XLI CILAMCE
XLI Ibero-Latin American Congress on Computational Methods in Engineering
16-19 November, 2020
FOZ DO IGUAÇU
PARANÁ - BRAZIL

Numerical analysis of compressed end-flattened steel bars of three-dimensional trusses

Henrique de A. R. Cruz[1], Welington V. da Silva[1], Luciano M. Bezerra[1]

[1]*Dept. of Civil Engineering, PECC/ENC/FT, University of Brasilia*
SG-12 building, 1st floor, Darcy Ribeiro Campus, University of Brasilia, 70910-900, Federal District, Brazil
henrique.arcruz@gmail.com, welington.vital@gmail.com, lmbz@unb.br

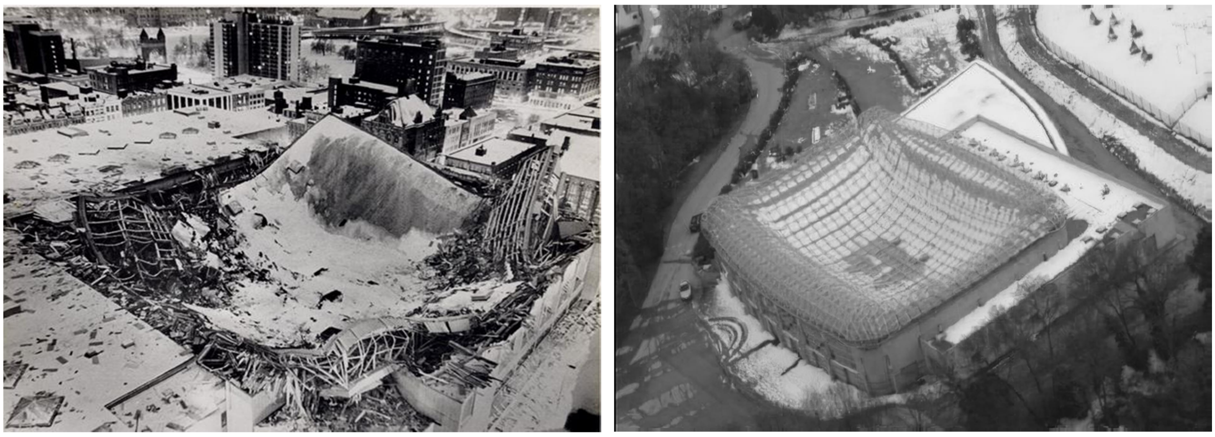
Abstract. On the field of steel structures, one of the most commonly used types of structural systems is the three-dimensional truss. It is applied in a wide range of sizes and shapes, with its constituent elements usually prescribed as hollow circular cross-section bars. In order to assemble them in a practical and efficient way, one alternative often chosen by designers is to flatten their ends and attach these bars in bolted connections. Although such constructive method has notorious advantages and is already present in a large number of engineering projects in different countries, it is still necessary to conduct more studies that analyze its singular structural behavior and thereby contribute to the establishment of forthcoming normative criteria. In this sense, this work presents an association of numerical analysis and empirical data of an example of end-flattened steel bar, especially regarding the variation of the stress field developed along the structure subjected to different levels of load. The results obtained provide a better understanding of the consequences of the reduction of stiffness due to the flattening process of the bar ends.

Keywords: end-flattened steel bar, three-dimensional truss, steel structures, stress field.

1 Introduction

The application of three-dimensional trusses as a structural system solution for various types of engineering works is remarkable. This is due to several factors, such as its inherent resilience and efficiency in the transmission of acting loads, which in general allows the design of slender and economically advantageous structures. These are frequently adopted as roof support structures in sport gymnasiums, airports, warehouses, large textile industries and railway stations.

