

## NUMERICAL SIMULATION OF BOLTED CONNECTIONS

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**Abstract:** This article presents the modeling of a complete bolted connection based on a model with one bolt connecting two or three plates. Initially, the behavior of this model with one bolt is analyzed by comparing it with existing bibliography for 3 different types of applied load: tension, shear and a combination of these two. This model includes all necessary considerations: contacts between the plates and the nut, head and shank of the bolt; contact between the plates, as well as friction between them; and pre-load on the bolt. The model also responds properly to loads parallel and perpendicular to the contact surface between the plates, including prying action effects. These calibrated models are then introduced as super-elements in empty spaces left on the full connection, through a relatively simple process using the finite element software ANSYS. Upon filling these spaces, two complete connection models will be evaluated: one with a single plate and one between two T-stubs. The results obtained with these models will be compared with experimental tests existing in the literature, consisting basically in load-deformation and ultimate strength curves. These two connection types have a practical application in the way they will be analyzed, and also as part of more complex connections: bolted girder splices (in the region of web beam), beam-to-column connections with splice plates or end plate connections, beam splices with end-plates, etc.

**Keywords:** Modeling of bolted connections, Simple shear connections, T-stub connections, Super-elements.

## 6<sup>th</sup> International Symposium on Solid Mechanics

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### ABSTRACT

This article presents the modeling of a complete bolted connection based on a model with one bolt connecting two or three plates. Initially, the behavior of this model with one bolt is analyzed by comparing it with existing bibliography for 3 different types of applied load: tension, shear and a combination of these two. This model includes all necessary considerations: contacts between the plates and the nut, head and shank of the bolt; contact between the plates, as well as friction between them; and pre-load on the bolt. The model also responds properly to loads parallel and perpendicular to the contact surface between the plates, including prying action effects. These calibrated models are then introduced as super-elements in empty spaces left on the full connection, through a relatively simple process using the finite element software ANSYS® [1]. Upon filling these spaces, two complete connection models will be evaluated: one with a single plate and one between two T-stubs. The results obtained with these models will be compared with experimental tests existing in the literature, consisting basically in load-deformation and ultimate strength curves. These two connection types have a practical application in the way they will be analyzed, and also as part of more complex connections: bolted girder splices (in the region of web beam), beam-to-column connections with splice plates or end plate connections, beam splices with end-plates, etc.

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### 1 INTRODUCTION

During the last years, in the discussions involving structural analysis and global performance of steel structures, the semi-rigid behavior of the connections has become a topic of extreme importance, and was introduced in the calculation procedures of AISC [2] and, later, in the design methodology proposed by Eurocode [3].

The semi-rigid behavior of the connections has been incorporated into the practice of structural analysis, not only because it better represents the actual behavior of the structure relative to its overall response, but also because it contributes to the design of more economical structural elements.

Among the connecting means employed in the practice, the bolted connections distinguish themselves for the simplicity and rapidity in the assembly process of steel structures. However, the large number of variables in this type of connection - the thickness of the plates involved in the connection, the diameter and positioning of the fasteners, etc. - make it difficult to analyze their behavior.

The main objective of this work is to develop a finite element model with one bolt connecting two or three square plates, in such a way that all the necessary considerations are included: contact between the plates and the nut, the head and the shank of the bolt; contact and friction between the plates; pretension in the bolt. This unitary model must adequately respond to forces acting parallel and perpendicular to the contact surface between the plates, capturing the effects of prying action. Finally, this model must have the possibility to be inserted in a complete connection, with any amount and position of the bolts.

## 2 METHODOLOGY

The methodology adopted for this study consists in validating a finite element model with only one bolt through comparisons with experimental results available in the literature, considering bolts subjected to tension, shear and a combination of tension and shear. Subsequently, inserting this model with one bolt in a complete connection, modeled with finite elements too, and compare the numerical results of these connections with actual standards. Two types of connections were chosen: with the bolt group loaded eccentrically and subjected, essentially, to shear; and a T-stub type connection, where the bolts are subjected to tension. All models were developed using the APDL language of software ANSYS® [1].

