Numerical and theoretical evaluation of the influence of edge-to-hole distance on possible failure modes of sleeve connections in thin-walled square hollow sections

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Abstract. Tubular members in truss structures allow for spanning large distances with reduced self-weight. To facilitate manufacturing, transportation, and assembly, these members are subdivided and therefore require connections to join the segments. One example is the sleeve connection, which uses through bolts and eliminates the need for welded or flanged joints, making assembly quicker and more practical. The present study aimed to conduct a theoretical and numerical analysis of the influence of the edge-to-hole distance in sleeve connections with aligned bolts, applied to thin-walled square hollow sections. For this purpose, a numerical analysis was carried out using the finite element method through ANSYS software, with variations in edge-to-hole distance of 2, 2.5, 2.7, 3, and 3.5 times the bolt diameter, as well as variations in the number of bolts between 2 and 3. From this study, the possible failure modes of the connection were identified, with the dominant failure mode being the bearing failure of the bolt holes, also observed in the theoretical evaluation, occurring in the outer tubes. Furthermore, variations in the edge-to-hole distance and the number of bolts did not change this failure mode.

Keywords: Steel structures; Hollow sections; Numerical analysis; Splice Connection; Sleeve Connection.

1 Introduction

Tubular profile is a hollow structural member, generally made of steel, characterized by a circular, square, or rectangular cross-section. Steel tubular profiles are already widely used in various parts of the world, including Europe, Southeast Asia, Australia, and North America. These profiles provide an effective solution for structural elements required to span large clear distances, as they are lighter and more economical due to their high strength-to-weight ratio. Another notable advantage of this type of profile is its standardization, which facilitates both fabrication and connection, thereby enabling faster structural assembly by Gerken [1].

Despite the advantages reported by Gerken [1], in Brazil the use of such profiles remains largely limited to space frame roofs employed in shopping centers, airports, sports stadiums, and industrial warehouses. This restriction may be related to the lack of precise and comprehensive technical information regarding the material, given that research on tubular profiles is relatively recent in the country, as highlighted by the recent publication of the Brazilian standard NBR 16239 [2], issued in November 2013.

It is also worth noting that tubular sections exhibit superior performance under axial loads when compared to open-section profiles. Such characteristics make this type of profile widely used in trusses and other structural systems according to Araújo et al. [3]

However, in the fabrication, transportation, and erection of structures employing tubular profiles, it is often necessary to divide the members into shorter segments than required for the final configuration. This leads to the need for structural connection elements capable of joining the profile segments to meet the specific demands of each structure.

This justifies the need for studies focusing on tubular profile connections, which has led to an increasing number of investigations into the behavior and development of new connection typologies that take advantage of the mechanical properties of these members and facilitate structural assembly by Araújo et al. [3].

In this context, more innovative solutions have been sought, including a new splice connection typology referred to as the sleeve connection. The sleeve connection was developed to provide ease and speed of assembly, offering designers an alternative to welded and flanged joints. The latter, although the most common, may cause some aesthetic discomfort to users due to the visible discontinuity in the structural member. The sleeve connection uses an internal tube as a splice, with through-bolts to secure the assembly. Figure 1 presents the sleeve connection typology for rectangular hollow sections, previously investigated by Roquete et al. [4] and Oliveira et al. [5].

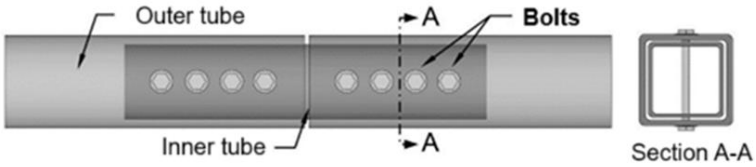


Figure 1. Rectangular sleeve connection

Roquete et al. [4]

It is also important to mention that thin-walled sleeve connections often present bearing failure as the dominant failure mode, and there is currently no analytical equation that adequately represents the observed behavior of this type of connection (Roquete et al. [6]). The authors present an initial experimental study with four prototypes, observing this dominant failure mode. They emphasize the need for further experimental tests for better evaluations, which will serve as a basis for the validation of numerical models.