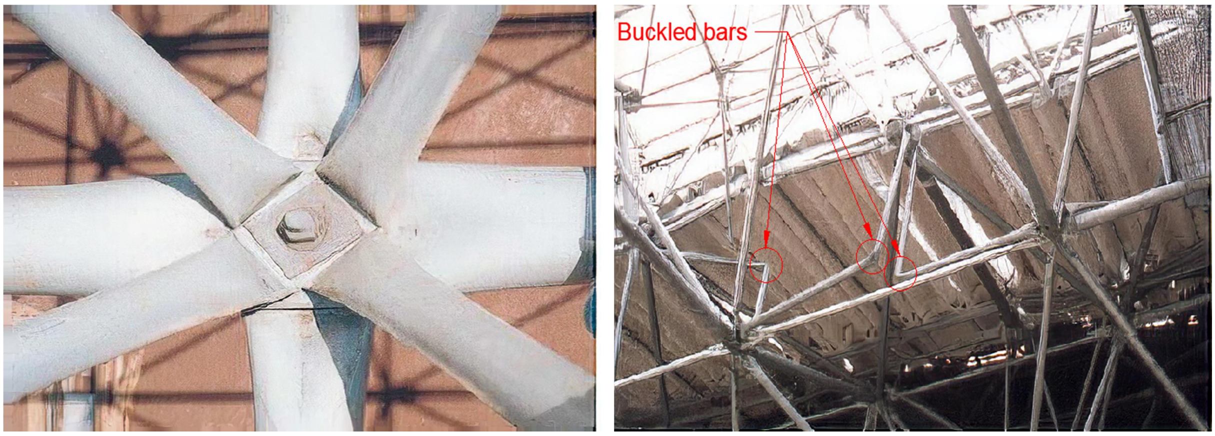
However, along with the beneficial aspects and the successes of projects that make use of such structures, there is a history of engineering failures that were the cause of the collapse of a significant number of three dimensional trusses worldwide. Precupas *et al.*[1] analyzed the ROMEXPO pavilion failure occurred in the winter of 1963-1964; Martin and Delatte [2] describe the global failure of the Hartford Civic Center Coliseum under a heavy snowfall on January 18, 1978; in similar weather conditions occurred the collapse of a sports center in Gerona in 2010 reported by Alegre *et al.*[3]; among other examples. Figure 1 illustrates these last two cases.



(a) (b)

Figure 1. Collapses of (a) the Hartford Civic Center Coliseum and (b) the sports center in Gerona [4,3]

In Brazil and many other countries, a subtype of three-dimensional trusses that has been widely adopted as a structural system is that composed of hollow circular cross-section bars, whose ends are previously flattened to provide the coupling with other connection members. The simplicity and low costs of its construction system are relevant factors in its choice of use among designers according to Bezerra *et al.*[5]. Despite this fact, some of its critical characteristics such as the potentially generated eccentricity bending moments and reduced stiffness due to the flattening process should be carefully regarded in the design process. It is imperative the establishment of specific normative criteria in order to provide an optimized and safe application of these types of structural elements. Figure 2 shows an example of such truss elements. It presents assemblage details of the referred connection system and depicts the failure of some diagonal truss elements due to the aforementioned critical features.



(a) (b)

Figure 2. End-flattened steel bars assemblage (a) and the collapse of a three-dimensional truss (b) [5]

Established the scenario of applicability of space trusses in the design of projects, observing the potential disasters associated with the risks of failure, it is evident the need to develop scientific studies that seek to understand the behavior of these structures under different approaches. One of these, which sets the general objective of this paper, is to present a numerical stress field analysis of its constituent elements subjected to a variety of compressive loads, focusing on the end-flattened steel bar truss subtype. For this purpose, as a computational tool to help this research, the software Abaqus® is used, from which the results that support the subsequent analysis and development of the article are extracted.

2 Modelling

The determination of the characteristics of the model developed in this work was based on a previous analysis of the structures currently designed. According to Maiola and Malite [6], the slenderness (λ) usual for elements of three-dimensional space trusses lies between the limits of 60 and 140. In this way, a slenderness equal to 100 was established as the reference to this study.

As for the steel to be used in the experimental and numerical tests, the standard steel SAE-1020 was adopted, whose mechanical properties were verified and are presented in Table 1. The reference bars for the study have a nominal diameter of 38 mm, a thickness of 0.95 mm and its geometric properties after the process of flattening and boring its extremities are those shown in Figure 3.

