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Structural assessment of lattice steel towers used in power transmission lines

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Abstract. The lattice steel towers have been widely used as supports for overhead power transmission lines. These towers have become essential elements to the transmission systems and their stability contributes to a better functioning and electrical safety. In this research work, a three-dimensional latticed structural system, composed by primary and redundant members was adopted to represent the steel towers. In current design practice, redundant members are not included in the finite element models and a linear analysis is performed for the structural design. Considering this methodology, several design recommendations indicates that the forces acting on the redundant members can be up to 2.5% of the forces on the primary elements (main elements). Therefore, the main objective of this investigation is to develop an analysis regarding the redundant member's structural behaviour of lattice steel towers used in power transmission lines, having in mind the assessment of the forces, as well as the design on these elements. Hence, five different steel towers associated to a 500 kV transmission line were investigated and a nonlinear analysis was performed aiming to determine the forces values acting on the redundant members and comparing with those calculated according to the design standards (linear analysis). The global structural behaviour related to the redundant elements failure was also studied, as well as the influence of the angle between the members, having in mind the forces values. The results obtained along this analysis have shown relevant quantitative differences between the forces values established by the design standards and those calculated through a nonlinear analysis based on finite element models.

Keywords: steel lattice towers, power transmission lines, nonlinear analysis.

1 Introduction

Lattice steel towers are widely used as supports for overhead power transmission lines. These towers have become essential elements to transmission systems and their stability contributes to the systems' overall performance and electrical safety [1].

In general, a three-dimensional latticed structural system is used for lattice towers, composed by primary and redundant members. The primary members (main members) make up the tower silhouette, baring the highest percentage of the imposed loads, forming the triangulated system, carrying the loads from their application points to the foundation system. Regarding the redundant members, their function is to provide intermediate bracing points to the primary members, therefore, increasing capacity for compression to the latter, resulting in a reduction of primary members unbraced lengths [2].

In current design practice, lattice steel towers used in power transmission lines are currently analysed using a first-order elastic structural analysis, which assumes that the loaded configuration of the structure is practically identical to its unloaded configuration. Therefore, the secondary effects of the deflected structure are ignored and the forces in the redundant members are equal to zero, as a consequence, these members do not need to be included in the finite element models. [3].

In a second-order elastic structural analysis, structural displacement could produce forces on the elements in addition to those obtained in a first-order elastic analysis. Therefore, a second-order elastic analysis may show redundant members are subjected to additional forces [4].

According to the methodology presented in the standard ASCE 10 “Design of Latticed Steel Transmission Structures” [3], redundant members may be subjected to forces between 1.5% to 2.5% of the maximum load of the primary member it supports; the methodology describes three different analysis methods based on post buckling member behaviour models.

Method 1 assumes that the redundant member is capable of carrying compression forces on a geometrically buckled configuration (Figure 1-a), method 2 assumes that redundant members do not carry forces on a geometrically buckled configuration (Figure 1-b) and method 3 assumes that the redundant members are capable of carrying reduced forces on a geometrically buckled configuration (Figure 1-c).

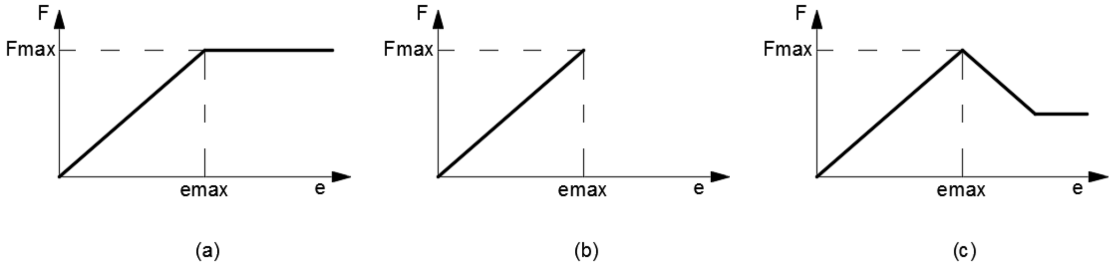


Figure 1. Methodology used to model post buckling behaviour of redundant members [3].