Therefore, the present study evaluates the structural behavior of sleeve connections used as splices for thin-walled rectangular steel hollow sections, considering variations in the edge-to-hole distance and in the number of bolts employed.

2 Numerical evaluation

The analysis was carried out in the ANSYS [7] software. The numerical model was developed for a sleeve connection with two and three bolts, as shown in Figure 2, consisting of an inner tube with a thickness of 6.0 mm, height and width of 56 mm, and an outer tube with a thickness of 1.8 mm, height and width of 60 mm. The hole configurations varied between two and three bolts, and the bolt diameter (d_b) used was 12.7 mm.

The edge-to-hole distances (l_{f1}) were varied as $2.0d_b$, $2.5d_b$, $2.7d_b$, $3.0d_b$, and $3.5d_b$. The steel yield strength (f_y) adopted was 356.61 MPa for the outer tube (OT), 345 MPa for the inner tube (IT), and 635 MPa for the bolts. The ultimate tensile strength (f_u) was 404.39 MPa, 485 MPa, and 825 MPa for the OT, IT, and bolts, respectively.

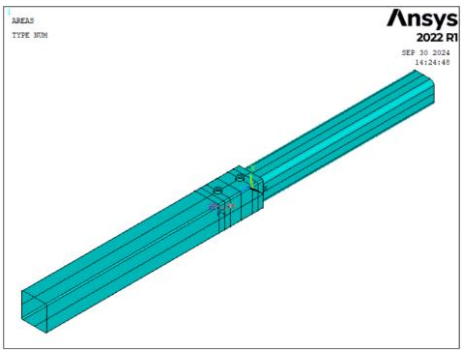
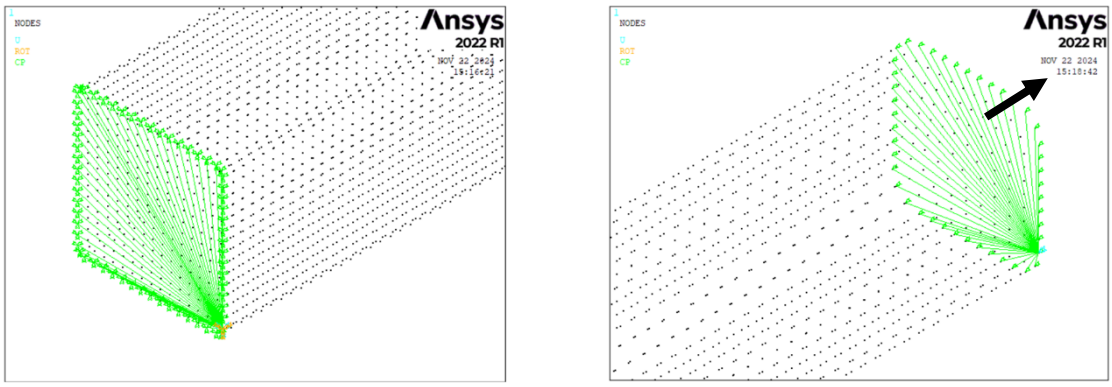


Figure 2. Numerical model

As in previous studies on sleeve connections, shell elements (SHELL) were used for modeling the tubes, and solid elements (SOLID) were used for the bolts. The selected shell element was SHELL181, a homogeneous structural element with four nodes and six degrees of freedom per node, allowing for irregular meshing and load application in all directions. For the bolts, the chosen solid element was SOLID186, a twenty-node element with three degrees of freedom per node, also allowing irregular meshes and multi-directional loading. An unstructured mesh was adopted, with quadrilateral elements as the preferred option, while permitting the use of tetrahedral and triangular elements, in accordance with previous studies by Roquete et al. [8], Roquete et al. [9], and Oliveira et al. [10]. In the simulation, one end was assumed to be fixed. A 15 mm displacement was then applied to the other end along the longitudinal axis of the profile, which simulated a tensile load on the connection, as illustrated in Figure 3.



