Stress numerical analysis of cold-formed steel angles

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Abstract. This work is a stress numerical study of cold-formed tensile-loaded steel angles with bolt-connections. Due to the bolted connection, the angle does not deform evenly, resulting in a phenomenon known as shear lag, which reduces the resistant capacity of the angle under tension. This phenomenon is also investigated in this work. For the calculation of the piece final capacity, the hypothesis of rupture of the net section is examined and the phenomenon of shear lag considered through the C_t factor. In order to verify the behavior of cold-formed angles with bolted connections subjected to traction, several angles were modeled using the ABAQUS commercial finite element analysis package, considering geometric and material non-linearity. The results obtained in the numerical analysis were compared with results of experimental tests, reaching a good agreement between them. However, it was verified the feasibility of numerical modeling in the support and complementation of experimental research involving thin sheet profiles.

Keywords: Metallic Structures, Angles, Bolted Connections, Net section reduction coefficient, ABAQUS.

1 Introduction

With the beginning of the use of metallic structures in civil construction in the 18th century until the present day, steel has enabled engineers and architects around the world to build more efficient, bold, daring and high quality.

Hancock [1] concluded in his review research those significant developments continue to occur in the design of cold-formed steel structural members and connections. This is to be expected as the growth in the use of cold-formed steel has significantly outpaced the structural components of hot-rolled steel, particularly with the increased use of cold-formed steel in residential construction around the world.

Cold-formed steel profiles start as flat sheets of various thicknesses, often up to 6.35 mm thick, according to Yu [2], these sheets are rolled and pressed until they gain the desired size and shape.

Currently, in Brazil, light steel-structured constructions are in great use, also called light steel frames, where cold-formed steel profiles can be used. Among the types of connections, bolted has some advantages over welded, such as, for example, the practicality of execution, allows assembly and disassembly of the structure in loco, does not require a specific energy source, so it can be used anywhere, and it is more resistant under alternating charging. Therefore, the connection is an extremely important factor for the proper functioning and safety of the structures, as it connects beams, columns and bracings.

One of the most used profiles to carry out the connection of steel parts is the L-profile, also known as an angle, cold formed, which is extremely important for the stability of the structures. Angles are profiles composed of two symmetrical or not symmetrical flaps, forming an angle of 90 degrees, and the shear lag effect is one of the phenomena that most influences the strength of the connection in profiles formed in cold by bolted connections and under tension. This phenomenon occurs when the profile is not connected through all its flaps, causing a reduction in the tensile strength of the part due to the rupture of the liquid section [3]. According to Salmon and Johnson [4], the shear lag phenomenon is a non-uniform stress distribution condition in the vicinity of the connection. The importance of studying stresses in metallic connections is also associated with their importance in the collapse of metallic structures and composite structures. More than 90% of collapses in metallic structures occur in connections [4]. Therefore, understanding the field and stress gradients in connections is essential for building safety. It is also noted that the research line of steel connections in the Postgraduate Program in Structures and Civil Construction (PECC) at the University of Brasília (UnB) was recently awarded at the 2018 IBRACON Congress, in Foz do Iguaçu, with the best thesis [5, 6] in this area in 2018 focused on connections in composite steel-concrete structures. Therefore, this research comes to collaborate even more with the understanding of the rupture mechanisms and strength of steel connections in PECC/UnB.

2 Literature review

Experimental and/or numerical research are presented below regarding some works by researchers who considered the problem of quantifying the loss of efficiency of the section of an angle bracket with bolted connection due to the effect of the shear lag phenomenon, whether in laminated or cold-formed profile.

Paula [3] carried out an experimental and numerical study of cold-formed steel angles, connected by screws and under tensile load, focusing on the effect of the shear lag phenomenon. From a statistical analysis of the experimental data, she proposed a new equation that quantifies the reduction in the efficiency of the cross section of angles. The numerical study was performed using the ANSYS program, and its results were satisfactory.

Figure 1 illustrates one of the cases studied by Paula [3], specifically the C141 angle bracket, a 100x100 profile, in COR 420 steel, 2.25mm thick and 4 screw sections in a row. In the analysis carried out by the author, it was concluded that the equation prescribed by the Brazilian standard for the design of cold-formed profiles, NBR 14.762-2001 [7], based on the North American standard AISI-2001 [8], results in a large number of situations with values C_t of breaking loads of the net section of angles higher than those actually found in the tests carried out. In the aforementioned standard, the failure modes of crushing and breaking of the liquid section indicated for angles were not proven in most of the tests, mainly due to the inadequate estimate of the breaking load of the liquid section, both for more and for less. Therefore, there is this imprecision to be studied in NBR 14,762-2001 [7].

Fasoulakis, Raftoyiannis and Avraam [9] performed experimental and numerical analyzes on cold-formed steel angles connected by screws and under tension or compression. Numerical analysis was performed using the Finite Element Method (FEM) using the ABAQUS/CAE software [10]. The aforementioned authors used a simplified multilinear model based on the results of the experiments for the material parameters and did not consider the profile effect (ie, stress/residual stress) arising from the cold formation process of the analyzed profile. The aforementioned authors adopted as boundary conditions fixed nodes for the outer edges of the end plates, perpendicular to the longitudinal axis of the beam. In addition, 14 contact interactions are considered using surface-to-surface contact elements between the parts: bolt-nut-washer-angle-plate. C3D8R solid elements were selected for the simulation of thin plates, nuts, bolts and washers, while C3D8I elements were preferred for angled elements.