Table 1. Steel mechanical properties

Mechanical property	Value
Elastic modulus	200 GPa
Poisson's ratio	0.29
Yield strength	198 MPa
Ultimate strength	264 MPa

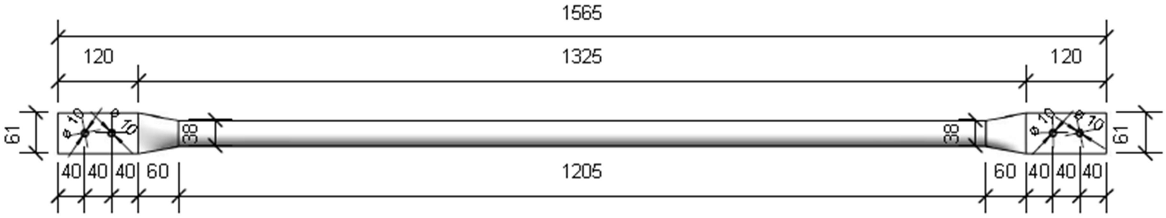


Figure 3. Geometrical properties in millimeters of the end-flattened steel bars (λ = 100)

2.1 Experimental tests

To perform the tests, a sample of three end-flattened bars with the aforementioned mechanical and geometric characteristics was constituted. Each was subjected to an increasing axial compressive load by means of a hydraulic press, as shown in Figure 4. The bars were positioned with their longitudinal axes aligned to the vertical direction and their ends were fixed to the press with the aid of bolted confining plates.

According to Dundu [7], there are two possible failure modes for the end-flattened steel bars under compressive loads: the overall flexural buckling or the excessive deformation of the cross sections' transition zones of these members. The resultant behavior is determined by some of their geometric characteristics, in which their slenderness and diameter-to-thickness ratios play a significant role.

The test was conducted until the failure of the structural elements was observed, characterized prominently by the material yielding and consequent excessive deformation of their extremities. Figure 4 also contains this final configuration of the tested bars. The average ultimate load (Pult) of the sample to reach such a state was 7.4 kN, a value reached in the numerical model after applying some specific intermediate load stages described in the next section.

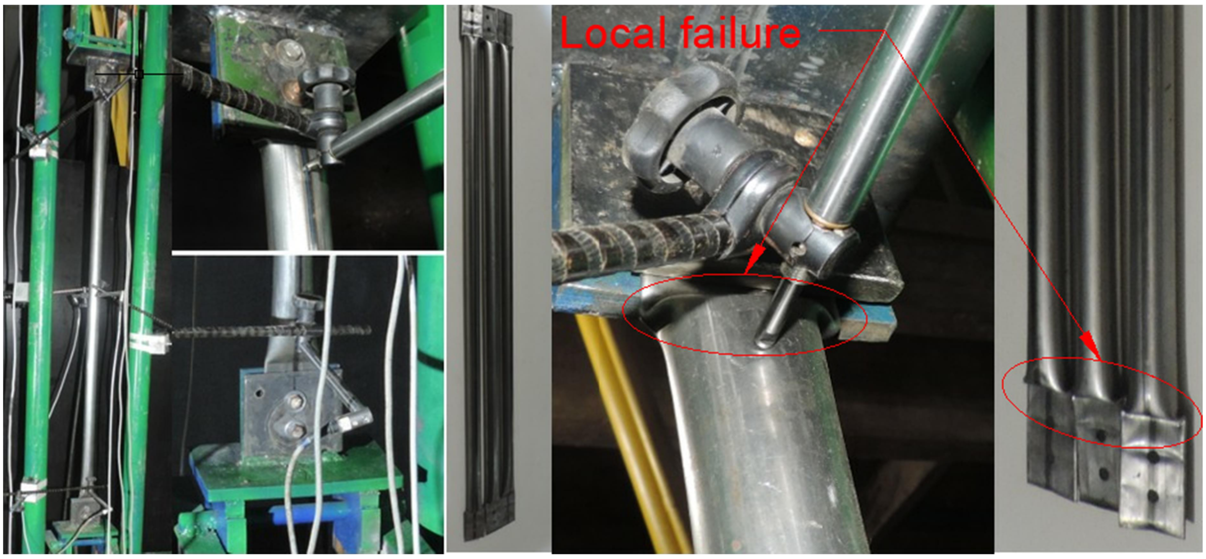


Figure 4. Configuration of experimental tests

2.2 Numerical simulations

With the numerical simulation of the end-flattened steel bar, the objective is to analyze the development and variations in the stress field along its structure. For this, different levels of loading are proposed, namely: 40%, 60%, 80% and 100% of the ultimate load established by the experimental tests.