(a) Fixed end detail (b) Loaded end detail

Figure 3. Detail of the model's ends

3 Theoretical analysis

The theoretical analysis of the connection was conducted according to NBR 14762 [11] and based on existing studies. This study evaluated the contact pressure in the holes, associating it with the bearing failure mode. According to Roquete [12], the evaluation of the ultimate limit state related to the crushing of the hole wall involves analyzing the failure that can occur due to contact pressure between the holes, as established by NBR 14762 [11]. The crushing of the hole wall subsequently results in a final deformation that gives the hole an ovalized shape. Thus, as in the studies by Roquete et al. [8] and Oliveira et al. [10], this limit state will be referred to as bearing failure and can be defined by Equations (1), (2), and (3).

$$F_{OF,NBR} = \alpha_e dt f_u \tag{1}$$

$$F_{\mathrm{OF,R2021}} = d_\mathrm{b} t f_\mathrm{u} \tag{2}$$

$$F_{\mathrm{OF,O2020}} = \frac{\pi}{2} d_\mathrm{b} t f_\mathrm{u} \tag{3}$$

Where d_b is the nominal diameter of the bolt and t is a factor equal to (0.183t+1.53), with t in millimeters.

4 Results

The developed numerical model was evaluated using the results obtained from the ANSYS software, according to the aforementioned variations and characteristics described in Section 3. From these results, the graphs shown in Figures 4 and 5 were constructed.

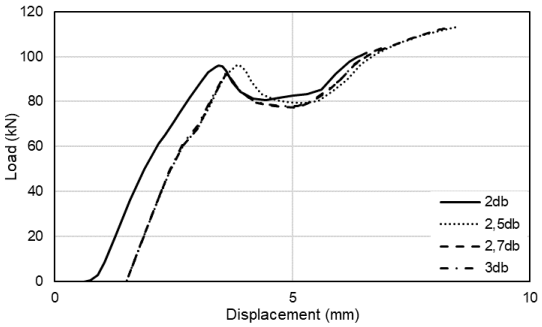


Figure 4. Results for 3 bolts

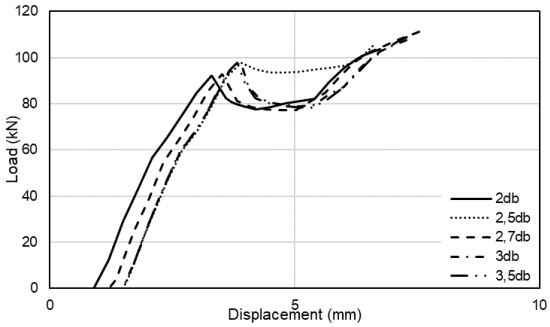


Figure 5. Results for 2 bolts

Figures 4 and 5 present an initial horizontal section, which is associated with the clearance between the holes and the bolts. Both figures show a gain in load with displacement until an initial load peak is reached. Furthermore, it is important to note that the model exhibits a drop in loading followed by a new gain in loading after the initial peak, as can be observed in Figures 4 and 5. This behavior may be associated with the contact between the inner and outer tube walls, which occurs after excessive deformation of the model, indicating a possible failure mode. The numerical models' bearing failure was characterized when the total von Mises strain in the contact region between the hole and the bolt was equal to or greater than the ultimate strain, according to Roquete [12], as shown in Figure 6. It is worth noting that for all numerical models analyzed, the dominant failure mode was bearing failure.