Figure 2 shows the configuration of the experimental test used, the finite element model and the comparison of experimental and numerical buckling curves. In the figure it is possible to observe the mesh geometry, and the comparison of the results obtained comparing the experimental and numerical C29, C30, C31 data and ABAQUS models, proving a good approximation between the results.

Makesh and Arivalagan [11] performed a numerical study by the finite element method using ANSYS software to simulate the behavior of cold-formed steel angles under tension with one or two 2mm thick flaps, comparing with experimental results and with standards international. They concluded that the ultimate loads of angles are between 10% and 12% lower than all the requirements of the international standards NAS [12], AISI [8], AS/NZS [13] and BS [14]. The authors also concluded that the stresses obtained in the finite element analysis indicate that maximum stresses occur in the innermost screw holes from which the experimental failures were initiated.

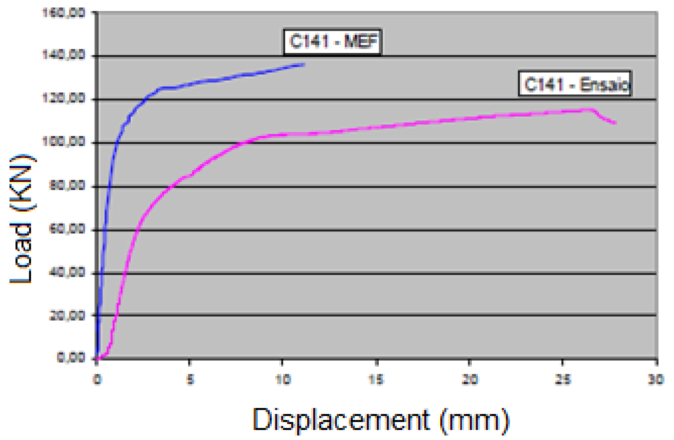

Figure 1 - Load-displacement curve of the test and the numerical model of the angle C141 [3].

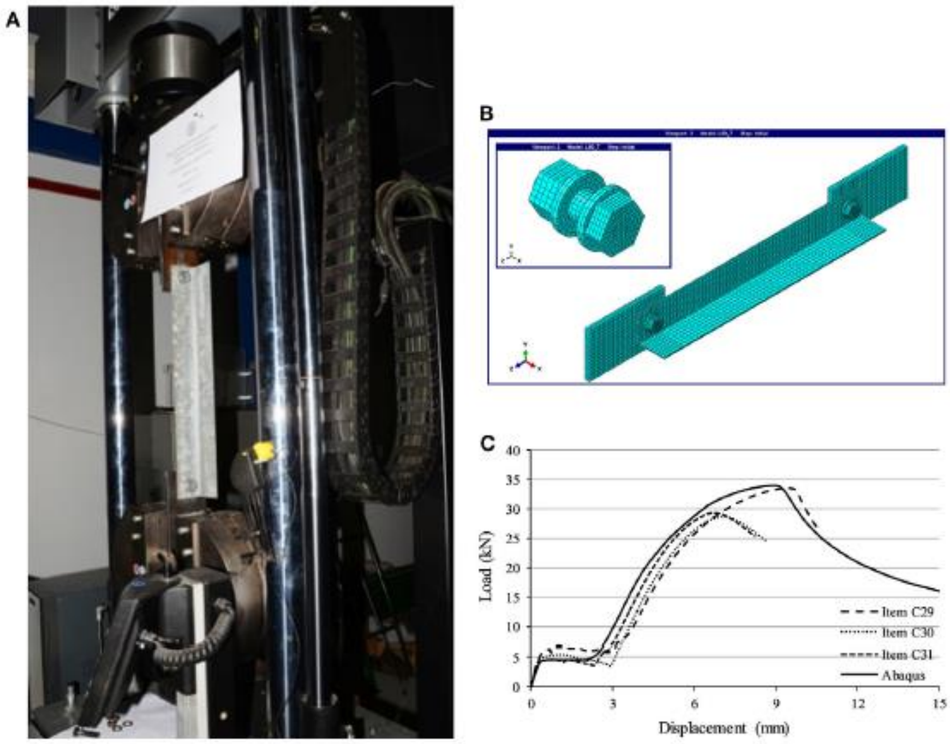

Figure 2 - Overview of (A) tensile test configuration, (B) ABAQUS FEM model and (C) comparison of experimental and numerical buckling curves for the L45 cross section [7].

3 Numerical modeling

Three angles of the same dimensions, thickness and material were chosen to be modeled numerically. The experimental models tested by Paula [3] were used in this study for the calibration and validation of the numerical model and for different analyses. The modeled experiment was the simulation of a tensile test on cold-formed steel angles screwed onto fastening plates, with the load being applied to the upper end of the fastening plate and the plate at the lower end being held by grips of the testing machine the pull.

In this work, the ABAQUS/CAE software was used to develop the numerical model of traction in bolted angles. The model consists of an angle bracket, two fixing plates and screws, where the number of screws varies according to the profile used.

The screws and fixing plates were modeled using the C3D8R element. Due to the high concentration of stresses in the gusset holes, the gusset was modeled with the SC6R element (flat element of continuous shell of a 6-node triangular prism and reduced integration) contained in the ABAQUS library [10] as a shell continuum, requiring only the reducing the size of elements closer to the holes. The mesh of the elements in the model is shown in Figure 3.

