Numerical Evaluation of Stainless Steel Joints Subjected to Tension

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Abstract

The use of stainless steel in structural engineering applications is still seen by a number of architects and engineers as an extravagant solution. However, attitude changes towards a sustainable development environment have boosted the stainless steel structures use. Despite theses facts, a substantial majority of stainless steel structural design codes is still based on carbon steel analogies. At this point it is interesting to observe the stainless steel presents four non-linear tension versus strain curves (tension and compression, parallel and perpendicular to the rolling direction) without a defined yield plateau and strain hardening zones, characteristics that substantially alters its global structural response. The present investigation adopted the austenitic stainless steel grade 304 and the carbon steel USI300, both with similar yield stresses, but with different tension stresses and ductility capacities.

Structural elements subjected to tension axial forces usually presents the net section rupture as one of its controlling ultimate limit states. The present paper describes a numerical model developed to evaluate and investigate the tension capacity of staggered bolted members calibrating their results with an innovative experimental programme. The experiments were made with carbon and stainless steels to compare and access their similarities and differences in terms of structural performance. The controlling ultimate limit states were significantly influenced by various parameters like: the loading plate thickness, layout, configuration and number of adopted joint bolts, and stainless steel properties like ductility capacity and the ratio between yield to rupture tension stresses.

Keywords: Stainless steel structures, bolted joints, finite element analysis, plastic analysis, non-linear analysis.

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 as it can be observed in the Figure 1. Despite this fact the current stainless steel design codes like the Eurocode 3, part 1.4, 2003 are still largely based in analogies to carbon steel structural behaviour. Several investigations have pointed out that the stainless steel presents four nonlinear tension versus deformation curves (tension and compression, parallel and perpendicular to the lamination direction) without a defined yielding stress and a strain hardening region (to see Figure 4), fact that significantly modifies their global structural response.

An important step to increase the understanding and the use of the stainless steel in structural systems was the development, and subsequent publication of specific design codes, like the Eurocodes. 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 net section rupture represents one of the ultimate limit states usually verified for structural elements submitted to tension axial stress. The present paper presents a finite element numerical model developed, using the Ansys [1] program, evaluate the tension capacity of stainless steel bolted structural elements. The numerical results were calibrated and compared to previously performed experiments in terms of load versus deformation curves, stress distributions and failure modes.

Figure 1 – Sá Ferreira Airport - Porto - Portugal

2 Eurocode 3 Provisions [4]

As previously mentioned, the current investigation uses the European design code for stainless steel elements - Eurocode 3, part 1.4 [4]. 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, where the second failure process evolution can be visualized in Figure 2.

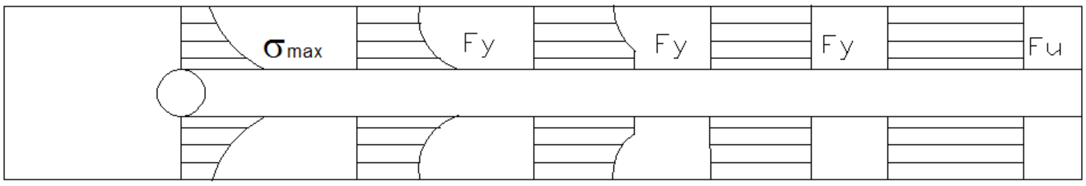


Figure 2 – Normal stress distribution present in a plate under tension axial loads

The presence of staggered holes in the transversal section as presented in Figure 3, 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.

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

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) [4], 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.

$$N_{u,Rd} = \frac{k_r \cdot \mathrm{A_n} \cdot f_u}{\gamma_{M2}} \tag{3}$$

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.

$$k_r = \left(1 + 3r\left(d_0 / u - 0.3\right)\right) \tag{4}$$

where 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 $u \leq p_2$ 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 in the direction perpendicular to the load axis.