The improper design of redundant members may cause failures in the primary members or even a structural collapse. Figure 2 shows three different cases of structural failures due to failures in redundant members, which, after buckling, did not perform their structural function of lateral containment (bracing) of the primary members, resulting in an increase in buckling length and subsequent failure of these elements [5].

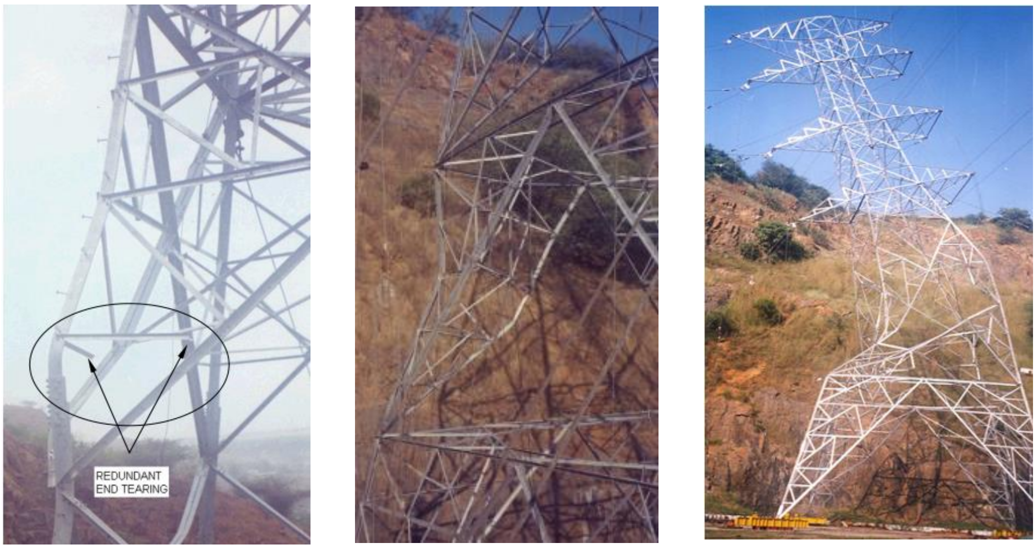


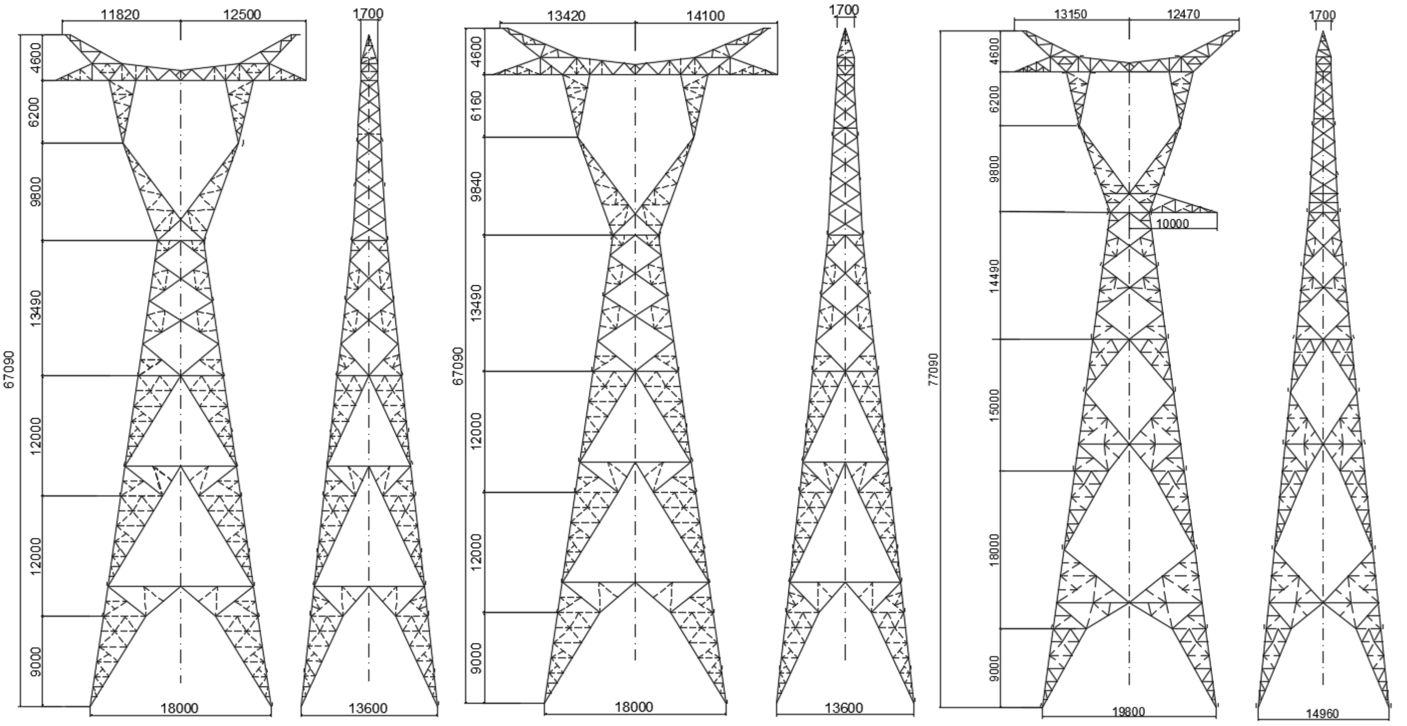
Figure 2. Structural failures in lattice steel towers [5]

Therefore, the main objective of this study is to develop a technical analysis regarding the behaviour of redundant members