For the constitution of the bar geometry, the AutoCAD® software was used, whose tools allowed the construction of the basic shape of the projected element. Only area elements were used to compose its surface and the transition zone between the circular and flat cross sections was formed by a three-dimensional curved mesh structured by the program. This geometry was then exported to the Abaqus® software, in which the last element geometry adjustments were made. Once this stage was completed, the general configuration of the simulation was continued. The type of analysis conducted in this work was the general linear static, due to its approximation to the behavior of the experimental data, with consequent optimization of computational effort.

As for the boundary conditions, the supports provided by the press were represented in the model by the restriction of translation of the holes in the flattened regions of the bars, with translation only being allowed in the axial direction of its upper end. Rotation restriction was also established at both ends in the same direction due to the contact provided by the adjoining plates and then the loads were applied in the region of the holes in the upper end in contact with the press actuator.

Finally, the finite element mesh was generated along the bar structure. In order to present an adequate configuration, with elements of efficient size and shape and few abrupt transitions of geometry, partitions of surfaces and edges were performed. Shell elements of the S4R type were used, which at the end of the modeling totaled 21850. Figure 5 depicts the arrangement of the elements of the referred mesh.

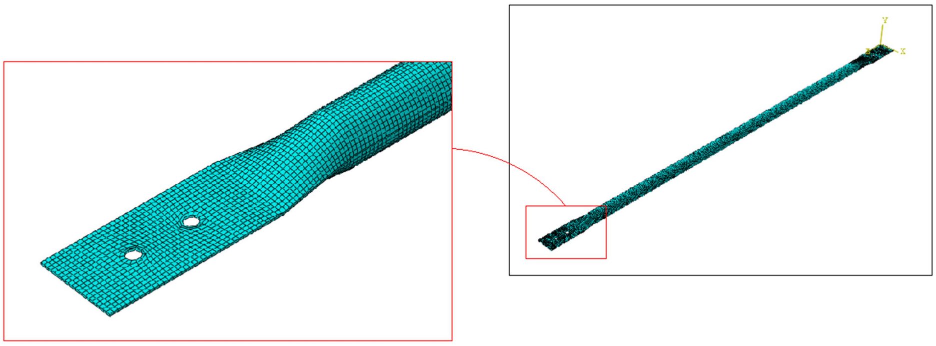
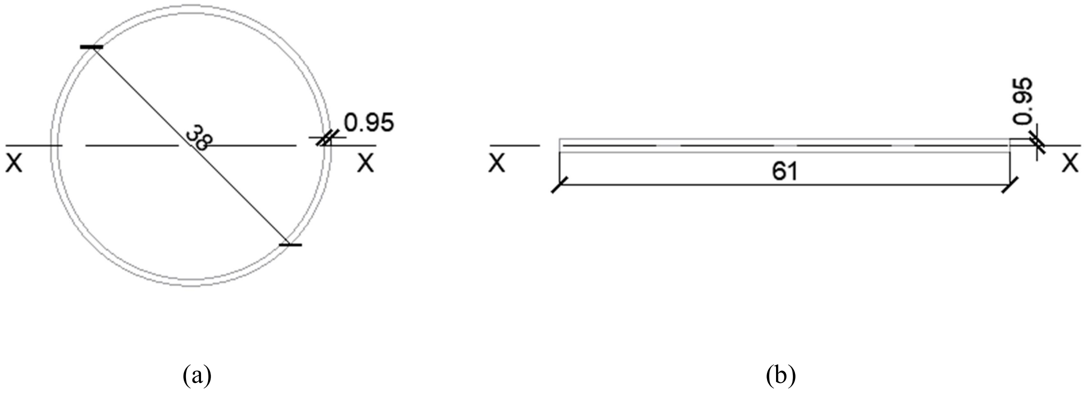


Figure 5. Meshing of the end-flattened steel bar

3 Analysis

The end-flattening process represents in terms of modification of strength characteristics of the steel bars a reduction of its moment of inertia and so of its flexural stiffness. Due to eccentricities often observed in the connection members, especially those in the diagonal elements of space trusses, bending moments are generated and make the structure more susceptible to collapse. In order to demonstrate the differences of strength between the original circular hollow section and the end-flattened section applied in this study, Figure 6 and Table 2 present the comparison of some of their geometrical and mechanical properties.