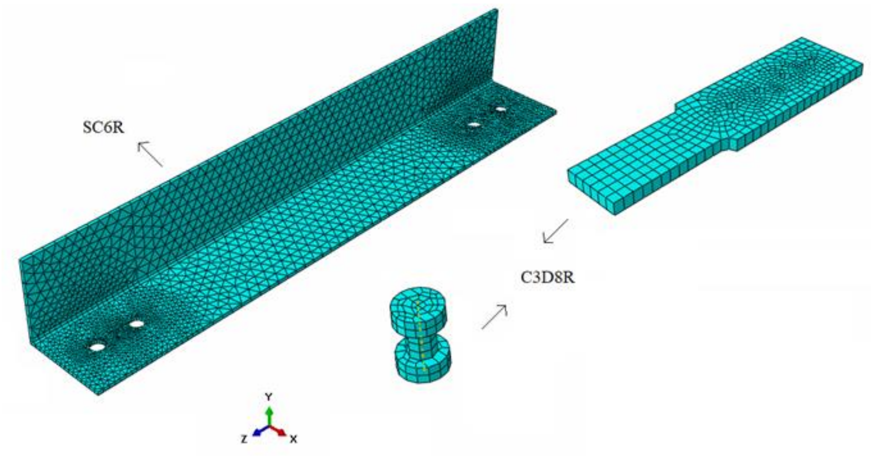

Figure 3 - Meshes and finite element types.

The angles were modeled in COR 420 steel, the fixing plates in SAE 1040 steel and the screws in ASTM A325 steel. The modeling of steels in this work will be carried out with the use of an elastic-plastic constitutive model, with isotropic flow. This model is available in the ABAQUS materials library [10], under the name PLASTIC. In the elastic-plastic constitutive model, the response obtained is independent of the strain rate. Due to the uniaxial behavior implemented in the model, it consisted of the bilinear stress-strain relationship for all modeled components.

In the modeling, there was a contact interaction with the small sliding formulation, with the surface-to-surface discretization method, with the hard normal property. Contact was introduced between the clamping plate and the angle at the end of the load application, and between the left side of the bottom of the bolt heads and the top of the angle.

There was a tie restriction between the fixation plates and the shaft of all screws and between the shaft of the screws and the angle bar. This measure unifies the displacements of the nodes of the surfaces involved, in this way, the slip between the surfaces is eliminated, greatly reducing the deformation of the part.

To simulate the execution of the tensile test on angle bars, the fixing plates were restricted for displacements, being able to only translate in the Z direction (longitudinal of the part under tension) of load application. The fixation plate locked in the experiment apparatus was also simulated, restricting any type of movement at that end.

Load application was modeled as a concentrated load applied to the cross section of the free end clamping plate pulling the angle.

In this study, the implicit static analysis method was applied. This method was chosen because it is a simplified modeling of the experimental test, so that few variables were applied and it becomes easy to use. The load applied in the simulation was done using the Riks method, which uses the load magnitude as an unknown additional; resolves simultaneously for loads and displacements – for details see [10].

4 Results

Three cold-formed steel angles were numerically modeled, all with dimensions 80x80 (mm) and thickness of 3.35mm, varying only the amount of screw row and screw sections per row, with the B221 angle bracket having 2 sections, B231 angle bracket with 3 and the B241 angle bracket with 4 sections of screws in one row. These three profiles (B221, B231, B241) were chosen because they are pieces commonly found in practice and with this it is possible to analyze the influence of stress variation when one or two sections of screws is added.

The validation (or synchronization, fit) of the finite element model developed was performed with the Paula tensile tests [3].

The load-displacement curves obtained by the experimental tests were compared with the numerical curves obtained by the Finite Element Method (FEM), as seen in Figure 4, Figure 5 and Figure 6.

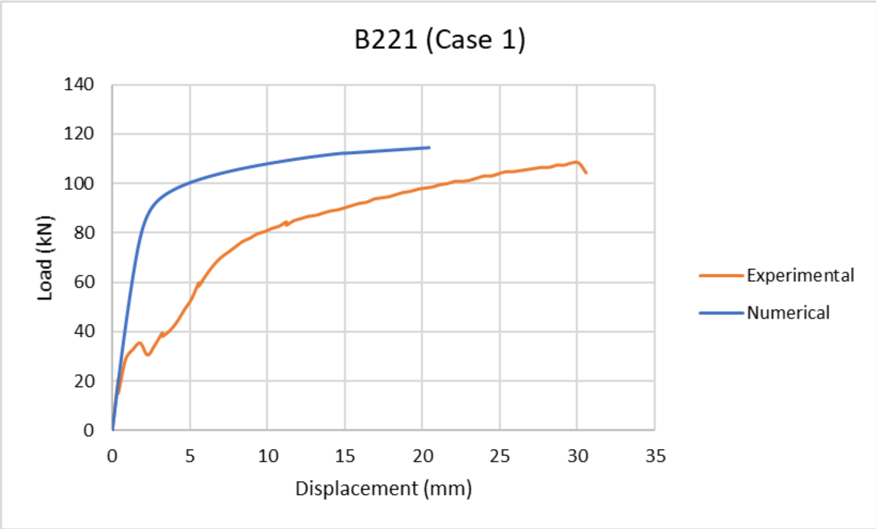

Figure 4 - Load-displacement curve of the modeled B221 angle (Case 1).