of lattice steel towers to assess the forces acting on redundant members compared to the expected forces indicated in the ASCE 10 standard [3].

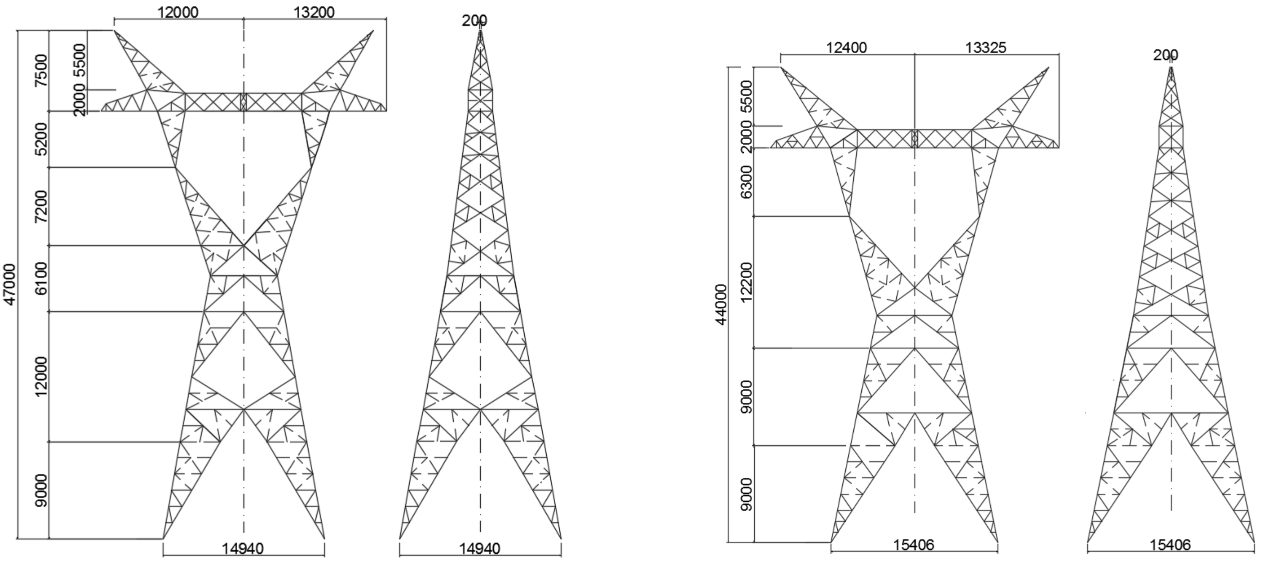
Five different steel towers associated with a 500 kV transmission line, simple circuit, were analysed, and a nonlinear structural analysis was performed to determine the values of the forces acting on the redundant members and then comparing them with those calculated according to the design standards (linear analysis). Additionally, structural behaviour was also analysed when redundant member failure occurred, as well as the influence of the angle between the members, taking into account force values.