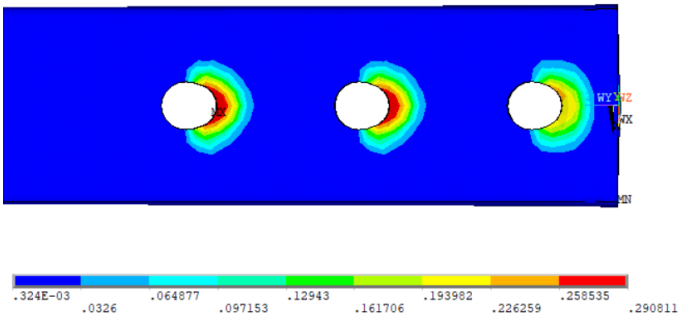


Figure 6. Detail of bearing failure in the holes of the outer tube from the numerical model

Table 1 presents the results of the theoretical analysis for the same models studied for bearing failure modes, according to the equations presented previously. The table's columns show the model and the results of the failure modes based on the author (Roquete et al. [8]-[R2021], Oliveira et al. [10]-[O2020], or NBR14762 [11]). Table 1 also includes the numerical value for the hole's bearing failure mode, as found in the numerical model. It should be noted that model 20 did not achieve numerical convergence, so its analysis was discarded.

Table 1 also presents the ratio between the theoretical failure load (F_{OF}) and the numerical failure load (P_{num}). The ideal scenario is when this ratio (F_{OF}/P_{num}) approaches unity (1.00), which indicates that the theoretical equation is a good representation of the numerical model.

When the ratio is above unity, it suggests that the equation underestimates the model, meaning it predicts a failure mode superior to what occurs in practice. Conversely, when the ratio is less than unity, it indicates that the theoretical equation overestimates the model, predicting a failure mode value that is inferior to the actual occurrence.

It is highlighted in Table 1 that the coefficient of variation (CoV) was approximately 0.06 for the formulations of NBR 14762 [11], Roquete et al. [8], and Oliveira et al. [10]. This value, being below 10%, suggests good results.

This behavior can also be observed in Figures 7 through 9. In these figures, the closer the points are to the 45º inclination line, the closer the numerical value is to the theoretical value.

Table 1. Theoretical and Numerical Results

Model	N° of bolts	Variation	$F_{OF,NBR}$ [kN]	$F_{\mathrm{OF,R2021}}$ [kN]	$F_{\mathrm{OF,O2020}}$ [kN]	P_{num} [kN]	$F_{OF,NBR}$ /P_{num} [kN]	$F_{\mathrm{OF,R2021}}$ /P_{num} [kN]	$F_{\mathrm{OF,O2020}}$/ P_{num} [kN]
1	2	2.0 d_b	68.76	36.98	58.08	52.73	1.30	0.70	1.10
2	2	2.5 d_b	68.76	36.98	58.08	51.05	1.35	0.72	1.14
3	2	2.7 d_b	68.76	36.98	58.08	61.21	1.12	0.60	0.95
4	2	3.0 d_b	68.76	36.98	58.08	51.61	1.33	0.72	1.13
5	2	3.5 d_b	68.76	36.98	58.08	53.46	1.29	0.69	1.09
6	2	2.0 d_b	103.13	55.47	87.13	77.44	1.33	0.72	1.13
7	2	2.5 d_b	103.13	55.47	87.13	93.37	1.10	0.59	0.93
8	2	2.7 d_b	103.13	55.47	87.13	77.3	1.33	0.72	1.13
9	2	3.0 d_b	103.13	55.47	87.13	79.46	1.30	0.70	1.10
10	2	3.5 d_b	103.13	55.47	87.13	79.56	1.30	0.70	1.10
11	3	2.0 d_b	67.51	36.31	57.03	53.41	1.26	0.68	1.07
12	3	2.5 d_b	67.51	36.31	57.03	51.61	1.31	0.70	1.11
13	3	2.7 d_b	67.51	36.31	57.03	60.62	1.11	0.60	0.94
14	3	3.0 d_b	67.51	36.31	57.03	52.07	1.30	0.70	1.10
15	3	3.5 d_b	67.51	36.31	57.03	52.02	1.30	0.70	1.10
16	3	2.0 d_b	101.27	54.46	85.55	86.66	1.17	0.63	0.99
17	3	2.5 d_b	101.27	54.46	85.55	82.19	1.23	0.66	1.04
18	3	2.7 d_b	101.27	54.46	85.55	78.72	1.29	0.69	1.09
19	3	3.0 d_b	101.27	54.46	85.55	78.54	1.29	0.69	1.09
20	3	3.5 d_b	101.27	54.46	85.55	-	-	-	-
						Mean	1.26	0.68	1.07
						CoV	6.14%	6.14%	6.14%

