Numerical analysis of the structural behavior of flat plates under tension loads

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Abstract. Based on the guidelines provided by the ABNT NBR 8800 [1], the present study analyzes the prescription for determining the strength of cross-sections with holes arranged straight or zigzag for elements subject to tensile load. In case of misaligned holes, these calculations are performed by a semi-empirical parameter, defined by the Cochrane equation. This additional parameter covers an increase of resistance from an additional equivalent portion of the cross-sectional area. In this work, it is intended to simulate numerically the structural behavior of flat steel plates under tensile stress through a finite element modeling processed by Ansys 16.0 and verify the compatibility with the analytical methods prescribed by the code. Three plates were modelled according to the study by Oliveira and Wietzikoski [2] to attest the collapse modes, rupture profile, and resistance obtained experimentally and validate the analytical prescriptions from the results of the numerical modeling.

Keywords: steel structures, tensile elements, numerical analysis, finite element method.

1 Introduction

Tensile elements are found in many structural steel systems, such as roofs, transmission towers, and bridges. According to Veronez [3], the simple or axial tension force is an effort that causes normal uniform stresses throughout the section of the element. It is assumed that, just the design criteria for a tensile element, based on the choice of a cross-section that resists axial tensile force, is enough.

However, one must consider the tensile element purpose and how it is used, focusing the attention on how it will be connected to the other structural components. Depending on the type of connection, the normal stress does not distribute evenly in regions close to the load's transmission.

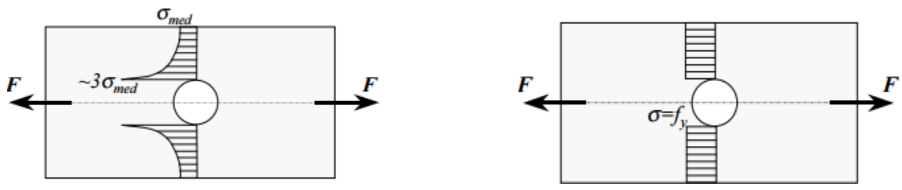
The traditional criteria for tensile elements design limits the average stress in the cross-section weakened by holes to the value of the steel's yield stress. The most modern criteria distinguish between the situation of limiting excessive deformability along the bar, using the yield stress as a limit; and the material rupture at stress concentration points, where the stress corresponding to the steel rupture is considered as a limit. This leads to a more logical and generally more economical design, without sacrificing safety.

2 Literature Review

According to Veronez [3], structural elements under to axial tensile loads and made of the same material may present different behaviors due to the residual stresses present in the material, resulting from the bar manufacturing process. These residual stresses are in balance in the element cross-sections, in some parts there is tension and in others, compression.

Patrick J., et al, apud Veronez [3]. An under-tension element without holes or other discontinuities reaches its service load utilization limit in the yield resistance of the material (f_y). It happens because in the plastic regime excessive deformation occurs and this represents the failure mode due to the material ductility. The element cross-sectional area is called the gross area (A_g).

According to Pfeil [4], the reduced cross-section for tensile elements with holes is called the net area (A_n). The holes in a plate cause stress concentration and modify the stress distribution. The Theory of Elasticity shows that the tension in the hole wall, in the cross-section through the center of the hole, is approximately three times the average tension in the net section (Fig. 1-a). However, as each fiber reaches yield deformation (ε_y), its stress becomes constant and equal to f_y (Fig. 1-b), showing increasing deformations by the rising in normal strength, until all fibers have reached or exceeded the ε_y.



(a) (b)

Figure 1. Stress concentration in the hole region.

The ABNT NBR 8800 [1], item 5.2.2, for the calculation of the yield resistance of the gross section area has specified the eq. (1):

$$N_{t,Rd} = \frac{A_g f_y}{\gamma_{a1}}. \quad (1)$$

Wherein A_g is the gross cross-section area of the element; f_y is the yield tensile stress of the steel and γ_{a1} is the reduction coefficient of steel yield resistance.