## 3 UNITARY NUMERICAL MODEL

The element type used on the modelling of the components is *SOLID186*. The plates of the unitary model are square and present a central hole with diameter that corresponds to the diameter of the standard hole indicated by the AISC [4] standard, bigger than the nominal diameter of the bolt. The geometry of the bolt presents some simplifications: the nut and the head of the bolt have the same diameter,  $D$ , and the same thickness,  $t$ , with values based on American specifications for high-strength bolts [5], ASTM A325; the thread region, whose effective area is equivalent to, approximately, 75% of the shank area, was modelled with the nominal diameter of the bolt, however with a less resistant material.

The trilinear stress-strain relationship used to define the material property of the plates and of the thread and shank portions of the bolt is shown in Figure 1. The first line segment represents the elastic range of the material, with slope equivalent to the Young's modulus,  $E$ , equal to 200 GPa [6], and yield stress equal to  $f_y$ . The second and third line segments represent the plastic range, where it is assumed that the tensile strength,  $f_u$ , is reached when the deformation values exceed 2%. The ultimate deformation,  $\varepsilon_u$ , corresponds to the deformation attained at the rupture of the material. Yield

stress and tensile strength for the thread material are equal to these values for the shank material of the bolt multiplied by 0.75 [7].

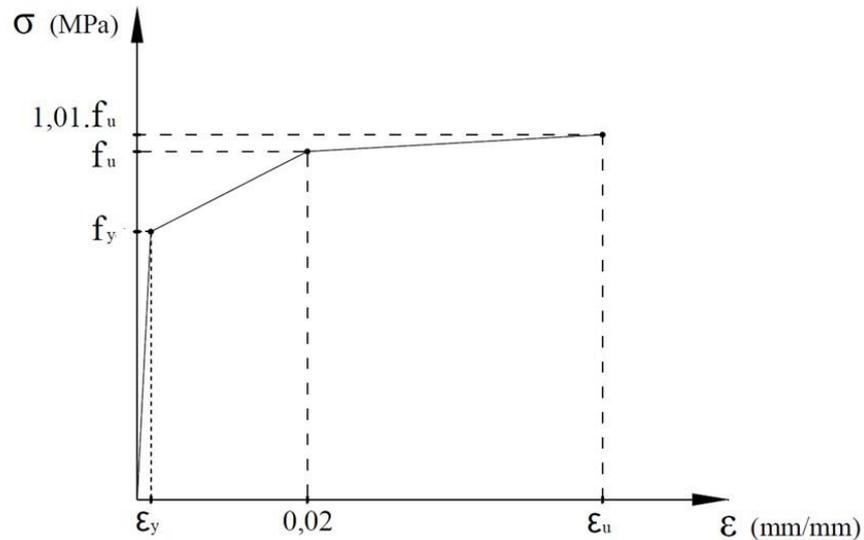


Figure 1: Stress versus strain relationship of the unitary model materials

For an adequate simulation of the contact between the parts, element types *TARGE170* and *CONTA174* were used. Bolt preload was applied through the *PRETS179* element.

For regions with high stress concentrations, such as on bolts and plate holes, mesh convergence studies suggest 20 to 24 elements around the circumference of a typical bolt diameter (7/8" to 1 1/4") [8]. Figure 2 presents the mesh of the unitary model components, with 24 elements around the circumference that define the diameter of the plate holes and bolt shank. The mesh configuration of the rest of the model is based on this value.