(a) (b)

Figure 6. Geometrical properties in millimeters of the original and flattened cross sections

Table 2. Geometrical and mechanical properties of the original and flattened cross sections

Property	Original cross section	Flattened cross section
Moment of inertia, X-X axis (I_{xx})	18986 mm^4	34.87 mm^4
Elastic section modulus (W)	999.26 mm^3	36.70 mm^3
Plastic section modulus (Z)	1304.35 mm^3	55.05 mm^3
Elastic moment (M_e)	197.85 N.m	7.27 N.m
Plastic moment (M_{pl})	258.26 N.m	10.90 N.m

The differences between both cross-section configurations reinforce the importance of controlling eventual eccentricities and initial imperfections of the structural elements. Regarding the first of these factors, it could be overcome by the design of spacers at the truss connections, as suggested by Bezerra *et al.*[5], for example. The second one is intrinsically associated with the manufacturing control technology and handling of the steel bars.

The flattening process usually reduces drastically the compressive strength of structural elements. On those related to this research, a comparison between the end-flattened and original steel bars is conducted. From the experimental perspective, the average strength capacity of the sample was determined in 7.4 kN. On the other side, according to the brazilian normative standard ABNT NBR 8800:2008 [8], the steel bars with their original circular hollow cross-sections present a strength in the order of 17.0 kN. This modification on the steel bars results then in a significant loss of over 50% of their compressive strength.

In three-dimensional trusses composed by end-flattened steel bars, these members present two probable modes of failure, namely the overall flexural buckling or the excessive deformation of the transition zone of cross-sections. Observing the results obtained in the experimental tests, it becomes evident how the second mode prevails between both alternatives listed. The behavior of the specimens agrees with the conclusions of the research conducted by Dundu [7], in which the related phenomenon was dominant in situations where the truss elements presented a large diameter-to-thickness ratio and low strength steel.

The numerical processing of the structure with the described settings was carried out for the various loading levels. In order to observe the stress field produced in each case and simultaneously adopt a comparative reference criterion, the Von Mises equivalent stress was used as a parameter in this study, being widely used in the analysis of steel structures according to Hansen [9]. The set of simulation results is summarized in Figure 7.