When there is a rupture by the effective net section in a tensioned plate containing holes, the resistant axial force is calculated by the eq. (2):

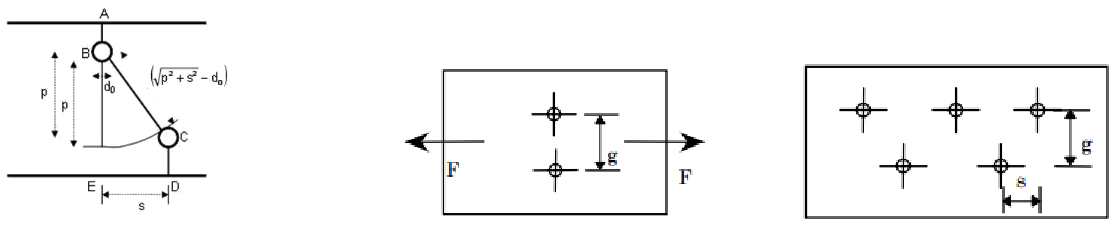
$$N_{t,Rd} = \frac{A_e f_u}{\gamma_{a2}}. \quad (2)$$

Wherein A_e is the effective net area of the element cross-section (given by $A_e = C_t.A_n$); A_n is the net area (given by $A_n = b_n.t$); b_n is the net width and t is the plate thickness; C_t is the resistance reduction coefficient associated with the eccentricity in the load transmission, as discussed in item 5.2.5 of ABNT NBR 8800 [1]; f_u is the ultimate tensile stress resistance of the steel and γ_{a2} is the reduction coefficient of steel ultimate resistance. The C_t parameter has a great influence in the structural behavior and strength of tensile members and was studied by several authors such as: Silva [5], Teh [6], Roquete [7] and Shanmugasundaram et al [8].

For tensile elements with more than one hole, and when the holes are not aligned transversely to the loading direction, that is, they are skewed (Fig. 2-a), there is more than one possible breaking path in the connection region of the member. In these cases, the section that breaks first is the one with the smallest net area. The calculation of the net width (b_n) in bolted connections with a series of aligned holes (Fig. 2-b) or zigzag (Fig. 2-c) is done by a semi-empirical procedure, given by eq. (3):

$$b_n = b_g - \sum bh + \sum_{i=1}^{n} \frac{{s_i}^2}{4g_i}. \quad (3)$$

Wherein b_g is the total width of the cross-section; Σbh is the sum of the widths of all the holes in the break line considered; n is the number of diagonal segments (not perpendicular to the tensile forces); s is the spacing between the holes, measured in the direction of loading and g is the distance measured in the normal direction of loading.



(a) (b) (c)

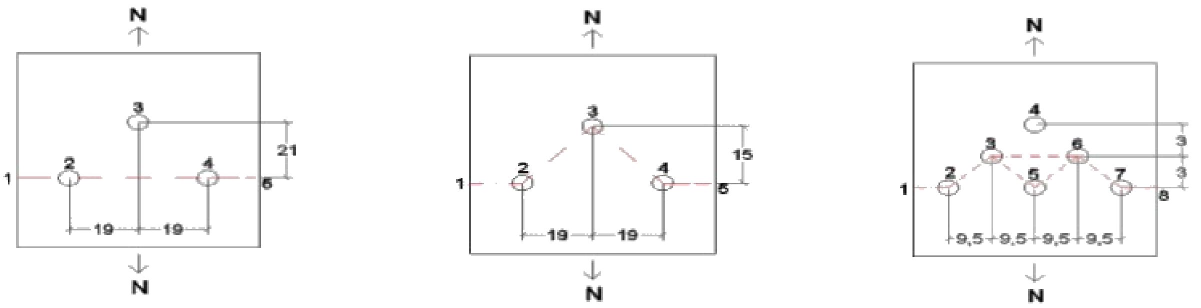
Figure 2. Elements with more than one hole and not aligned transversely holes configuration.

The Brazilian standard codes ABNT NBR 8800 [1] and ABNT NBR 14762 [9] make use of the last portion of eq. (3) for dimensioning elements with alternating holes. The main international standard codes dealing with steel structures design also adopt this parameter such as the European EUROCODE 3 [10], the American ANSI /AIS 360-05 [11] and the Canadian CAN / CSA S16-01: 2001 [12].

This expression was obtained empirically, according to studies conducted by Victor H. Cochrane, who claims that one of the first theoretical methods that assumed the effect of alternating bolts considered that the effects of resistance in the cross-section and the section of alternating bolts were equal when the maximum tension was reached. In November 1922, Cochrane published a study based on the analysis of Fig. 2-a in the “ENR: Engineering News-Record” of New York, under the title “Rules for rivet-hole deductions in tension members”, where he proposes the equation to be used safely.

