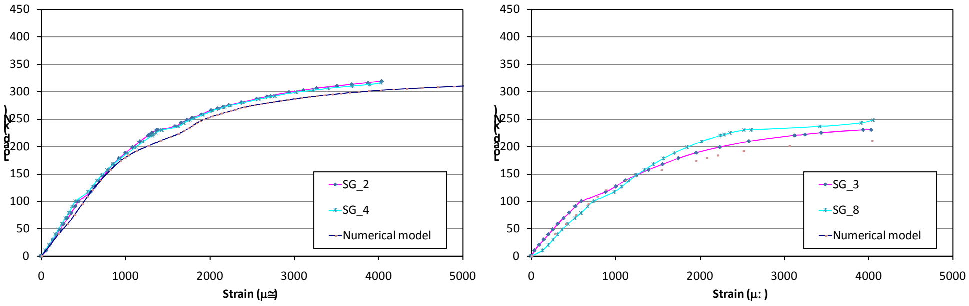


a) E5_INOX_50



b) E7_INOX_30



c) E9_INOX_23

Figure 6: Load versus strain (experimental & numerical)

Test	Failure Mode (exp.)	Exp Peak Load (kN)	Num Failure Mode	Num Peak load (kN)	Δ(%) Num x Exp	Δ(%) Num x EC3
E5_INOX_S50	2F	480.0	2F	389	19.0	28.8
E7_INOX_S30	2F	459.0	2F / 3F	389	15.2	28.8
E9_INOX_S23	3F	436.0	3F	385	11.6	27.5

Table 1: Comparison between numerical, experimental and analytical (Eurocode 3) results

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