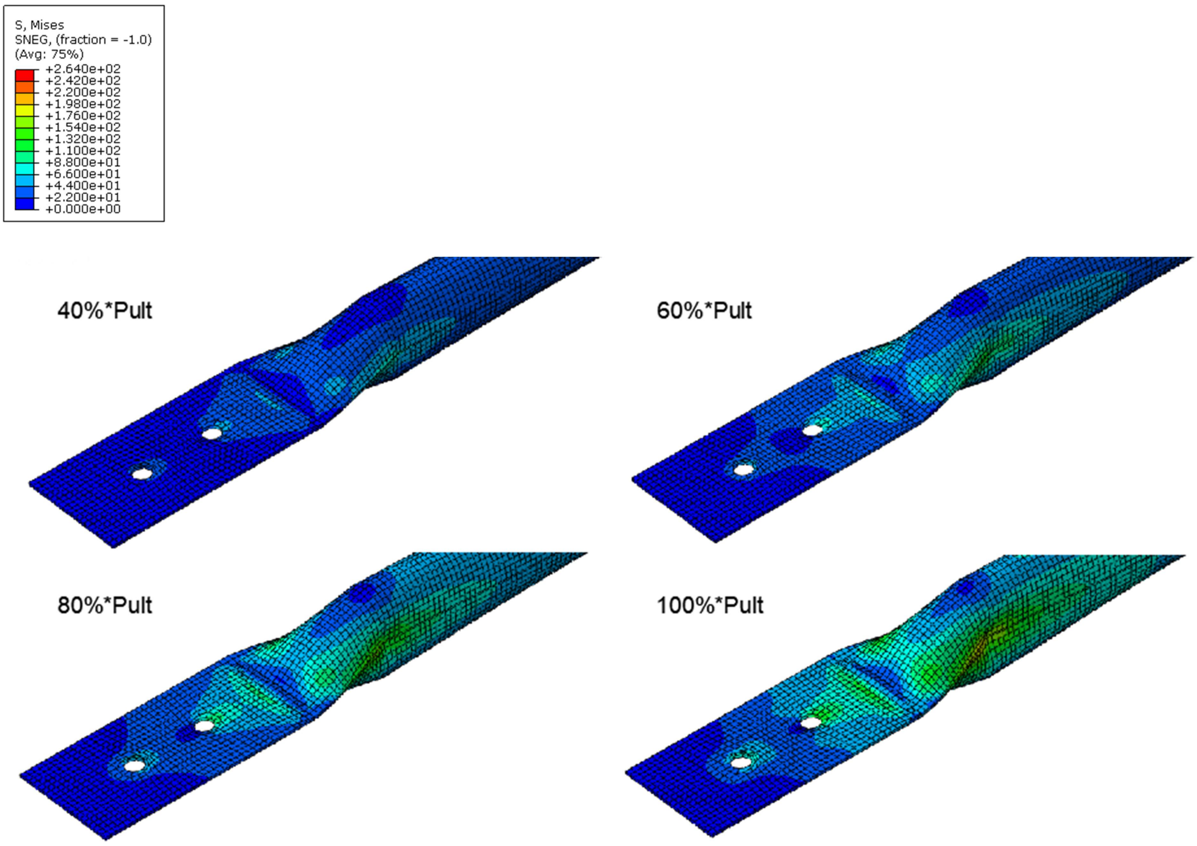


Figure 7. Variation of the stress field during the loading of the end-flattened steel bar

To obtain the results presented, a magnification factor of displacements of 1.0e(+ 2.0) was applied, and a single stress scale was defined for all analyzes. On this scale, the upper stress limit was that related to the ultimate strength of the material, which is presented in Table 1.

The stress concentration in the transition region of the cross-sections is notorious from lower loads until the ultimate load, which shows the effect of reducing stiffness promoted by the process of flattening the ends of the bars. This phenomenon is initially manifested at the ends and sides of this region and, as the load reaches higher levels, the tensions are distributed in a significant proportion also to its upper part.

As for the region close to the bolt holes, in which the load flows from the press actuator to the structure of the flattened bars, the expectation of observing a stress concentration is realized in the numerical results exposed. It is also worth mentioning the difference in the intensity of load transmission between the internal and external holes. The first is significantly more stressed, as shown in detail in Figures 8 and 9.

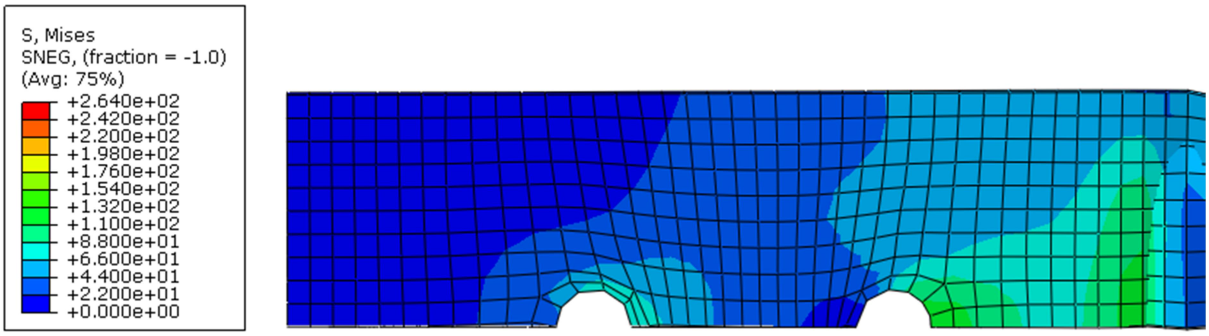


Figure 8. Stress concentration due to the ultimate load in the region close to the bolt holes