3 Methodology

In this paper, a study is developed aims to verify the validity of the Cochrane equation (last part of eq. 3) for the situation of tensile strength resistance determination of flat steel plate elements, as well as the analytical prescriptions contained in the ABNT NBR 8800 [1]. From the 9 prototypes analyzed by Oliveira and Wietzikoski [2], 3 of them, named CP1, CP2, and CP9 were chosen and, for a better analysis organization in this study, will be called of CH1, CH2, and CH3. So, a numerical simulation was performed using Ansys software [14], and the three models before mentioned have dimensions of 250x50 mm and the thicknesses (t) as shown in Fig. 3.

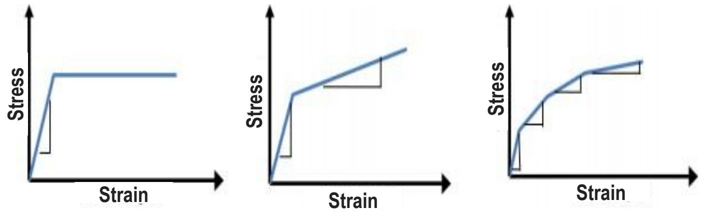


CH1 (t = 2.00 mm) CH2 (t = 3.00 mm) CH3 (t = 2.65 mm)

Figure 3. Configuration of prototypes CH1, CH2 e CH3.

To determine the analytical resistance of the prototypes, the first rupture path ($N_{t,U1}$) through the aligned holes in a horizontal way, and the second rupture path ($N_{t,U2}$) through the zigzag holes, will be considered.

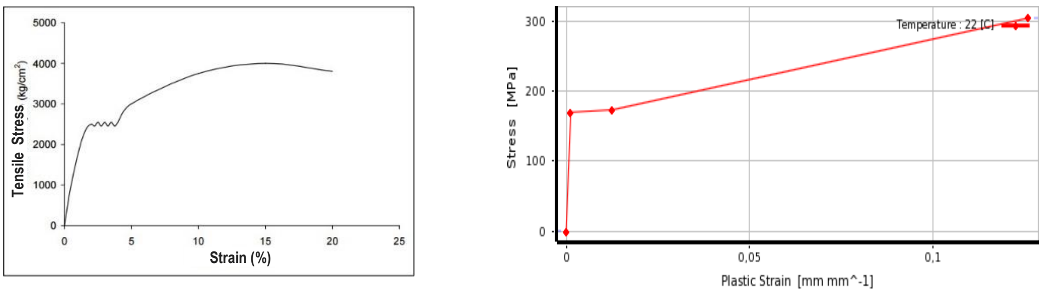
There are several elastoplastic models in the literature to represent the stress versus strain diagram of steel behavior and Fig. 4-a gives the perfect elastoplastic model. The bilinear model, presented in Fig. 4-b, when crossing the yield boundary shows that the deformation is governed by a yield rule directly proportional to the increase in stress and inversely proportional to the tangent module. The multilinear model in Fig. 4-c is an expansion of the bilinear model, since it uses a greater number of parameters, the model's representativeness is considerably increased.



(a) (b) (c)

Figure 4. Steel stress versus strain diagrams.

The specification of the steel used is SAE 1008 carbon steel, which presents a real behavior of the stress versus strain diagram shown in Fig. 5-a. A physical nonlinear analysis is performed, considering the multilinear model of the material behavior, displayed in Fig 5-b.



(a) (b)

Figure 5. Steel stress versus strain diagrams.

