BEHAVIOUR OF BOLTED JOINTS IN STAINLESS STEEL PLATES SUBJECTED TO SHEAR

COMPORTAMENTO DE LIGAÇÕES APARAFUSADAS DE CHAPAS GROSSAS DE AÇO INOXIDÁVEL SUBMETIDAS AO CISALHAMENTO

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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 an increase in the stainless steel use. Despite this fact the current stainless steel design codes, like the Eurocode 3, part 1.4 (2006) 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, the force-displacement curves A comparison with Eurocode 3 predictions is also presented. When the stainless steel is used in structural engineering, the design criteria based on deformation limits need to be defined and proposed such as the criteria adopted in steel structural tubular joints, due to the large strain observed in these structure.

Resumo

Mudanças de atitudes na construção civil e uma transição global para um desenvolvimento sustentável além da redução em impactos ambientais tem provocado um aumento substancial do uso do aço inoxidável. As normas de projeto de aço inoxidável, Eurocode 3, são em grande parte baseadas em analogias assumidas com o comportamento de estruturas em aço carbono. Portanto, considerando-se que estas normas representam uma primeira tentativa de se definir procedimentos de dimensionamento para elementos estruturais constituídos de aço inoxidável, a idéia de usar regras similares as adotadas para elementos em aço carbono, possibilitam aos engenheiros, fazerem uma transição natural para o dimensionamento em aço inoxidável. Este artigo apresenta uma investigação experimental com o objetivo de avaliar a resistência a tração de elementos em aço inoxidável com ligações aparafusadas. Os resultados obtidos são discutidos em termos de distribuição de tensões, curvas carga versus deslocamento onde estes valores são comparados com a formulação presente no Eurocode 3. Para elementos estruturais constituídos de aço inoxidável, critérios de dimensionamento baseados em deformações limites ainda precisam ser definidos e propostos, como os critérios adotados em ligações tubulares, devido às grandes deformações observadas nestas estruturas.

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 (2006) are still largely based in carbon steel structural behaviour analogies. 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 (see Figure 4), fact that significantly modifies their global structural response.

An important step to increase the understanding and the stainless steel use 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 according to Eurocode 3, part 1.8 (2003), enabled engineers to perform a smooth transition for the stainless steel design.

The net section rupture represents one of the controlling ultimate limit states for structural elements submitted to tension axial forces. The present paper presents a experimental programme developed to evaluate the tension capacity of stainless steel bolted structural elements. The experimental results were compared to analytical values according to Eurocode 3, part 1.4 (2006) in terms of load versus deformation curves, stress distributions and failure modes.

Figure 1 – Sá Ferreira Airport - Porto - Portugal

2 Eurocode 3, part 1.4 (2006) Provisions

As previously mentioned, the current investigation uses the European design code for stainless steel elements - Eurocode 3, part 1.4 (2006). 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 2, complicates an immediate identification of the plate critical net section. This process is not new since Crochrane (1922), 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 (2006), 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.

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

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 ≤ 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.