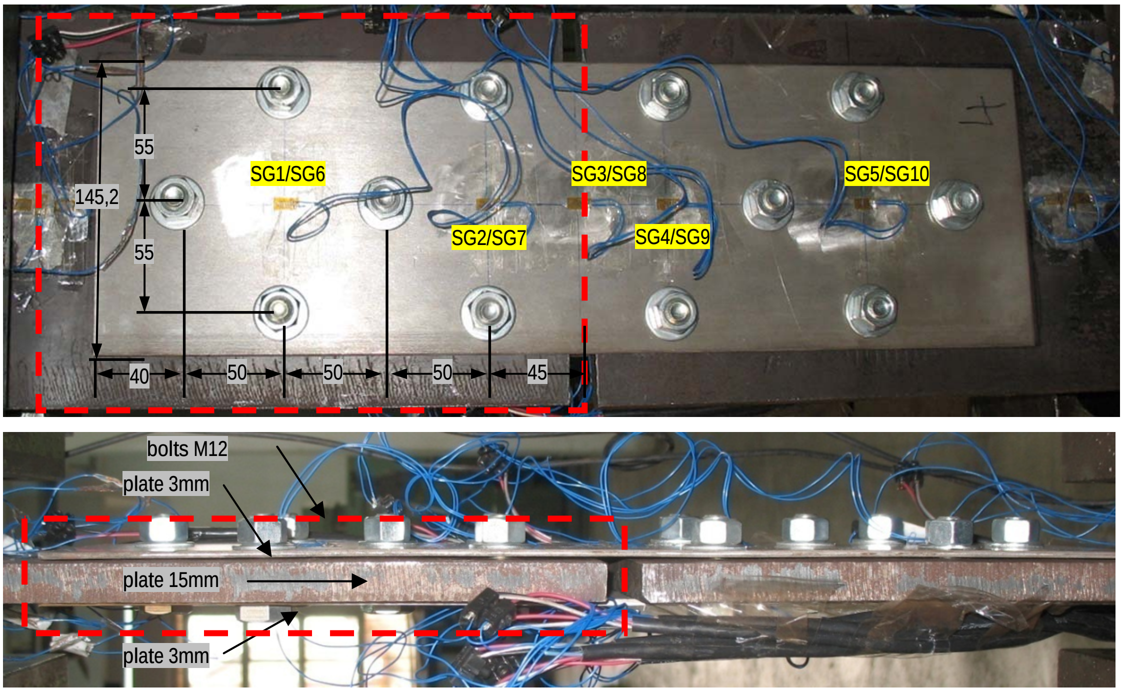


Figure 3 – Cover plate joint detail and strain gauges location

The tension joint design has also some additional recommendations:

a) in bolted joints, the hole width should be considered 2 mm larger than the nominal bolt diameter, perpendicular to the applied force direction;

b) in the case of staggered holes, when a diagonal direction to the load axis or zigzag is considered, the net width should be calculated first deducing from the initial gross width, all the holes present in it, and after that adding for each staggered holes a value equal to $s^2/4p$, where s and g, represent the considered longitudinal and traverse hole spacing;

c) the bolted joint critical net width is the smallest evaluated net width for all the different net rupture possibilities;

d) for angles, the dimension p of opposite legs holes is equal to the sum of the dimensions, measured from the angle corner, minus its thickness;

e) the net cross-section area for joints with fillet or spot welds present in the holes should not consider the weld metal area;

f) joints without holes should be evaluated considering that the net area is equal to the gross area, $A_{net} = A_g$.

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_50 [6]. 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 and vertical bolt pitch, g, and p were 50 mm and 55 mm respectively (see Figure 3). The strains measurements were performed using linear strain gauges located in both stainless steel plates named SG as it can be observed in the Figure 3.

The obtained curves in tensile coupons tests are presented in the Figure 4 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% deformation, Figure 4, leading to a value equal to 350.6 MPa while the ultimate tension stress was 960 MPa. Figure 4 also present the results of a true stress *versus* true strain curve obtained using the equations (5) and (6), respectively. 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.

$$\sigma_t = f_y(1+\varepsilon_n) \tag{5}$$

$$\varepsilon_t = ln(1+\varepsilon_n) \tag{6}$$

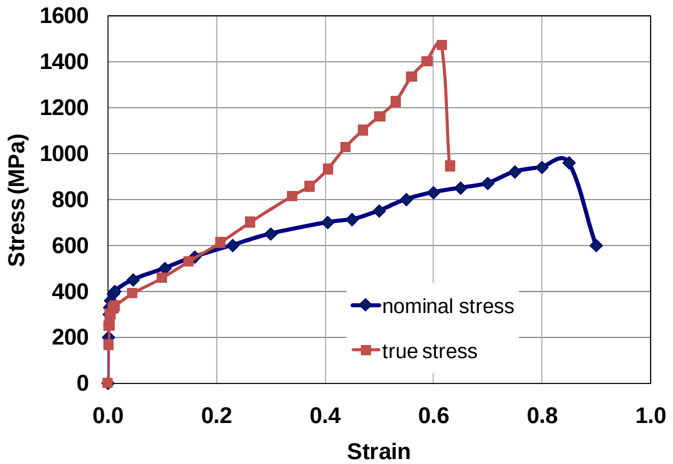
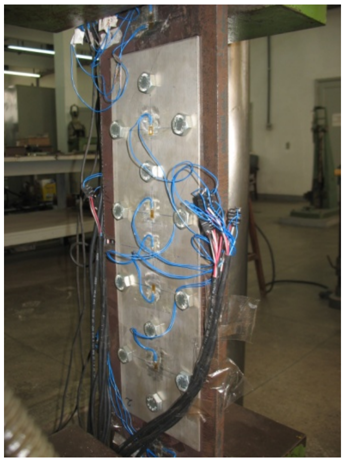