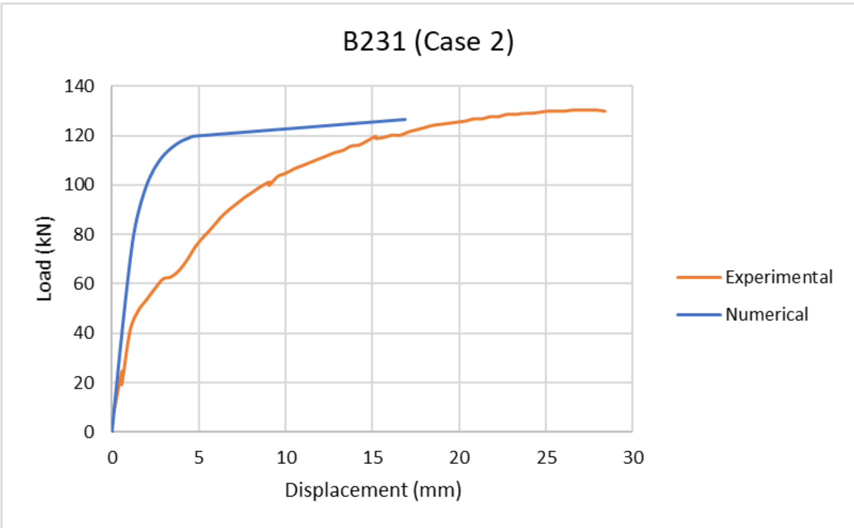

Figure 5 - Load-displacement curve of the modeled B231 angle (Case 2).

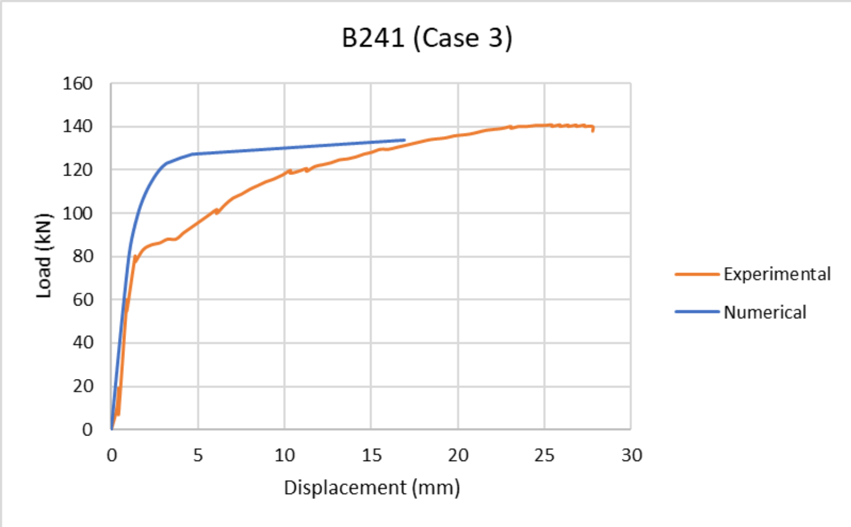

Figure 6 - Load-displacement curve of the modeled B241 angle (Case 3).

The difference in displacement is justified by the amount of tie restrictions in the model, this type of restriction prevents any type of displacement, greatly increasing the rigidity of the model, which does not happen in the real test. Also, there is initial accommodation of the profiles to the screws during the tests and sensitivity of the displacement transducer to other deformations besides the strictly longitudinal deformation (along the Y axis) and accommodation of the holes.

Anyway, it is expected that the numerical model using the finite element method leads to smaller displacements, since the displacements of the tests incorporate the displacements that occur after the rupture of the liquid section (opening of the section through which the screw passes). The fit between the experimental and numerical curves is satisfactory for the analysis of stresses and ultimate load in the angle, proving the efficiency of the finite element model proposed in this study.

Table 1 shows the ultimate loads of the angles obtained by the experimental tensile tests (P_{exp}) and by the finite element analysis (P_{MEF}). These results show the effectiveness of the proposed finite element model in simulating the resistant capacity of angle bars, decreasing its precision with the increase in the number of screws.

Table 1 - Comparison between the ultimate loads of the angles obtained by the experimental tests and the proposed numerical model.

Cantoneira	P_{exp} (kN)	P_{MEF} (kN)	P_{exp}/P_{MEF}
B221	108,31	114,47	0,95
B231	130,39	126,59	1,03
B241	140,10	133,77	1,05

Média	1,01
Coeficiente de Variação (%)	5,37

Table 2 shows the deformations of the angles obtained by experimental tensile tests (D_{exp}) and by finite element analysis (D_{MEF}). These results show that the numerical model is more rigid than the experimental tests, as justified above, increasing the deformation difference with the increase in the number of screws.

With experimental observations of tensile tests, Paula [3] found that the failure mode of cold-formed steel angles bolted and subjected to tension consists of failure of the liquid section, equivalent to the failure modes occurred in the numerical simulations.

Table 2 - Comparison between angle deformations obtained by the tests.

Cantoneira	D_{exp} (mm)	D_{MEF} (mm)	D_{exp}/D_{MEF}
B221	30,57	20,44	1,50
B231	31,70	16,89	1,88
B241	34,86	16,91	2,06

Média	1,81
Coeficiente de Variação (%)	15,93

The Figure 7 shows the distribution of the Von Mises stresses, in the angles modeled at the moment of the beginning of the breaking load at the edges of the holes. The central holes are always the first to suffer the effect of the applied traction and are the ones that deform the most, observing the beginning of rupture by liquid section due to the high stress values C_t concentrated on this edge. Confirming the equivalence between the rupture modes visualized in the numerical simulation results and the observation observed by Paula [3]. One of the advantages of numerical analysis by EF of experiments is to calibrate the behavior of the species tested in the laboratory, having confidence in the results of other configurations that were not even tested.