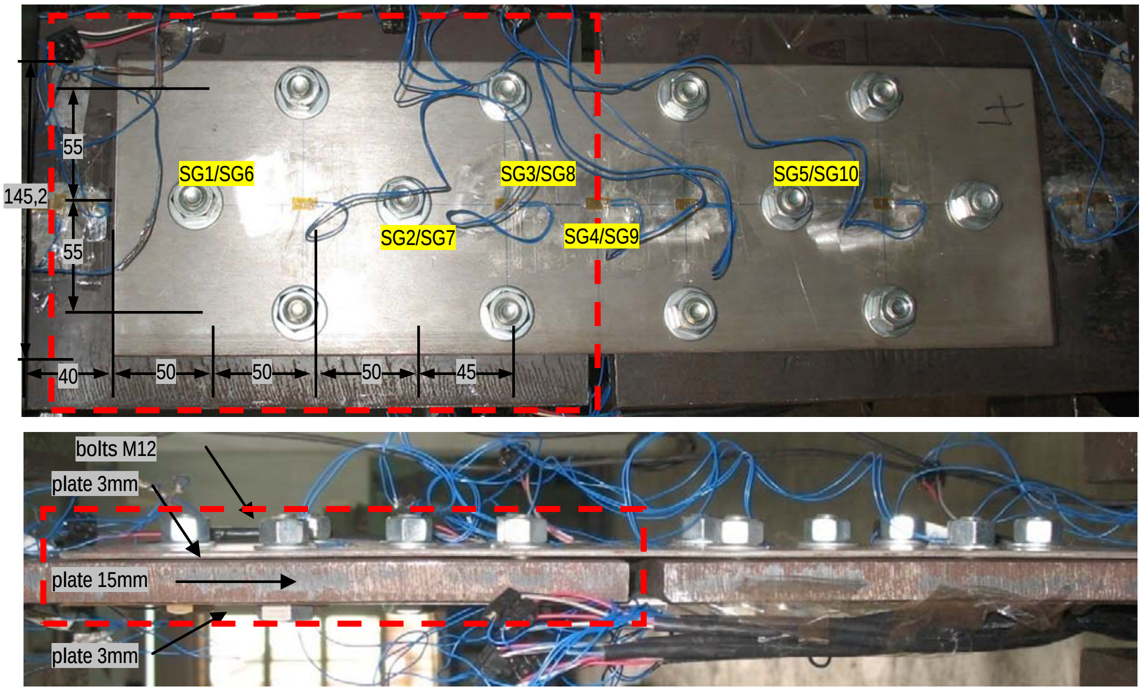


Figure 2 – Cover plate joint detail and strain gauges location

3 Experimental Tests

An innovative experimental program was used to calibrate a numerical model developed by Santos (2008)0. The experiments involved bolted cover plate joints made of stainless steel A304 denominated E5_INOX_S50, E7_INOX_S30 and E9_INOX_S23. 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 for the tests, g, were 50, 30 and 23 mm and the vertical bolt pitch, p, were 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 2.

The obtained curves in tensile coupons tests are presented in 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 performed by Silva (2009) in the software Ansys 11.0 (2008) 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.

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.