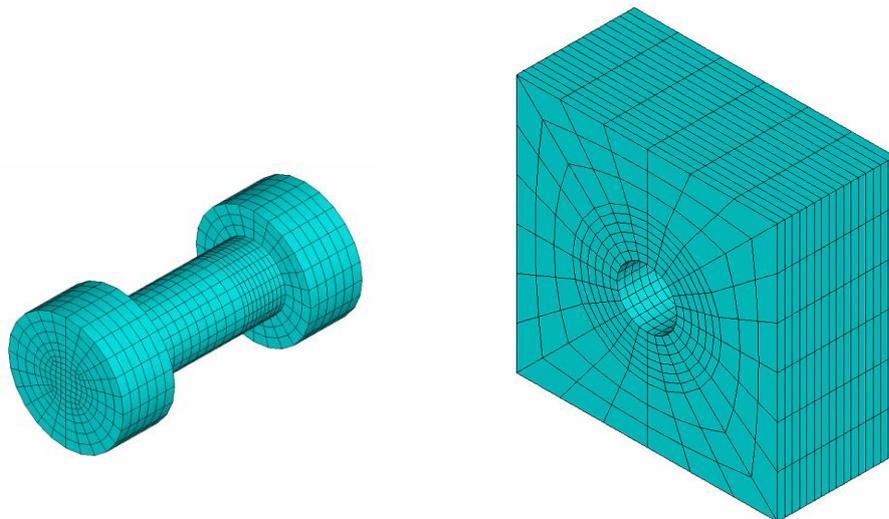


Figure 2: Mesh of the unitary model

The unitary model was validated according to the experimental results [9], [10] and [11] for bolts subjected, respectively, to tension, shear and a combination of these efforts. The numerical results showed good agreement with the experimental results, as explained in [7].

Figure 3 shows an example of a full connection with empty spaces, where the unitary model is inserted. The mesh of the matching edges must be the same so that the parts can be joined together.

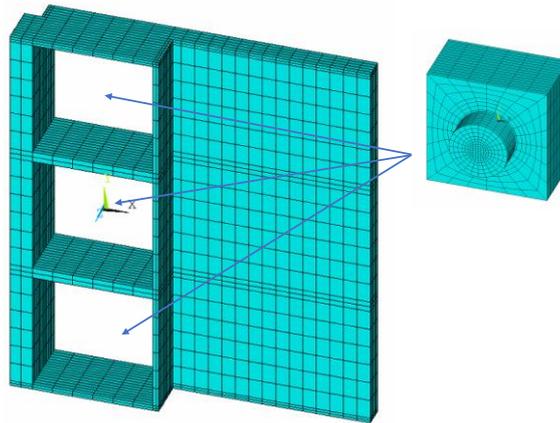


Figure 3: Full connection with empty spaces

## 4 COMPLETE BOLTED CONNECTIONS MODELS – ECCENTRICALLY LOADED CONNECTIONS

### 4.1 General

When the line of action of an applied load does not pass through the center of gravity of a bolt group, the moment resulting from this eccentricity must be considered in the connection design. The eccentricity produces both rotation about the centroid of the bolt group and translation of one connected element with respect to the other. The combined effect of this rotation and translation is equivalent to a rotation about a point, defined as instantaneous center of rotation, and its location depends on the geometry of the bolt group as well as the direction and point of the load application [12].

The AISC Steel Construction Manual [12] presents some tables that employ the instantaneous center of rotation method for different bolt patterns and eccentric conditions. The available strength of the bolt group for any of the arrangement of the tables is defined by  $\phi R_n$ , which is equivalent to the coefficient C multiplied by  $\phi r_n$ , the available strength of a single bolt.

### 4.2 Numerical model description

This work analyzes some configurations of eccentrically loaded bolt groups provided in the AISC manual [12], varying the values of the horizontal component of the load eccentricity,  $e_x$ , number of bolts in one vertical row,  $n$ , and bolt spacing,  $s$ . Figure 4 illustrates three of the complete

eccentrically loaded models that were simulated: the first has 3 bolts, spaced vertically by 3"; the second, 3 bolts spaced by 6"; and the third, 5 bolts spaced by 3".