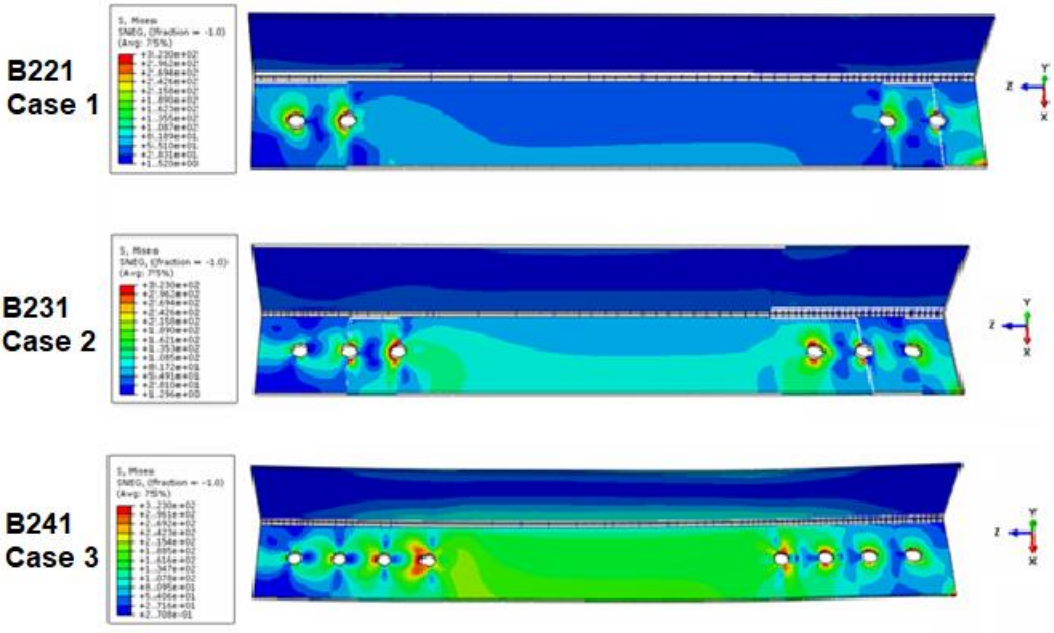

Figure 7 - Von Mises stress distribution (MPa) at the liquid section rupture beginning of cases 1, 2 and 3.

Comparing

Figure 8, it is evidenced the conformity between the failure modes in the experimental tests and in the numerical simulations with the proposed model. Note the similarity in the deformation of angles for numerical and experimental results. These results demonstrate the ability of the proposed finite element model to numerically simulate the behavior of cold-formed steel angles connected by screws and subjected to tension, proving the same type of rupture per net section due to the loss of capacity due to the shear lag effect.

Figure 8 - Numerical and experimental deformation of the B221, B231 and B241 angle at the moment of ultimate load.

For the numerically modeled angle bar B221, analyzing the longitudinal stress (S12 – Figure 9) at the moment of elastic deformation, with an applied load of 20kN, we have the distribution of stresses along the angle.

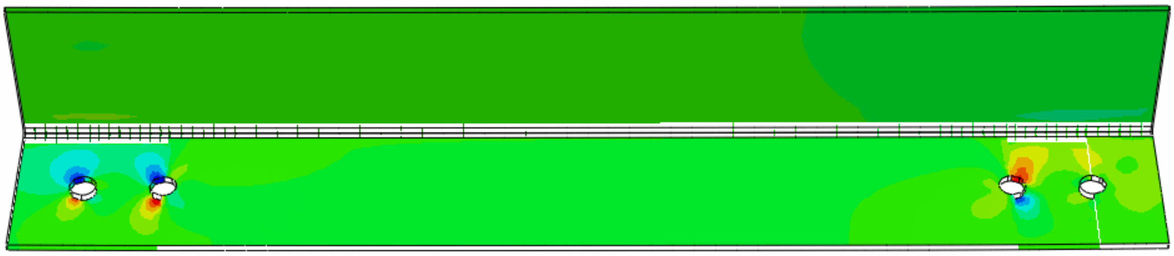

Figure 9 - Longitudinal tension with 20kN applied to the B221 angle (Case 1).

According to each section (see lines intersecting the screws in the figures), graphs of stress distribution were drawn up in vertical sections (Figure 10) and horizontal section (Figure 11) passing through the holes.

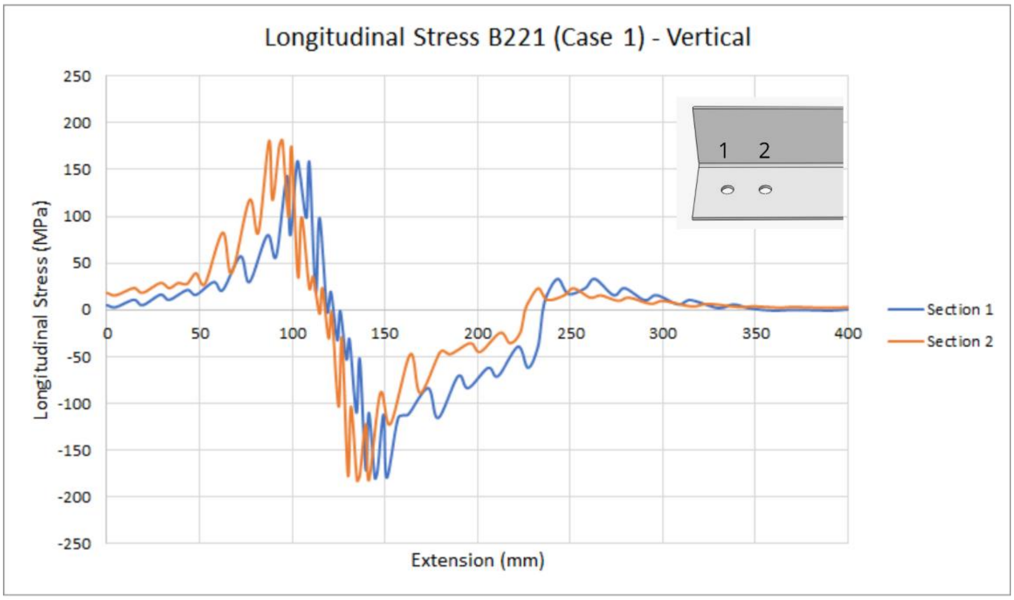

Figure 10 - Stresses at vertical sections in angle B221 (Case 1).