Figure 4 – Stress *versus* strain curves for the stainless steel A304

The bolted cover plate joint tests were carried out on a 600kN universal Lousenhausen machine, Figure 5. The data acquisition in terms of deformations, displacements and applied load was performed using the National Instruments system NI-PXI-1050.

a) Universal machine Lousenhausen, 600kN



b) cover plate joint detail

Figure 5 – Test layout

4 Numerical Model

Finite Element numerical analyses provide a relatively inexpensive and time efficient alternative to physical experiments. Despite this fact, due to their nature these numerical simulations have to be properly calibrated against experimental test results [2]. If the validity of FE analysis is assured, it is possible to investigate the structural behaviour against a wide range of parameters with the FE 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 [1]. 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 [2]. The Figure 6 presents a typical mesh configuration of the complete model. It is emphasized here that only half of the model was considered using the symmetry boundary conditions being sufficient to characterize the joint ultimate limits states. Future steps of this investigation will consider other symmetry simplifications to further reduce the mesh size.

Contact elements (CONTA174 and TARGE170) presented in the Ansys Elements Library [1] were considered between the plates and between the holes and the bolt shanks. The load was applied by means of axial displacements in the load plate such as presented in Figure 6. 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 considered material properties were: Young's modulus of 210 GPa (see Figure 4) and a Poisson's coefficient of 0.3. As previously mentioned, stainless steel true stress *versus* true strain curves with a nonlinear behaviour were adopted using data from the tensile coupons tests [6].

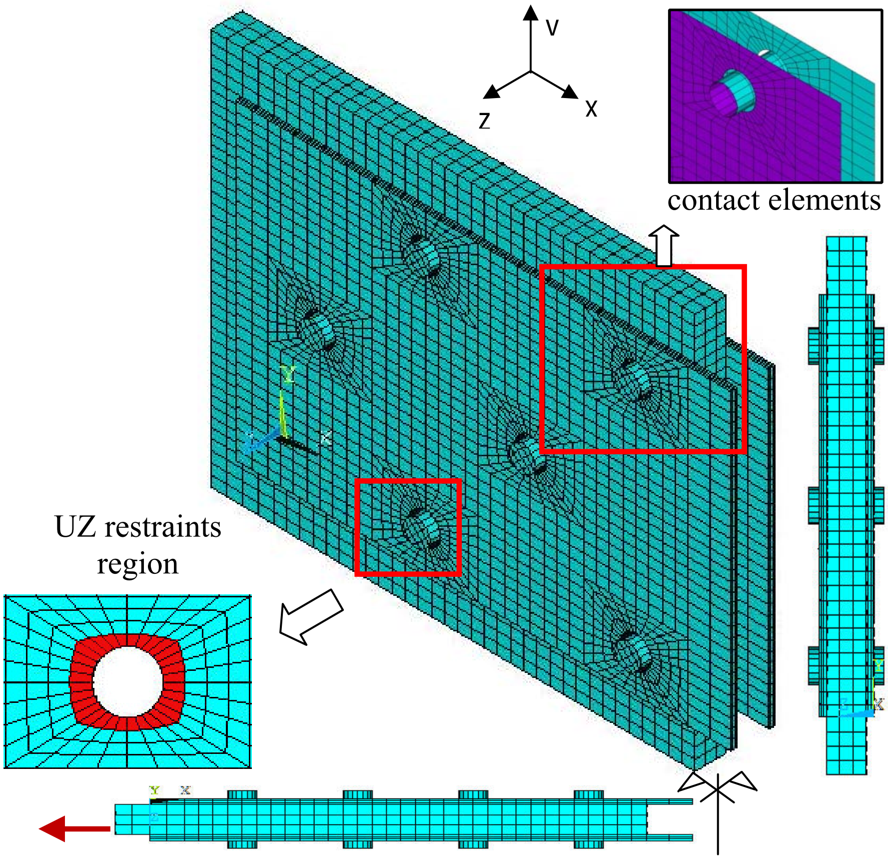


Figure 6 – Finite element model and contact elements

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, namely the stress distribution (that detects, among other data, first yield), or the force-displacement curve for any node within the connection.