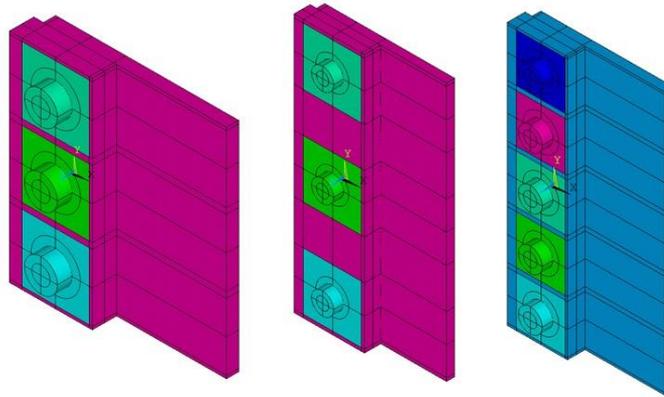


Figure 4: Geometric configurations of the evaluated connections

On the evaluated numerical models, a thickness of 1" was adopted for plate 1 and a thickness of 1/2" was used for plate 2, which length varies according to the value of  $e_x$ . The friction coefficient between the plates was considered equal to 0.3. All bolts are of type ASTM A325, have a diameter of 3/4", thread length of 1/8" to guarantee shear plane out of the thread region, and an initial preload equal to, approximately, 70% of the minimum specified tensile strength of the bolt. The material of the plates is ASTM A36. Table 1 describes the values adopted for the definition of the trilinear curves of these materials.

Table 1 Values of the trilinear curve stress-strain for the materials of the complete model with eccentrically loaded bolt group

	Stress (MPa)	Strain (mm/mm)
Bolt shank (ASTM A325)	0	0
	$f_{yb} = 635$	$\epsilon_{yb} = 0.003175$
	$f_{ub} = 825$	$\epsilon_{ub} = 0.02$
	$1.01 f_{ub} = 833.25$	0.3
Bolt thread (ASTM A325)	0	0
	$f_{yb,r} = 476.25$	$\epsilon_{yb} = 0.002381$
	$f_{ub,r} = 618.75$	$\epsilon_{ub} = 0.02$
	$1.01 f_{ub,r} = 624.94$	0.3
Plates (ASTM A36)	0	0
	$f_{ych} = 250$	$\epsilon_{ych} = 0.00125$
	$f_{uch} = 400$	$\epsilon_{uch} = 0.02$
	$1.01 f_{uch} = 404$	0.3

### 4.3 Results

Table 2 presents a comparison between the values of the coefficients  $C$  recommended by the AISC manual [12] and the coefficients obtained through the numerical simulations for the indicated values of  $n$ ,  $e_x$  and  $s$ . This coefficient was determined dividing the resistant shear force of the complete connection (last converged step) by the resistant shear force of the unitary model.

Table 2 Variables of eccentrically loaded connections and respective coefficient values,  $C$

Ultimate strength of the unitary model = 145 kN						
	$s$ (in.)	$e_x$ (in.)	Ultimate strength of the complete model (kN)	Numerical coefficient, $C$	AISC coefficient, $C$	Difference (%)
$n = 3$	3	2	319.5	2.20	2.23	1.4%
		4	201.6	1.39	1.4	0.9%
		6	140.1	0.96	0.97	0.6%
		8	105.1	0.72	0.73	0.9%
		10	84.5	0.58	0.59	1.4%
	6	4	325.3	2.21	2.23	1.0%
		6	254.9	1.73	1.75	1.1%
		8	204.6	1.39	1.4	0.8%
		10	166.9	1.13	1.15	1.5%
$n = 5$	3	6	370.6	2.55	2.59	1.4%
		10	235.4	1.62	1.66	2.3%

A good agreement was observed between the numerical results and the AISC [12] recommended values. Plates with different thicknesses were not evaluated, once numerically obtained coefficients  $C$  were calculated based on the ultimate bolt resistance, that is, considering the attendance of the other ultimate limit-states applicable to the plates. Figure 5 presents a distribution of von Mises stresses for the last converged step of the models with  $n$  equal to 3 and 5,  $s$  equal to 3" and  $e_x$  equal to 6". When a group of bolts is eccentrically loaded, the bolts of the extremities are the most requested. Such behavior can be seen in Figure 5, where the external bolts failed, while the internal bolts did not develop all of their strength.