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

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

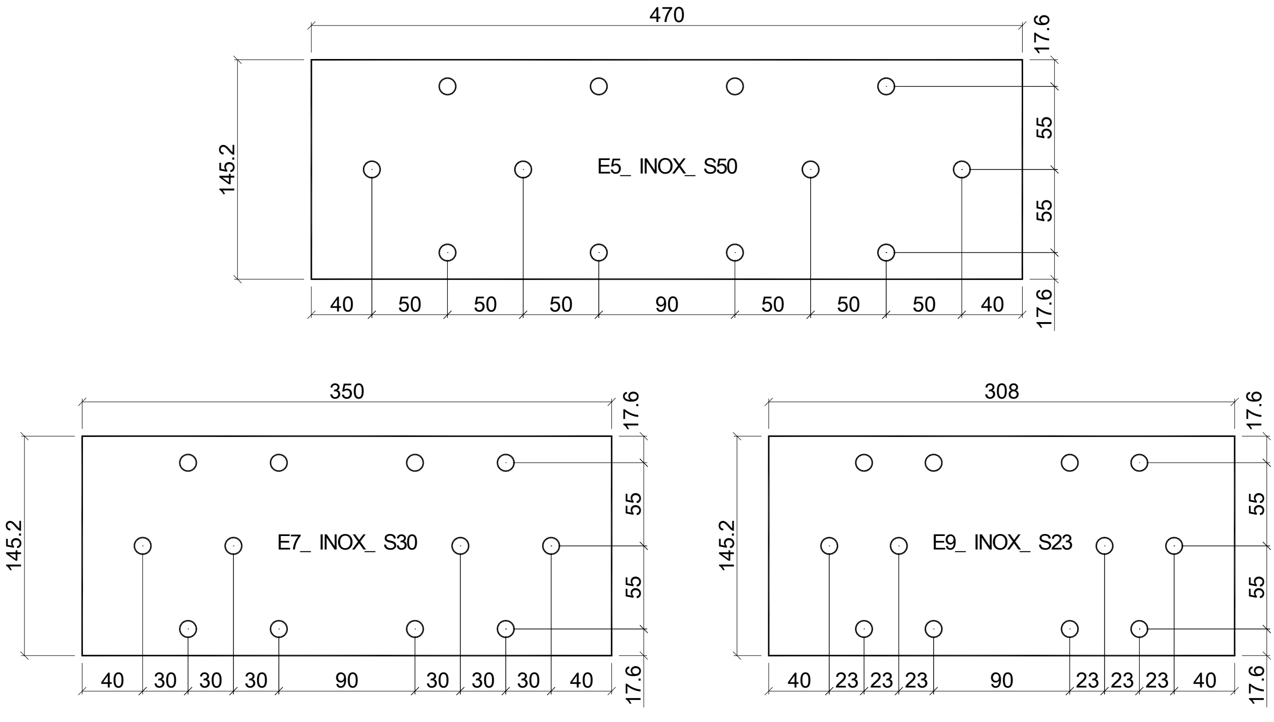


Figure 3 – Adopted Experimental Geometry

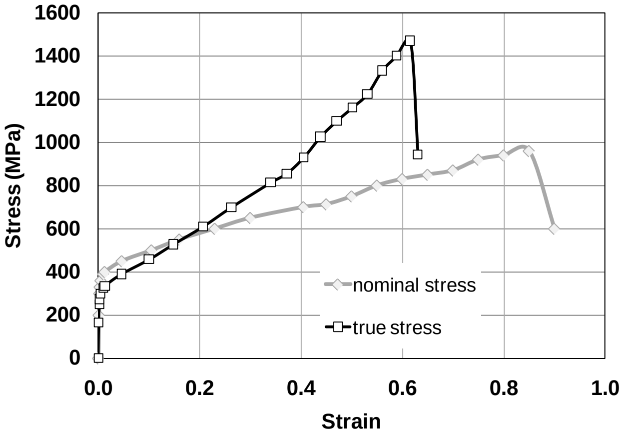
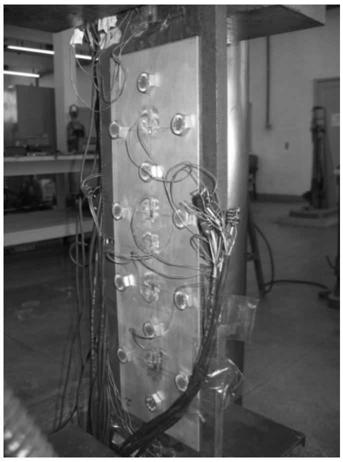


Figure 4 – Stress *versus* strain curves for the stainless steel A304

a) Universal machine Lousenhausen, 600kN



b) Cover plate joint detail

Figure 5 – Test layout

5 Results Analysis

5.1 Test E5_INOX_S50

For the bolted cover plate E5_INOX_S50 tested in the laboratory, according to Figure 6, the ultimate load reached 480.0 kN when a tension net rupture in a position passing trough two bolt holes occurred. Based on the Eurocode 3 - part 1.4 (2006) provisions, the ultimate limit states were: gross section yield of 305.5 kN, bolt shear of 376 kN and finally, net section capacity of 592.4 kN. Comparing the Eurocode 3 and the experimental values (see Figure 6), it may be observed that the gross section yield was the first limit state reached, being characterized by the knee of the experimental curve. The ultimate load of the experimental test was equal to 480 kN, lower than the Eurocode 3 design predictions. Figure 6 also depict the residual bearing deformations present at the bolts.

5.2 Test E7_INOX_S30

For the bolted cover plate E7_INOX_S30 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 (2006) provisions, the ultimate limit states were: gross section yield of 302.9 kN, bolt shear of 376 kN and finally, net section capacity of 469.8 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, being characterized by the knee of the experimental curve. The ultimate load of the experimental test was equal to 469.4 kN lower than the Eurocode 3 design predictions.