The formulation from NBR 14762 [11], as shown in Figure 7, presents values that could lead structural engineers to conservative results. This is because these values estimate a failure mode that occurs at a load higher than what was numerically observed. Despite a CoV value below 10%, which indicates good applicability to the studied models, the formulation by Roquete et al. [8] also presents conservative results, as shown in Figure 8. The formulation that best adapted to the numerical model is the one proposed by Oliveira et al. [10]. As shown in Table 1 and Figure 9, this formulation has an average ratio of 1.07 and yielded the best results, making it the most suitable for evaluating this failure mode in the connection.

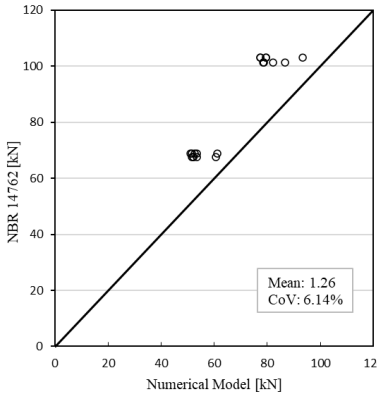


Figure 7. NBR 14762

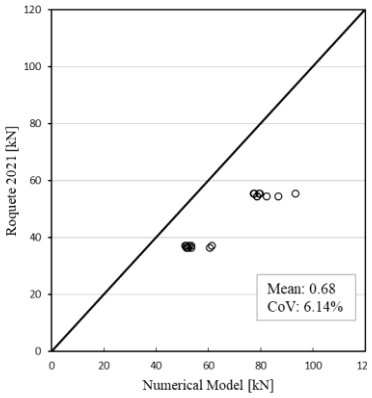


Figura 8. Roquete et al. 2021

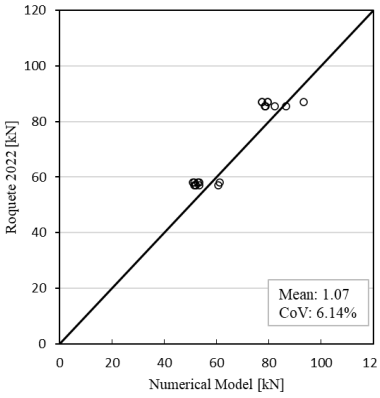


Figura 9. Oliveira et al. 2020

5 Final considerations

In this study, a numerical model was developed using the finite element method with the aid of the ANSYS software, with the goal of evaluating the behavior of a rectangular sleeve connection. The model was built using shell and solid elements to represent the bolts and tubes.

During the analysis, 20 connection models were simulated, varying the number of holes, ultimate strength, yield strength, and the distance between the hole and the edge.

After the analyses, one model did not achieve numerical convergence and was discarded. The results obtained showed that, for all remaining models, the dominant failure mode was bearing failure. It was observed that varying the hole-to-edge distance did not alter the dominant failure mode of the connection. This suggests that using the minimum distance recommended by the standard is sufficient. In this study, increasing the number of bolts from 2 to 3 did not alter the characteristic value of the failure mode.

It was also noted that the formulations available in the literature can represent the behavior of the connection, with the formulation proposed by Oliveira et al. [10] the best results for the numerical model. However, the need for further analyses with a larger number of numerical models, in addition to experimental analyses, is highlighted.

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