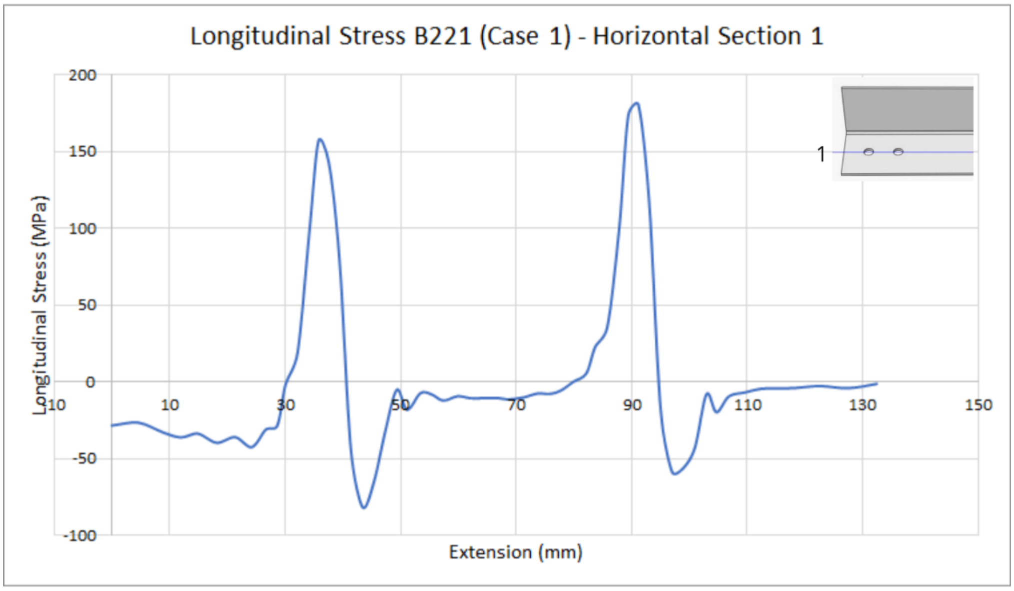

Figure 11 - Stresses at horizontal section in angle B221 (Case 1).

Comparing vertical section 1 with vertical section 2 (each going through a hole), we notice that the tension is greater in the innermost hole, 157 MPa and 181 MPa, respectively, a difference of 13% more than the first hole compared to the second hole.

It is observed in horizontal section 1 that the stresses increase in the innermost hole, being, respectively, 157 MPa and 180 MPa, very similar to the stresses found in vertical cuts.

For the numerically modeled angle B231, analyzing the longitudinal stress (S12) at the moment of elastic deformation, with an applied load of 20kN, we have the distribution of stresses along the angle (Figure 12).

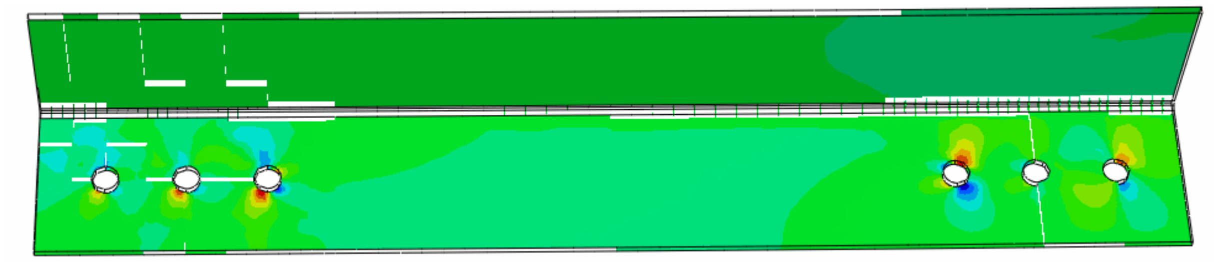

Figure 12 - Longitudinal tension with 20kN applied to the B231 angle (Case 2).

According to each cut, tension graphs were prepared in vertical sections (Figure 13) and horizontal section (Figure 14) passing through the holes.