2 Investigated structural models

The analysed structural models were extracted from a series of towers, composed of five self-supporting structures, applied in a 500 kV transmission line, simple circuit, located in the northeast region of Brazil, covering 260 km. The studied structures have a truss structural system and comprise heights between 44 and 77 meters, as can be seen in Figure 3, the primary members are presented as continuous lines and the redundant members are presented as dashed lines, dimensions in millimetres. The cross sections of the towers have a square or rectangular base, a pyramidal body and a hollow configuration at the top, where phases and shield wires are fixed. Angle profiles and steel ASTM A572 grade 50 and 60 type were used.



a) Light suspension tower (SL) b) Heavy suspension tower (SP) c) Transposition suspension tower (ST)



d) Anchor tower (AA) e) Anchor dead-end tower (AT)

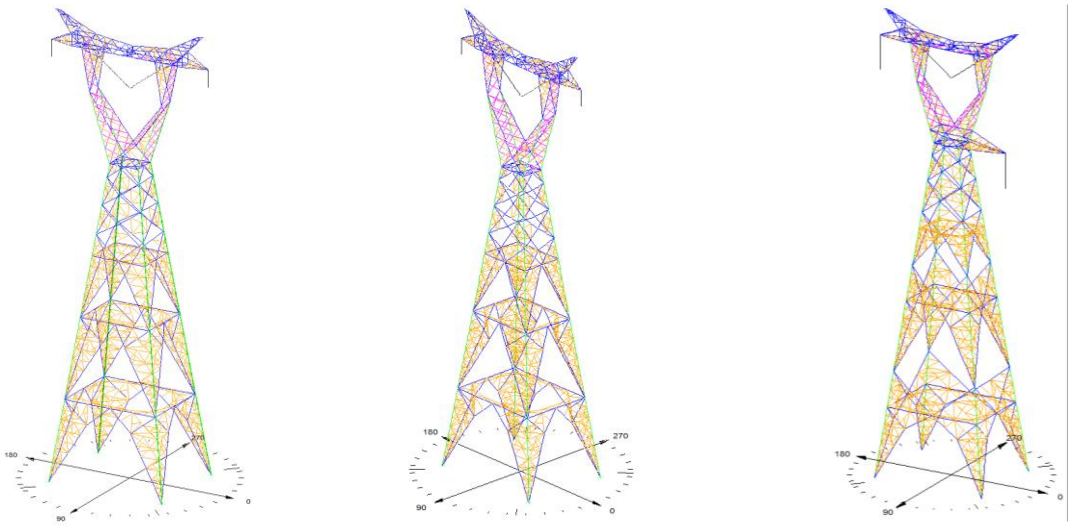
Figure 3. Structures investigated (dimensions in millimetres)