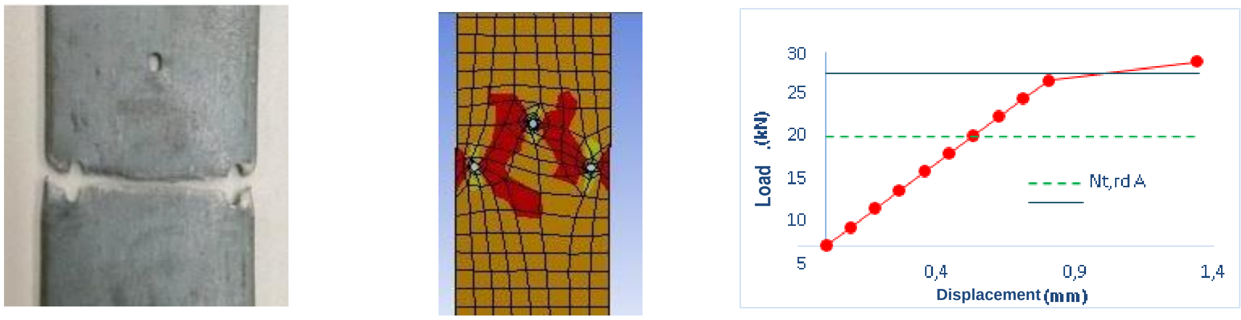
The finite element analysis relies on the discretization of the model to be studied, which is the subdivision of the parts until the convergence of the results is verified. As the focus of this analysis is the result of stresses generated around the holes in the plate, it was decided to maintain a smooth transition between the mesh that adapts to the round hole and the one that follows along with the rectangular plate, in order to minimize the effects of the sudden transition on the results. It was considered, as a simplification hypothesis, that refining the mesh around the holes to a 250 mm plate would not represent a convergence leap that would be worth the computational effort increased by the smaller mesh.

The chosen plates were submitted to a tensile load, so that one of the ends has a fixed connection and the other is free for the action of the force. The tension force value is calculated according to the parameters of ABNT NBR 8800 [1]. On the other hand, the numerical analysis consists of obtaining the values of maximum stress and stresses around the holes of the plate for the tensile force applied in the studied models, besides displacements and deformations.

4 RESULTS AND ANALYSIS

Three steel plates with zigzag holes were analyzed in agreement the experiments carried out by Oliveira and Wietzikoski [2], here called CH1, CH2, and CH3. With the values obtained in the numerical modeling performed with the aid of the Ansys software, the load versus displacement curves were plotted.

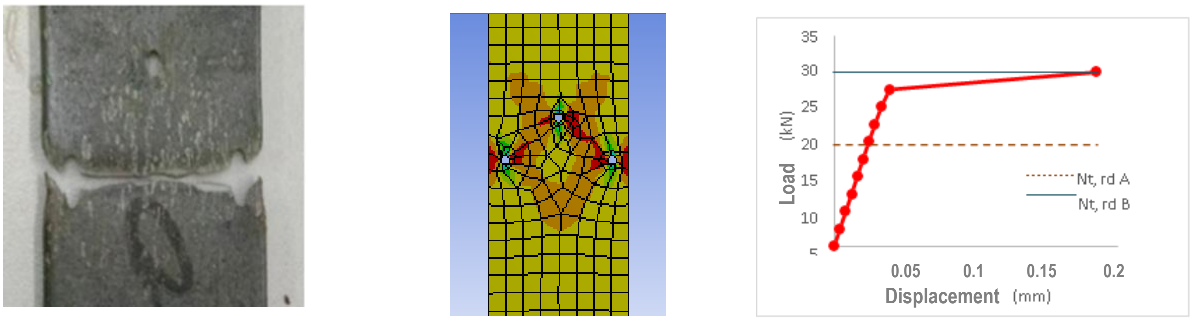
For the CH1 prototype, Fig. 6 shows: (a) the rupture configuration of the experimental test; (b) stress distribution configuration for the finite element modeling, and (c) the load versus displacement graphic.



(a) (b) (c)

Figure 6. Results for the CH1 prototype.

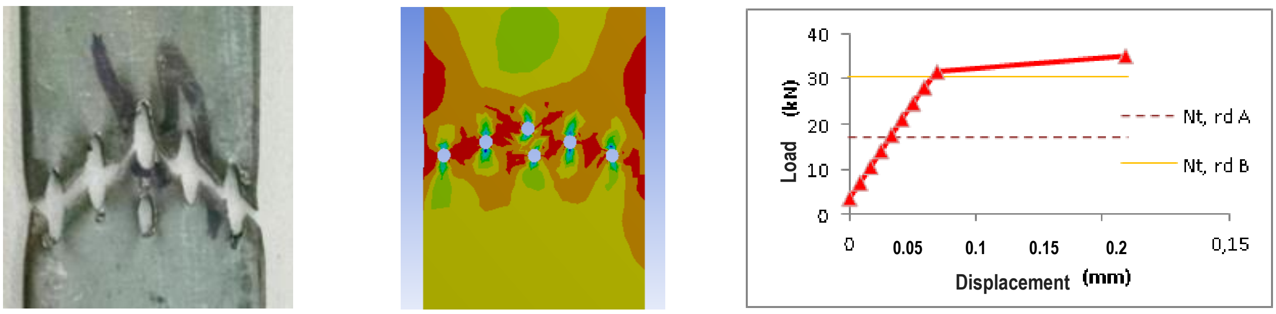
For the experimental result, it is observed that the path taken by the rupture line was different from analytical calculations and numerical modeling, as in both the rupture occurred on the skewed path. For the prototype CH2 Fig. 7 presents: (a) the rupture configuration of the experimental test; (b) stress distribution configuration for the finite element modeling, and (c) the load versus displacement graphic.