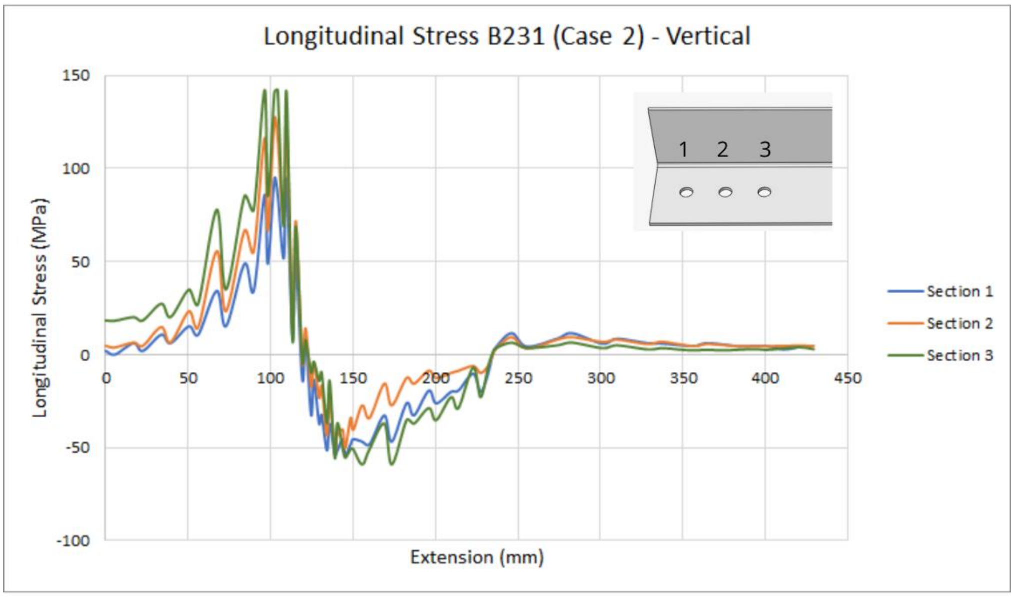

Figure 13 - Stresses at vertical sections in angle B231 (Case 2).

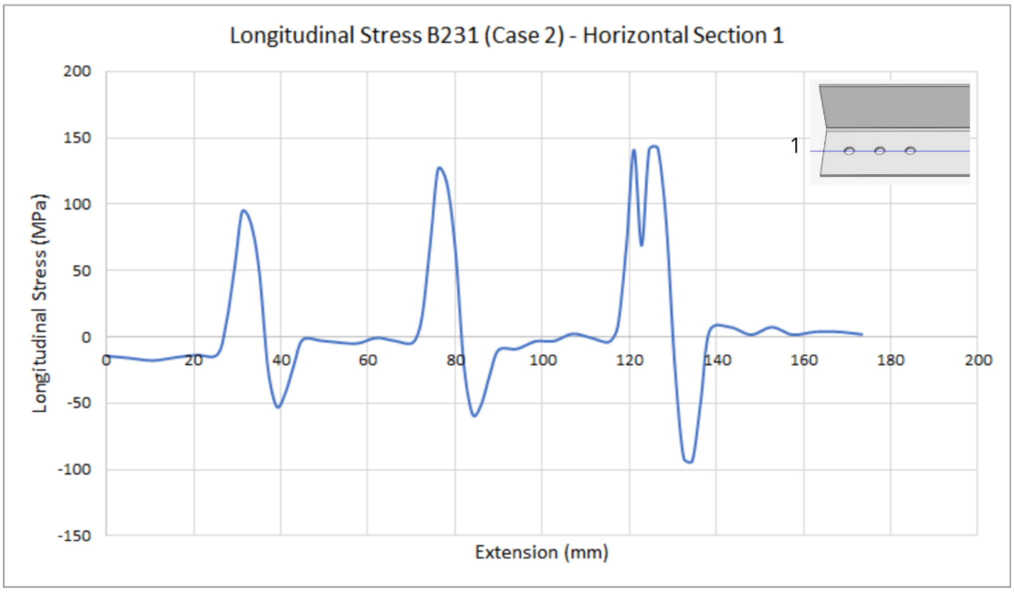

Figure 14 - Stresses at horizontal section in angle B231 (Case 2).

Comparing vertical section 1, with vertical section 2 and with vertical section 3 (each going through one hole), the results show that the tension is greater in the innermost hole, 94 MPa, 126 MPa, 141 MPa, respectively, a difference of 34% more than the first hole compared to the second hole and 11% more than the second hole compared to the third hole.

It is observed in horizontal section 1 that the stresses increase in the innermost hole, being, respectively, 94 MPa, 126 MPa and 142 MPa, very similar to the stresses found in vertical cuts.

For the numerically modeled angle B241, analyzing the longitudinal stress at the moment of elastic deformation, with an applied load of 20kN, we have the distribution of stresses along the angle (Figure 15).

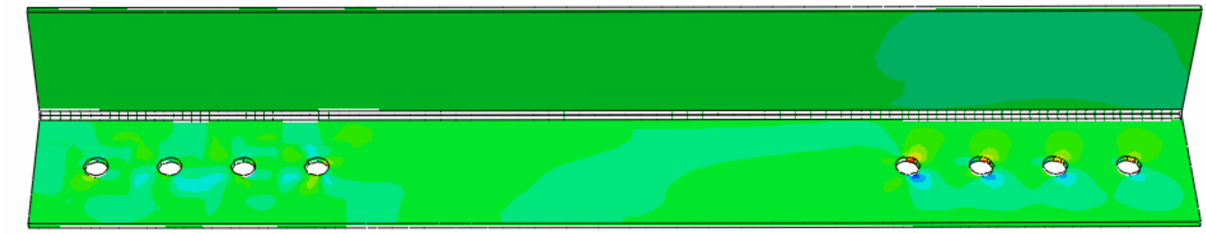

Figure 15 - Longitudinal tension with 20kN applied to the B241 angle (Case 3).

According to each section, tension graphs were prepared in vertical sections (Figure 16) and horizontal section (Figure 17) passing through the holes.