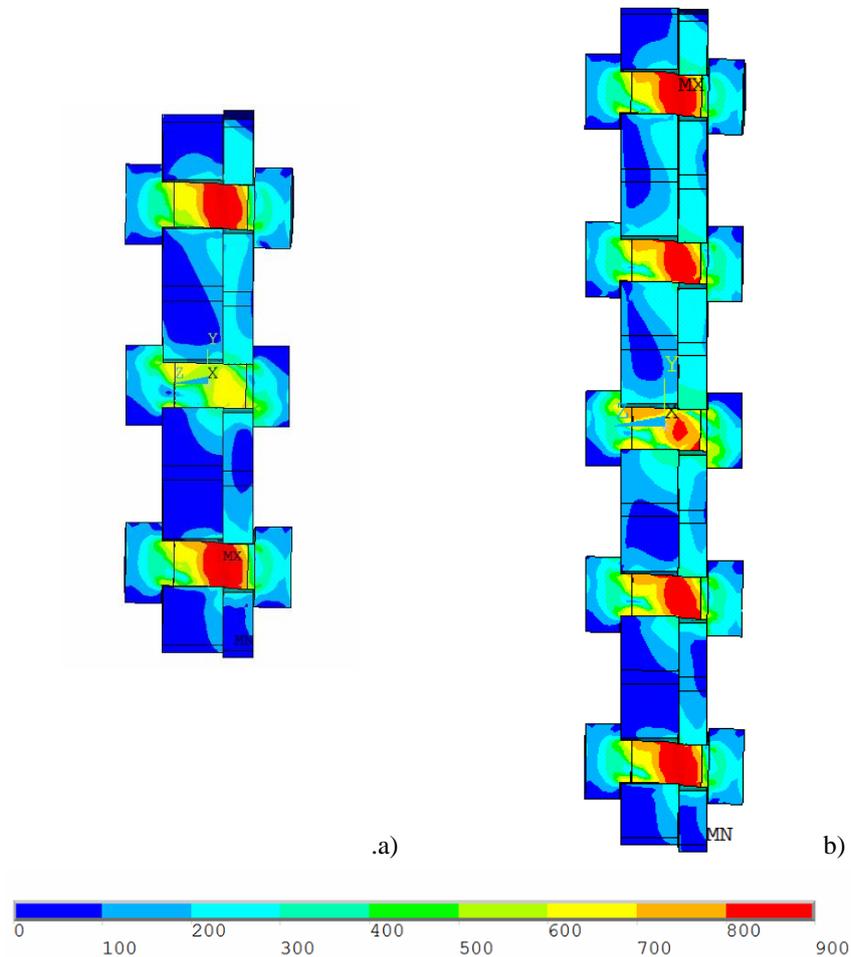


Figure 5: Distribution of von Mises stresses on eccentrically loaded bolt group models: a)  $n=3$ ; b)  $n=5$

## 5 COMPLETE BOLTED CONNECTIONS MODELS – T-STUB CONNECTIONS

### 5.1 General

The T-stub connection is one of the simplest connections where the bolts are subjected to tension. Depending on the geometric characteristic and the material employed on the connection, additional forces near the flange extremities can appear. This effect, known as prying action, increases the effort in the bolt, and should be taken into account in the analysis of the connection.

The American code provides a design procedure that includes the prying action, where bolt diameters and connected flange thicknesses are determined in such a way that bolt resistance, as well as flange stiffness and strength, are above the required.

Figure 6 presents the variables involved on consideration of prying action. The force per bolt can be determined by  $T+q$ , where  $T$  represents the tension force per bolt due to the external acting force,  $2T$ , and  $q$  is the additional tension force per bolt due to prying action.

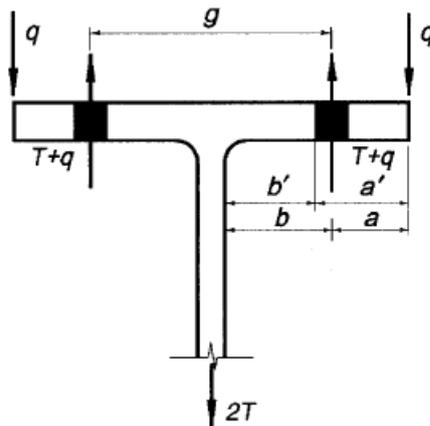


Figure 6: Prying forces in tee

When the connection geometry is known, the available tensile strength including the effects of prying action,  $T_{avail}$ , can be obtained multiplying the available tensile strength per bolt,  $B$ , by  $Q$ :

$$T_{avail} = B \cdot Q \quad (1)$$

where  $Q$  is the factor that represents the presence or not of sufficient strength and stiffness of the flanges to develop all the available tensile strength of the bolts.