5 Results Analysis

5.1 Experimental Results

For the bolted cover plate tested in the laboratory, according to Figure 7, the ultimate load reached 469.4kN when a tension net rupture in a position passing trough two bolt holes occurred. Based on the Eurocode 3 - part 1.4 provisions [4], the ultimate limit states were: gross section yield of 305.5 kN, bolt shear of376 kN, plate bearing of 466.9 kN and finally, net section capacity of 592.4 kN. Comparing the Eurocode 3 and the experimental values (see Figure 7), it may be observed that the gross section yield was the first limit state reached characterized by the knee of the experimental curve. The ultimate load of the experimental test was equal to 463 kN lower than the Eurocode 3 design values. Figure 7 also depict the residual bearing deformations present at the bolts.

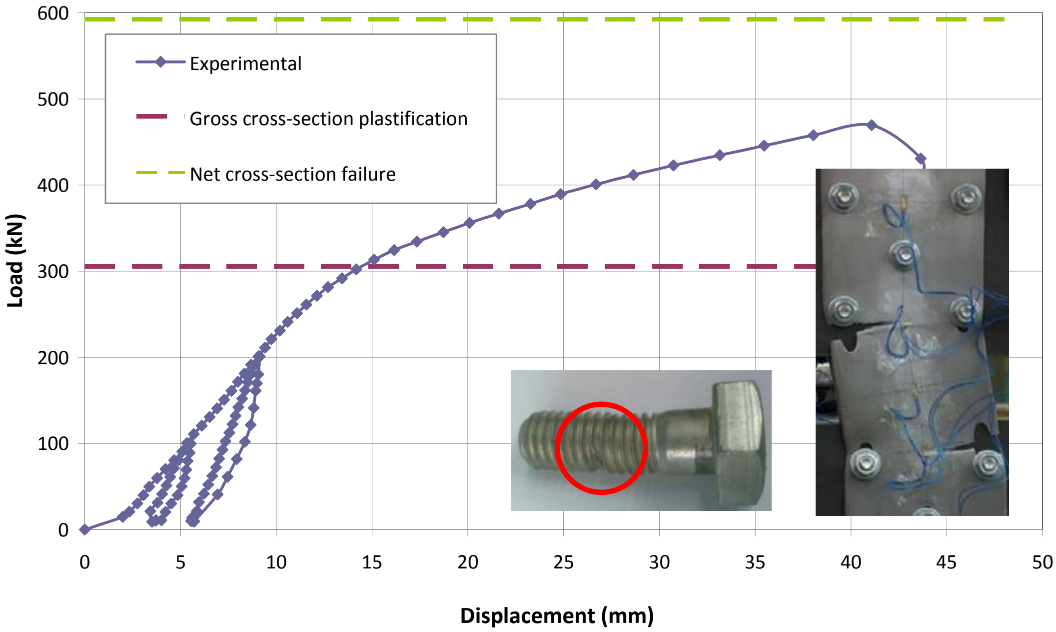


Figure 7 – Load *versus* displacement curve - Experimental

5.2 Numerical Results

The numerical model ultimate load was equal to 448.2 kN when a two bolt row net section failure started as can be observed in Figure 8. Figure 9 to Figure 12, illustrate the numerical Von Mises stress distribution evolution. An inspection of these graphs indicate that the net section failure occur near the symmetry section.