3 Finite element modelling

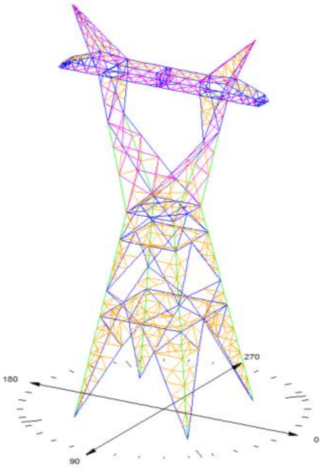
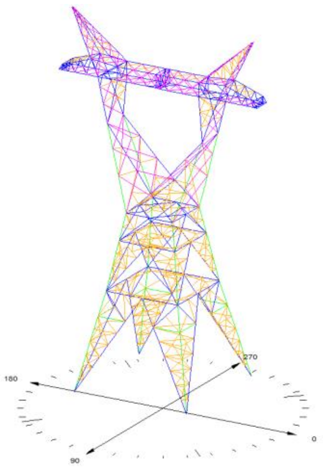
In this study, steel transmission towers were modelled using the Finite Element Method (FEM), using PLS Tower computational program, version 14.2. Beam finite elements BEAM (PLS TOWER, 2016) was used for modelling the tower legs and space truss elements TRUSS (PLS TOWER, 2016) was used to model the bracing elements. Figure 4 illustrates the towers finite element structural models and the main characteristics of each tower can be seen in Table 1. Boundary conditions were applied to the 4 nodes that represent the foundations of the towers, with restrictions for displacements and rotations in each of the three axes.

Table 1. Tower characteristics

Tower	Height (m)	Nodes	Elements	BEAM	TRUSS	DOF
SL	67.09	1083	2595	1646	949	6498
SP	67.09	1088	2607	1652	955	6528
ST	77.09	1011	2505	1489	1016	6066
AA	47.00	491	1289	802	487	2946
AT	44.00	460	1272	790	482	2760



a) Light suspension tower (SL) b) Heavy suspension tower (SP) c) Transposition suspension tower (ST)



d) Anchor tower (AA) e) Anchor dead-end tower (AT)

Figure 4. Finite element towers models

4 Structural analysis: second-order elastic analysis

Second-order elastic analysis was performed on the towers to determine the values of the forces acting on the redundant member and comparing the results with those calculated according to the design standards. For this, fourteen different load hypotheses were considered, based on the project used as a reference, which is a 500 kV transmission line, simple circuit, located in the northeast region of Brazil.

The load hypotheses considered are related to, not only the forces imposed by extreme winds (250 years, 10 minutes) acting in different directions (0º, 15º, 30º, 45º and 90º) on the structures, but also the rupture of conductors or shield wires, the construction and assembly of the towers, the action of thunderstorm wind (250 years, 3 seconds), acting at 0º, 15º, 30º, 45º and 90º on the towers and finally, the cascade effect that can occur with the collapse of adjacent structures.

Wind loads in structures, cables and other elements were defined by the standard IEC 60826 "Design Criteria of Overhead Transmission Lines" [6]. Loads from conductors and shield wires were applied to their attachment points, and wind forces imposed on the towers were applied to the centre of gravity of each of its wind panels, defined with a maximum height extension of 9 meters.

The standard ASCE 10 [3] states redundant members can carry loads between 1.5% to 2.5% of the load in the supported member, as mentioned earlier; Figure 5 is presented in order to show the number of redundant members belonging to each tower, and the number of redundant members baring forces greater than the values provided by the standard.