## 5.2 Numerical model description

ASTM A325 bolts, with  $\frac{3}{4}$ " diameter, and ASTM A572 Gr50 tee shapes were considered for evaluation of the behavior of T-stub connection subjected to tension. Since bolts of these connections are essentially subjected to tension, the thread material was used to define the shank and thread of these model bolts (the stress-strain values are the same presented in Table 1). The variables in Figure 6 have the following values: distance between the holes,  $g$ , equal to 120 mm; distance from the bolt centerline to the face tee stem,  $a$ , equal to 40 mm; tributary length per pair of bolts, perpendicular to the page,  $p$ , equal to 120 mm. The other variable values are shown in Table 3, as well as the tee flange and web thicknesses of the evaluated cases. Figure 7 illustrates one of the complete simulated T-stub model.

Table 3 Geometric variables of evaluated T-stub connections

	Model 1	Model 2	Model 3	Model 4	Model 5
Flange thickness, $t_f$ (mm)	12.50	16.00	19.00	25.00	37.50
Web thickness, $t_w$ (mm)	12.50	16.00	16.00	16.00	25.00
$b'$ (mm)	44.23	42.48	42.48	42.48	37.98
$b$ (mm)	53.75	52.00	52.00	52.00	47.50
$a'$ (mm)	49.53	49.53	49.53	49.53	49.53

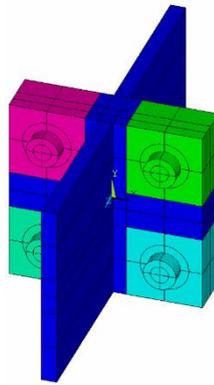


Figure 7: Complete T-stub model

### 5.3 Results

Knowing the geometry of the connection, it is possible to calculate the required flange thickness,  $t_c$ , to develop the available tensile strength of the bolt,  $B$ , without the effect of prying action. Besides these values, Table 4 shows the available strength of the evaluated connections,  $T_{avail}$ , considering the effect of prying action, if it occurs.

Table 4 Parameter values related to the T-stub models

	$t_f = 12.5$ mm	$t_f = 16.0$ mm	$t_f = 19.0$ mm	$t_f = 25.0$ mm	$t_f = 37.5$ mm
$t_c$ (mm)	26.33	25.80	25.80	25.80	24.40
$\alpha'$	2.288	1.086	0.573	0.044	-0.411
$B$ (kN)	176.4	176.4	176.4	176.4	176.4
$Q$	0.404	0.690	0.789	0.972	1
$T_{avail}$ (kN)	285165	486464	556321	685451	705432
$T_{numerical}$ (kN)	294000	454000	510000	646000	702000
$T_{numerical} / T_{avail}$	1.03	0.933	0.917	0.942	0.995

For flange thickness equal to 12.5 mm, the last step considered in the numerical model occurred for a load equal to 294 kN, when the stress level at the interface between the web and the flange reached the material strength of the plates, indicating connection failure. Figure 8a presents the von Mises stresses for the last step of the mentioned tee, where it is possible to observe an accentuated

bend of the plates and, also, the presence of extension regions with stress above steel yield stress at the centerline of the holes.

For flange thickness equal to 25.0 mm, the last step considered in the numerical model occurred for a load,  $T_{numerical}$ , equal to 646 kN, close to the value indicated by the formulation of AISC [12]. Figure 8b shows the von Mises stresses for this tee shape, where it is possible to observe a zone of intense plastification next to the web. Like in the previous analyzed model, the material strength of the plates is reached at the interface between the web and the flange.

For flange thickness equal to 37.5 mm, the last converged step occurred for a load,  $T_{numerical}$ , equal to 702 kN, which is equivalent to the available strength of the 4 bolts group. The high stiffness of flange tee shapes avoids the occurrence of prying action effects, what is in accordance with the AISC standard [12]. Figure 9 exhibits the von Mises stresses diagram for the connection ultimate load, indicating the presence of few points with stress above the yield limit.