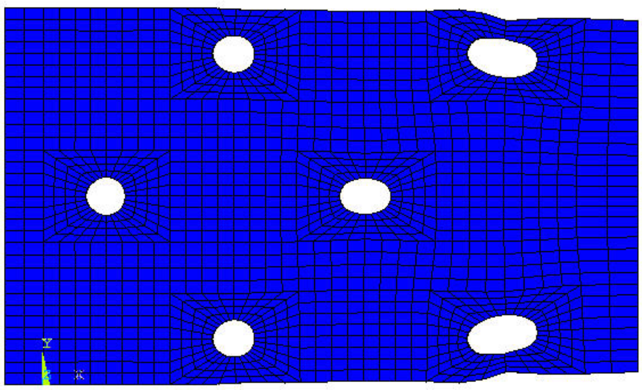


Figure 8 – Numerical model deformed shape

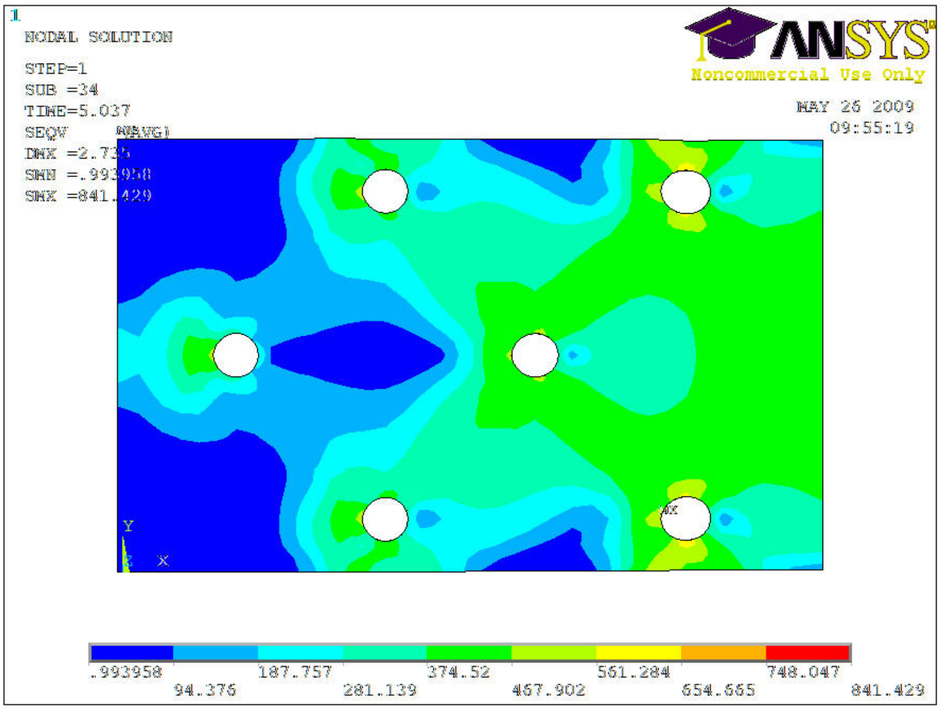


Figure 9 – Von Mises stress distribution - P = 321.6 kN

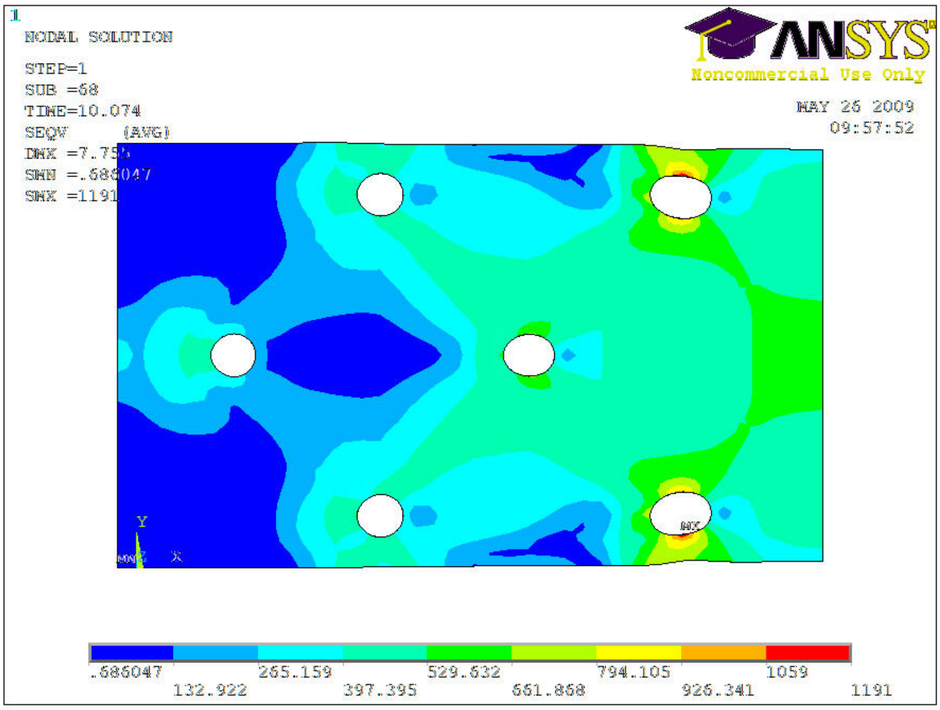


Figure 10 – Von Mises stress distribution - P = 390.7 kN

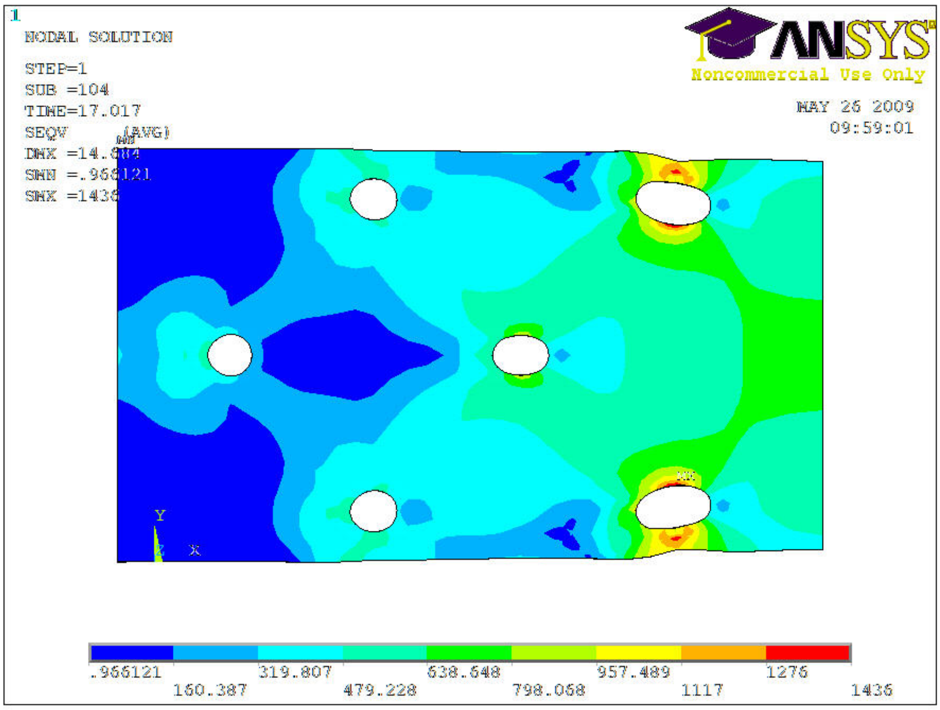


Figure 11 – Von Mises stress distribution - P = 444.7 kN

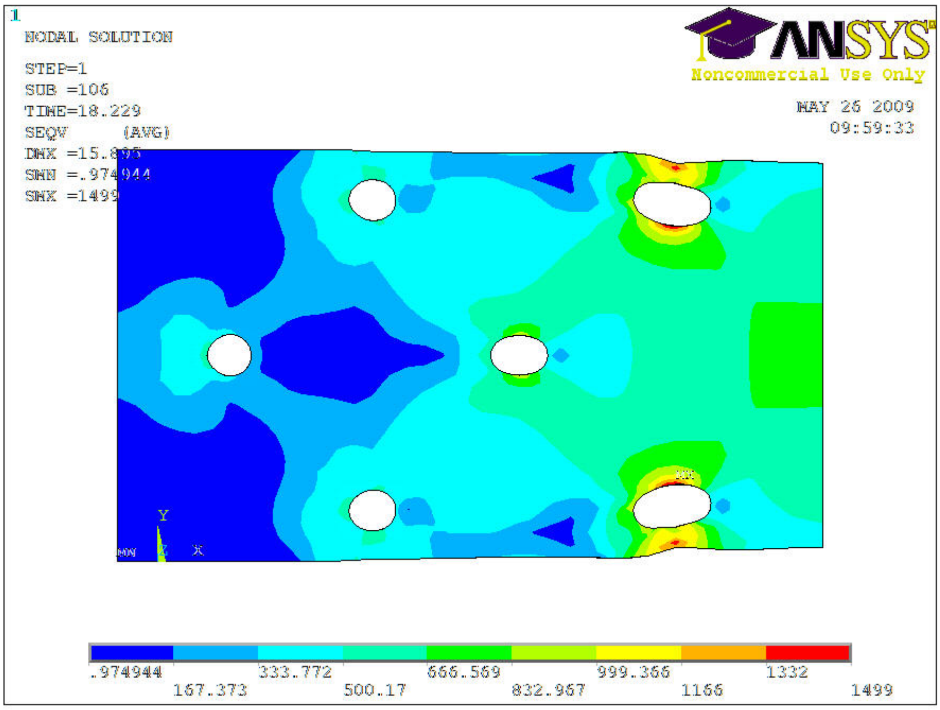


Figure 12 – Von Mises stress distribution - P = 448.2 kN

5.3 Comparison of Experimental and Numerical Results

The comparison between experimental and numerical results will be presented in terms of load *versus* strain curves. This strategy was adopted because the measured test displacements correspond to the total displacement of the universal test machine including a possible slip that usually occurs during the test. Figure 13 presents the experimental and numerical test deformed shapes. It may be observed that a good agreement between the results in terms of deformed shape occurred.