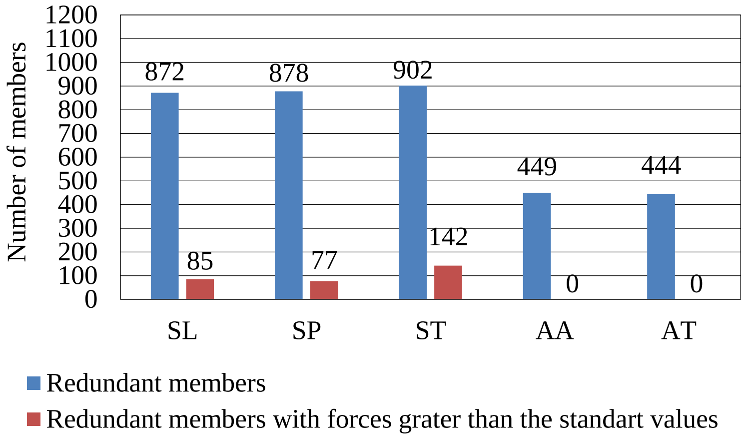


Figure 5. Force analyses in redundant members

Based on the presented results in Figure 5, it is possible to see that light suspension tower (SL), heavy suspension tower (SP) and transposition suspension tower (ST), respectively, presented 9.75%, 8.83% and 15.74%, of redundant members that are subjected to forces greater than the values provided by the standard. Anchor tower (AA) together with anchor dead-end tower (AT) did not present any redundant member subjected to forces greater than the values provided by the standard. The author's opinion is that the mentioned structures are less slender and more reinforced due to their structural configuration.

A redundant member for each structure was then selected, one which showed the greatest difference between the forces provided by the standard and that obtained by the finite element analysis. Another relevant aspect is the redundant member position regarding the overall structural stability. Figure 6 shows the position of the members studied.

The structural capacity of these elements was calculated according to the ASCE 10 [3], using method 2, assuming that a redundant member is not able to carry forces on a geometrically buckled configuration, thus not performing its structural function of lateral containment (bracing) of the primary members, resulting in an increase in buckling length of the latter.

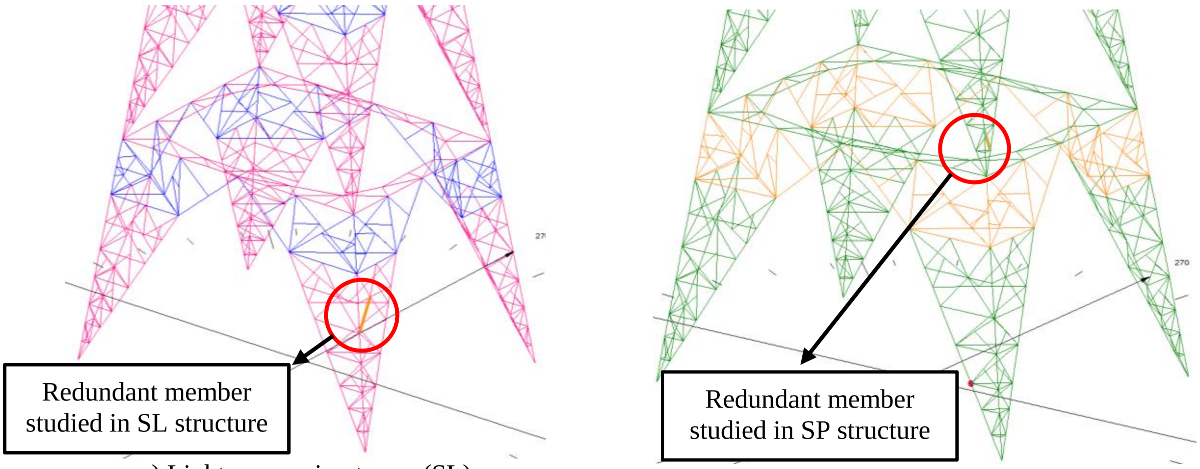
Table 2 shows the design and capacity forces of redundant members, as well as primary members braced by them.

It should be noted that, the redundant members with small angles, less than 20° in relation to the main members, present greater differences between the expected forces provided by the ASCE 10 [3] standard and forces obtained in the finite element analysis.