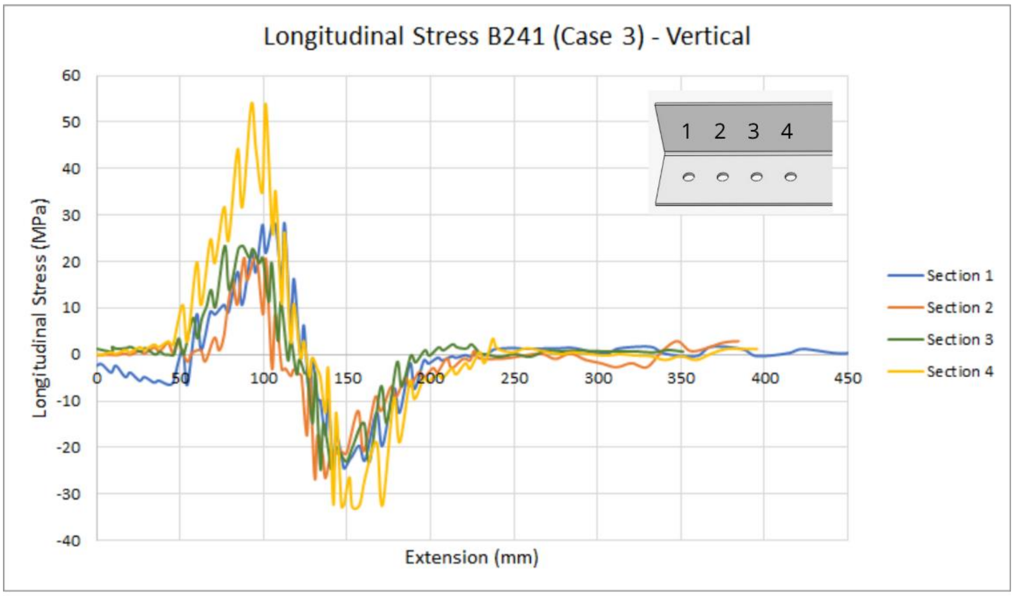

Figure 16 - Stresses at vertical section 1 in angle B241 (Case 3).

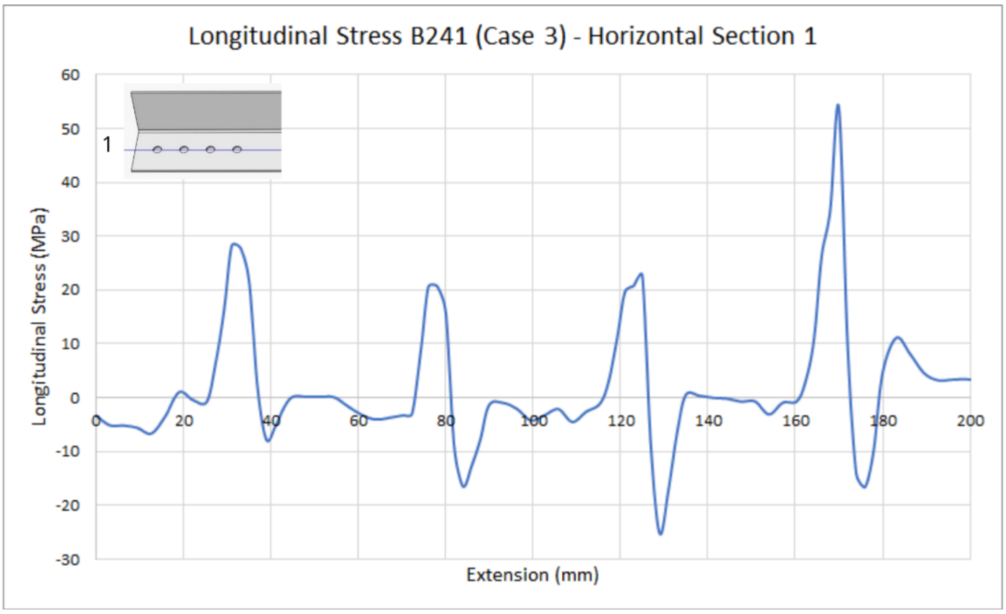

Figure 17 - Stresses at horizontal section 1 in angle B241 (Case 3).

Comparing vertical section 1, 2, 3 and 4 (each going through one hole), the results show that the stresses are 28 MPa, 20.7 MPa, 23 MPa and 53.8 MPa, respectively, with higher stress in the innermost hole of the angle.

We can see in horizontal section 1 that the stresses increase in the innermost hole, being, respectively, 28 MPa, 20.5 MPa, 22.7 MPa and 53.8 MPa, showing a difference when compared to the other cases in the innermost hole.

5 Conclusions

The good agreement between numerical and experimental curves with respect to applied load vs. displacement shows that the methodology used in this study is able to simulate the behavior of bolted angles subjected to tension. Despite the highly non-linear conditions of the structure, the implicit analysis of ABAQUS/Standard was sufficient to generate a simplified model of the angles and obtain satisfactory results. Throughout this study, it was possible to obtain the following conclusions: the profiles tested are well represented by numerical models, incorporating analyzes of large deformations and large displacements, properly simulating the stresses arising in the edges and holes of the angles, which are values C_t compatible with the macro behavior Load vs. Displacement of the analyzed angles. In the case with a line of screws, the innermost hole in the angle was the first to reach the ultimate strength of the piece. It is also noted that the hole with the highest longitudinal tension is always the innermost one of the angles and closest to the edge. This occurs because the line of holes closest to the free end has less rigidity and greater deformability, thus absorbing the higher tension. In elastic deformation, increasing the number of screws increases the stress distribution in each hole, reducing the maximum stress. Both in the case with two, three and four holes, the stress analysis showed the connection regions more subject to stress increase or gradient, partially explaining the collapse by liquid section that occurs in cold formed profiles.

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Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property and authorship of the authors.

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