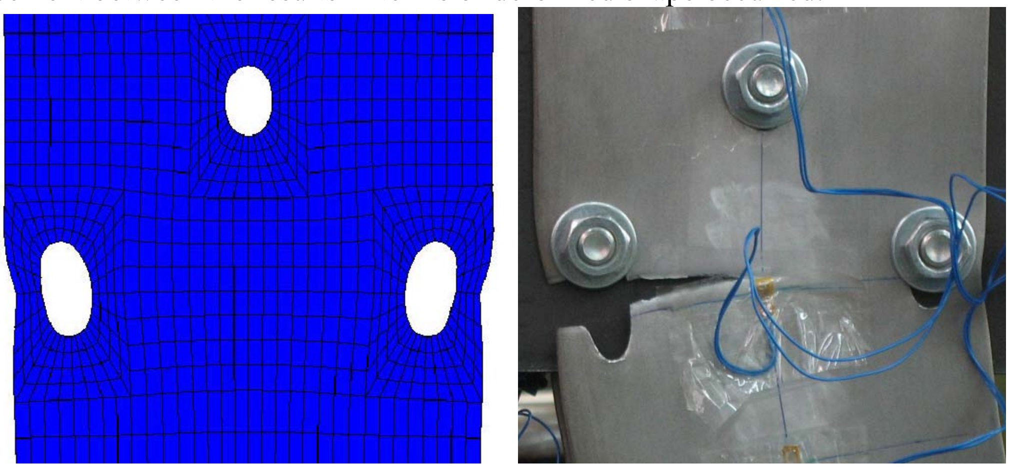


Figure 13 – Deformed shape - numerical *versus* experimental

Load *versus* strain curves associated to the cross-section failure are presented in Figure 14 where the codes SG_X and ANSYS_X correspond to the strain gauges measurement and to the numerical results, respectively. In this figure a good agreement between the results in terms of elastic strains was initially observed but after the load reached 200 kN, differences can be noticed.

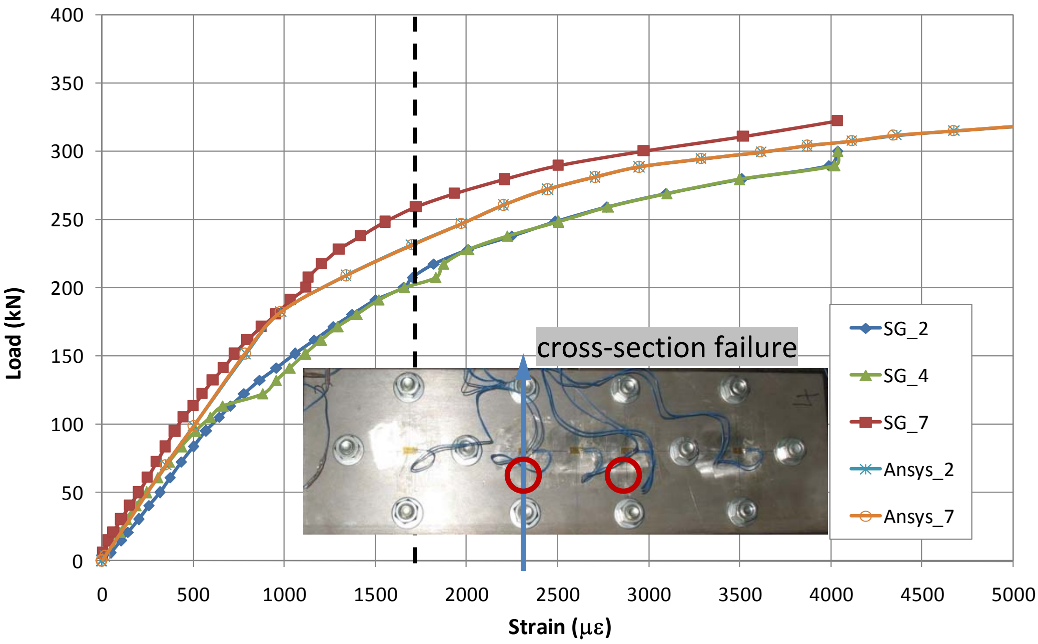


Figure 14 – Load *versus* strain curves - SG2, SG4 and SG7

Finally, Figure 15 depicts the strains at a cross-section present at the symmetry plane. The numerical results are located within the maximum and minimum experimental values. Some differences are still present in terms of ultimate load when the numerical and experimental results are considered.