(a) (b) (c)

Figure 7. Results for the CH2 prototype.

For the prototype CH3, in Fig. 8 can be seen: (a) the rupture configuration of the experimental test; (b) stress distribution configuration for the finite element modeling, and (c) the load versus displacement graphic.



(a) (b) (c)

Figure 8. Results for the CH3 prototype

The theoretical analysis was implemented using the analytical prescriptions found in ABNT NBR 8800 [1], already covered in Section 2. Table 1 presents a summary of the analytical, numerical, and experimental results obtained for the three plate configurations analyzed, as well as the relationship between them.

Table 1. Results obtained for all plates.

Prototype	$N_{t,y}$ (1)	$N_{t,U1}$ (2)	$N_{t,U2}$ (3)	Experimental (4)	Numerical (5)	(5)/(1)	(5)/(2)	(5)/(3)	(5)/(4)
CH1	17	26,84	17,93	16,56	28,5	1,68	1,06	1,59	1,59
CH2	26	26,84	28,61	21,54	29,0	1,11	1,08	1,01	1,05
CH3	23	30,33	28,09	26,81	34,0	1,48	1,12	1,21	1,21

It is observed that the relationship between the numerical resistance and the predicted yield of the gross section area ($N_{t,y}$) characterized by the relationship (5)/(1) varies from 1,48 to 1,68. This difference between the values indicates that the final strength of the plate is not limited by the yield of the gross section area.

Comparing the numerical result with the first rupture path ($N_{t,U1}$), given by the ratio (5)/(2), a variation of 1,06 to 1,12 is observed. As for the comparison with the second rupture path ($N_{t,U2}$), given by the ratio (5)/(3), there is a variation from 1,01 to 1,59. This behavior indicates that for the possible rupture lines analyzed, there is a better convergence between the numerical model and the first rupture path.

Analyzing the relationship between numerical and experimental results (5)/(4), a variation of 1,05 to 1,59 is observed. This indicates that, in general, the experimental results were lower than those obtained numerically, which may suggest that eventual inaccuracies during the execution of the experimental tests may have affected the results. Among these possible reasons, we can mention: inaccuracy in the location and in the process of opening the holes, adjustments, slips of the prototypes in the machine responsible for the tests and variations in the resistance of SAE 1008 steel available for this study.

It is worth noting that, for the CH2 prototype with a 3 mm thickness, which is thicker among the prototypes, the results show a better correlation. With a ratio of 1,08 for the comparison between the numerical model and the analytical prescription, and 105 when compared with the experimental results. This may indicate that, for thinner plates, there may be greater difficulty in guaranteeing a better quality of the experimental results.

5 Conclusion

This work had the objective to numerically analyze the structural behavior of flat steel plates under to tension force, comparing with the analytical methods present in the standard code prescriptions and the experimental results obtained by Oliveira and Wietzikoski [2].

It was found that the numerical modeling showed a satisfactory correlation with the strength results obtained through the analytical prescriptions established by ABNT NBR 8800 [1]. The verification of the validity of the Cochrane equation is highlighted, characterized by the presence of the rupture paths verified in the numerical models, indicated by the stress concentrations in biased paths.

However, for the CH1 and CH2 plates, the results differed from those obtained in the study of Oliveira and Wietzikoski [2]. This variation can be justified by several factors that could happen in the experimental test, among them: the plates were marked and perforated manually without the aid of more accurate measuring equipment; the plates were fixed directly to the claws of the tension equipment, which can generate eccentricities in the fixation and transmission of loads and possible variability in the resistance of SAE 1008 steel. Also, the numerical modeling can be improved with the mesh refining, especially in the region of stress concentration near to the hole.

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