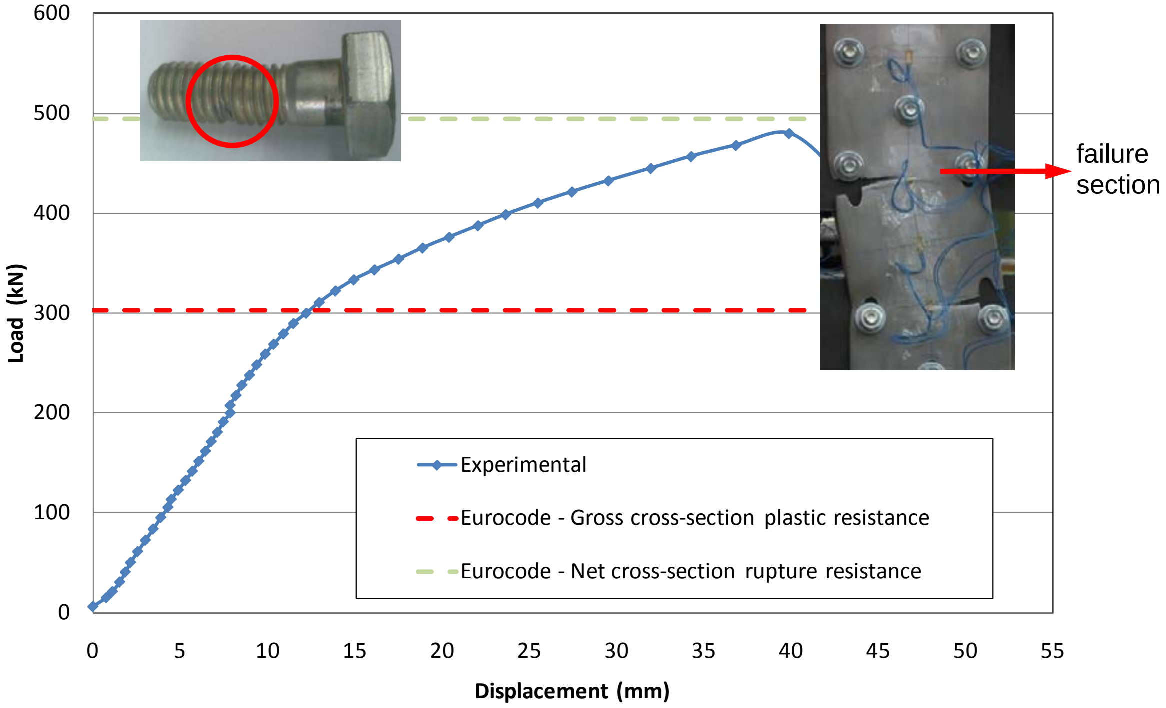


Figure 6 – Load *versus* displacement curve - E7_INOX_S50

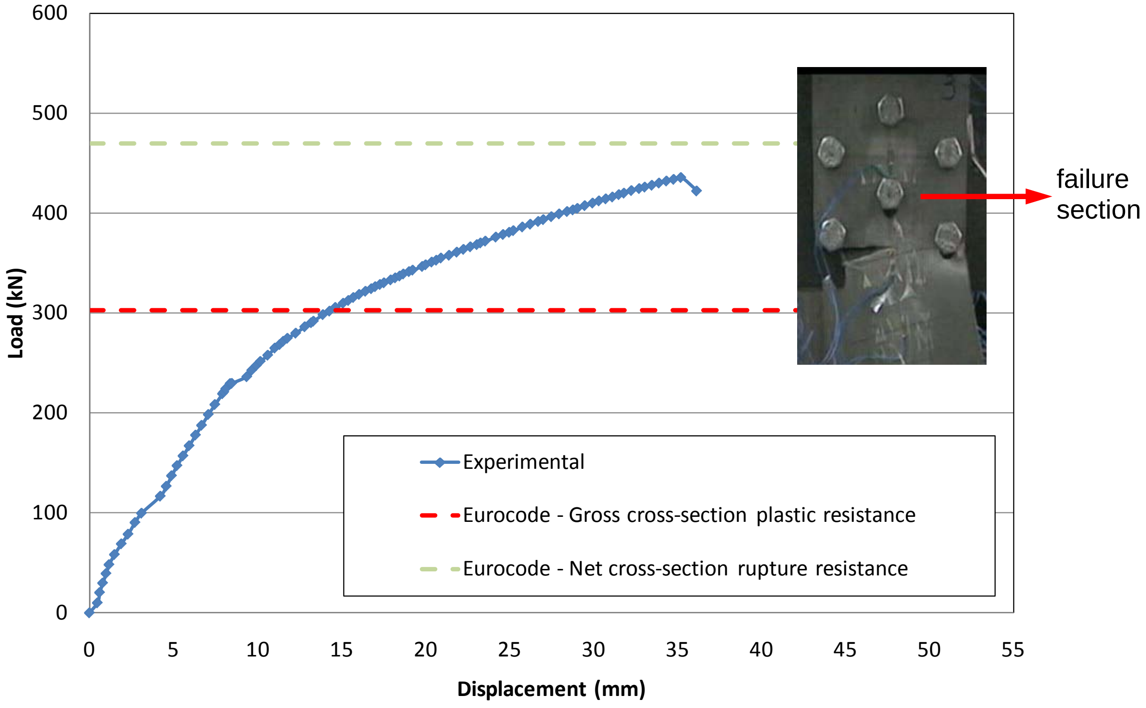


Figure 7 – Load *versus* displacement curve - E7_INOX_S30

5.3 Test E9_INOX_S23

For the bolted cover plate E9_INOX_S23 tested in the laboratory, according to Figure 8, the ultimate load reached 436.0 kN when a tension net rupture in a position passing trough three bolt holes occurred. Based on the Eurocode 3 - part 1.4 (2006) provisions, the ultimate limit states were: gross section yield of 302.9 kN, bolt shear of 376 kN and finally, net section capacity of 455.5 kN. Comparing the Eurocode 3 and the experimental values (see Figure 8), it may be observed that the gross section yield was the first limit state reached, being characterized by the knee of the experimental curve. The ultimate load of the experimental test was equal to 436.0 kN lower than the Eurocode 3 design predictions.

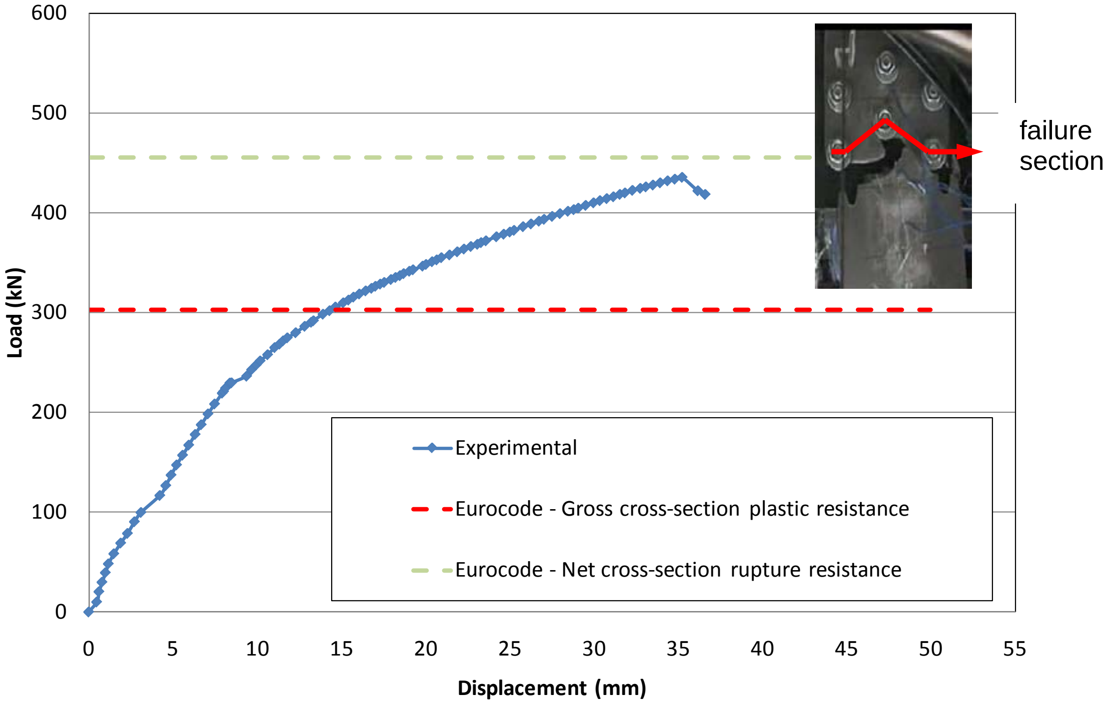


Figure 8 – Load *versus* displacement curve - E7_INOX_S23

6 Final Considerations

The present paper aimed to evaluate the structural response of stainless steel cover plate joints with staggered holes 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. Subsequently, an experimental investigation was performed considering three tests where the horizontal spacing s was modified in order to verify the net section failures path.

A comparison of the experimental and analytical results is presented in

Table 1. It may be observed that the results indicated a good agreement in terms of first ultimate limit state and failure modes. For the ultimate load (net cross-section failure), the experimental and analytical results presented some differences.

Future steps of this investigation will consider the development of additional 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.

Table 1 - Comparison between experimental and analytical results

Test	Failure path (experimental)	Experimental Gross section yield (in kN)	Analytical Gross section yield (in kN)	Experimental Ultimate load (in kN)	Analytical Ultimate load - EC3 (in kN)
E5_INOX_S50	2F	300.0	305.5	480.0	592.4
E7_INOX_S30	2F	280.0	302.9	469.4	469.8
E9_INOX_S23	3F	280.0	302.9	436.0	455.5

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