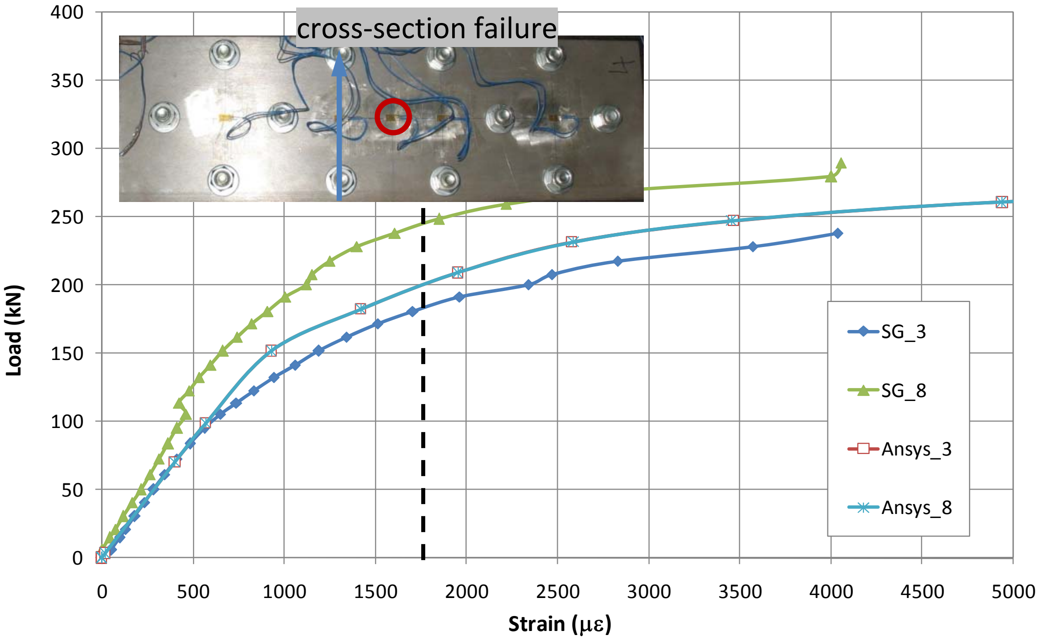


Figure 15 – Load *versus* strain curves - SG2, SG4 and SG7

The experimental ultimate load was equal to 463 kN and the numerical ultimate load was equal to 448.2 kN representing a ratio P_{num}/P_{exp} of 0.97. However, when these values are compared with Eurocode 3 results, the ultimate limit state related to the net section failure leads to an unsafe design prediction since this resistance, according to the Eurocode 3 recommendations is equal to 592.4 kN. When the stainless steel is used in structural engineering, the design criteria based in deformation limits need to be proposed such as the criteria adopted in steel structural tubular joints due to the large strain observed in these structure.

6 Final Considerations

The present paper aimed to evaluate the structural response of stainless steel cover plate joints under tension axial forces. The adopted methodology first considered the available stainless design procedures for structures subject to tension axial loads where the Eurocode 3, part 1.4 may be cited. Afterwards, a numerical model based on finite element method was developed, using Ansys 11.0 package, considering a full nonlinear analysis (material and geometric). The numerical model calibration was performed against experimental evidence in terms of load *versus* strain curves.

A comparison of the numerical and experimental results indicated a good agreement in terms of strain levels, ultimate loads and failure modes. The experimental and numerical ultimate loads were respectively equal to 463 kN and 448.2 kN representing a P_{num}/P_{exp} ratio of 0.97 on the safe side. Alternatively, when these results are compared with Eurocode 3 design values, some differences were still present.

Future steps in this investigation will consider the development of more tests with cover plate joints subjected to tension to enlarge the experimental dataset enabling its use in further numerical simulations. With this results in hand, the authors will envisage the production of some modifications to the actual stainless steel design codes rules aiming to produce more economical and safer solutions.

Acknowledgments

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