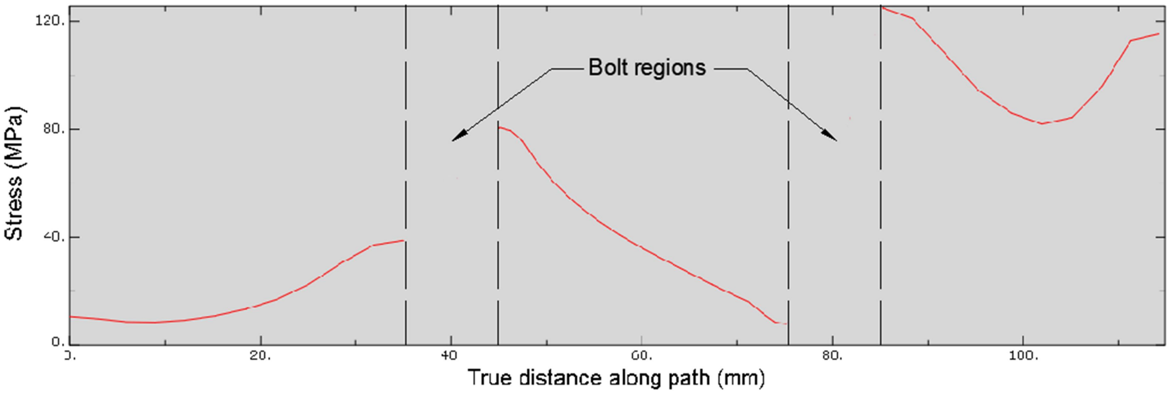


Figure 9. Stress distribution due to the ultimate load along the longitudinal path passing through the bolt holes

In regions where the stresses have reached maximum levels, especially at the stage where the entire compressive load has been applied, it is noted through the deformation of the structural element that local instabilities tend to manifest prominently. Such results are corroborated by those obtained experimentally, whose general aspect of the deformation of the bars showed a behavior similar to that of numerical simulations.

4 Conclusions

The application of end-flattened steel bars in three-dimensional trusses is in fact a simple and efficient alternative for the design of several structures. However, the experimental data and numerical results presented by this research show the singular effects of the reduced stiffness that these elements present. The development and distribution of the stresses during the loading process was explored, especially with regard to the excessive concentration of stresses near the flattened region and its associated local instabilities. Thus, the need to develop more studies that seek to characterize its structural behavior is here reiterated, in order to stimulate the institution of specific normative criteria and the assistance in the economic and safe conception of future projects.

Acknowledgements. The authors would like to thank the University of Brasilia for making its resources and facilities available for conducting this study.

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, or has the permission of the owners to be included here.

References

[1] V. Precupas, A. Ivan and M. Ivan, “Dynamic Analysis of the Dome with Arches and Rings from Romexpo Bucharest”. *International Journal of Civil and Environmental Engineering*, vol. 6, n. 9, pp. 1–6, 2012.
[2] R. Martin and N. J. Delatte, “Another Look at Hartford Civic Center Coliseum Colapse”. *International Journal of Civil and Environmental Engineering*, n. 6, pp. 246-251, 2012.
[3] V. Alegre, V. Ródenas and S. Villalba, “Colapso de la cubierta metálica de un polideportivo; patologías singulares y recurrentes”. *Rev. ALCONPAT*, n. 2, pp. 37–45, 2012.
[4] Space Frame Roofs Collapse Hartford Coliseum Following Heavy Snowfalls; ENR: New York, NY, USA, 1978
[5] L.M. Bezerra; C.A.S. De Freitas; W.T. Matias; Y. Nagato, “Increasing load capacity of steel space trusses with end-flattened connections”. *Journal of Constructional Steel Research*, n. 65, pp. 2197-2206, 2009.
[6] C. H. Maiola, and M. Malite, “Análise Teórica e Experimental de Treliças Metálicas Espaciais Constituídas por Barras com Extremidades Estampadas”. *Cadernos de Engenharia de Estruturas*, São Carlos, n. 20, pp. 105–125, 2002.
[7] M. Dundu, “Effect of flattening circular hollow sections in truss and dome structures”. *Thin-Walled Structures Journal*, vol. 80, pp. 57–65, 2014.
[8] ABNT NBR 8800:2008: Design of steel and composite structures for buildings. Associação Brasileira de Normas Técnicas (ABNT), 2008.
[9] T. Hansen. Theory of Plasticity for Steel Structures – Solutions for Fillet Welds, Plate Girders and Thin Plates. PhD thesis, Technical University of Denmark, Birch & Krogboe A/S Consultants ans Planners, 2006.