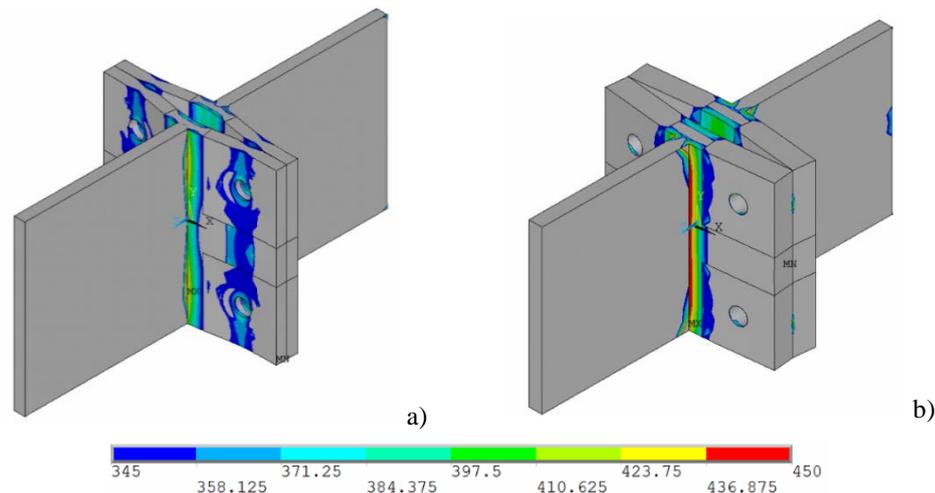


Figure 8: Von Mises stresses for complete T-stub model with flange thickness equal to: a) 12.5 mm; b) 25.0 mm

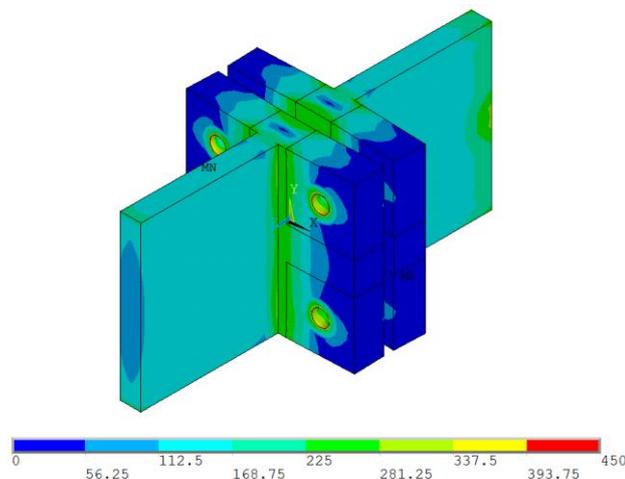


Figure 9: Von Mises stresses for complete T-stub model with flange thickness equal to 37.5 mm

## 6 CONCLUSIONS

This work developed a numerical methodology to evaluate the behaviour of one bolt subjected to tension, shear and a combination of these efforts, using software ANSYS® [1]. This unitary model was inserted, subsequently, in two types of complete connections, and the results were compared with standard predictions.

In the connections with an eccentrically loaded bolt group, it was possible to determine the coefficients  $C$  for different geometric configurations and all of them presented good agreement with the values suggested by AISC [12]. The maximum difference between the results was of 2.3%.

In the numerical T-stub connections, distinguished failure modes were observed for different evaluated flange thicknesses. For flange thicknesses smaller than 19.0 mm, the failure was characterized by the rupture of the plates due to bending. For flange thickness equal to 25.0 mm, the failure occurred simultaneously at the flange (interception with the web) and at the bolts. When flange thickness is equal to 37.5 mm, there were no prying action effects, occurring bolt ruptures due to direct acting of the external load through the tee web. The available strength of all the evaluated models differ up to 9% in relation with that determined by AISC [12].

Then, the proposed numerical methodology proves to be interesting, since it enables the evaluation of any bolted connection, including connections not provided by the reference standards.

## 7 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support received from Fundação de Amparo à Pesquisa de Minas Gerais – FAPEMIG.

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