Table 2. Structural design of redundant and primary members

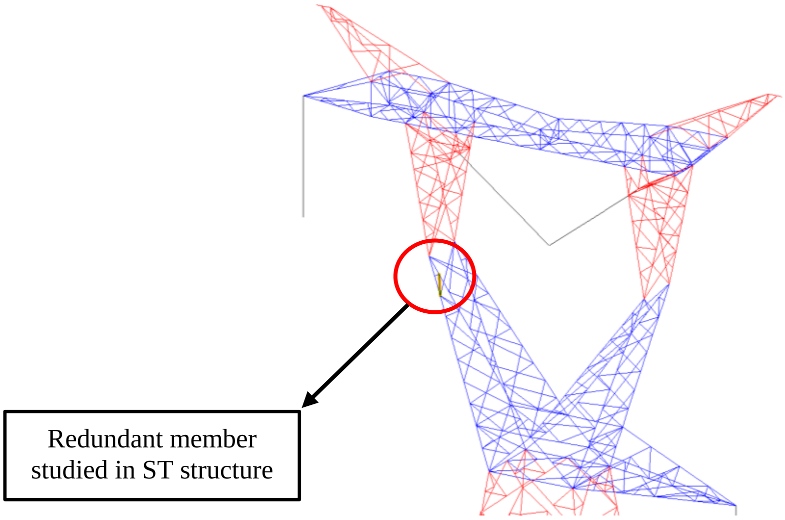
Tower	Redundant member design force (kN)	Redundant member capacity (kN)	Redundant member force ratio (%)	Primary member design force (kN)	Primary member capacity (kN)	Primary member force ratio (%)
SL	36	33	110	697	698	100
SP	44	24	185	787	839	94
ST	36	24	152	312	277	112

It can be seen from the results presented in Table 2, which for some cases, in addition to buckling of the redundant member, the buckling of the primary member can occur, causing damage to the structures or even causing collapse.



a) Light suspension tower (SL)

b) Heavy suspension tower (SP)



c) Transposition suspension tower (ST)

Figure 6. Redundant members analysed

The results obtained from this analysis have shown relevant quantitative differences between the values of the forces established by the design standards and those calculated through a nonlinear analysis based on finite element models. It is important to notice that the structural member's capacity analysis shows, in certain cases, in addition to the buckling of the redundant member, primary member buckling also occurs. It was also observed that redundant members with small angles, less than 20° in relation to the primary members, and present greater differences between the forces provided by the standard and obtained from the finite element analysis.

5 Conclusions

The final remarks are presented based on the investigated structural finite element models having in mind the second-order elastic analysis performed on five different types of lattice steel towers and the associated design verifications of primary and redundant members. This way, the following conclusions can be drawn from the results presented in this study:

1. The results obtained have shown relevant quantitative differences between the values of the forces established by the design standards and those calculated through a nonlinear analysis based on finite element models.
2. Based on the obtained results it is possible to see that light suspension tower (SL), heavy suspension tower (SP) and transposition suspension tower (ST), respectively, presented 9.75%, 8.83% and 15.74%, of redundant members that are subjected to forces greater than the values provided by the standard. Anchor tower (AA) together with anchor dead-end tower (AT) did not present any redundant member subjected to forces greater than the values provided by the standard. The author's opinion is that the mentioned structures are less slender and more reinforced due to their structural configuration.
3. It is important to notice that the structural member's capacity analysis shows, in certain cases, in addition to the buckling of the redundant member, primary member buckling also occurs. It was also observed that redundant members with small angles, less than 20° in relation to the primary members present greater differences between the forces provided by the standard and obtained from the finite element analysis.
4. This investigation indicated that the second-order elastic analysis is essential to understand structural behaviour, distribution of loads, design and overall stability of the structure. It is also recommended to avoid applying braces with small angles to the primary members so they can perform their function correctly.

Finally, it must be emphasized that there is an interest to further study the structural behaviour of redundant members, analysing the components related to the absorption of forces, allowing for optimization of the structure's geometry and also better understanding load distribution and structural behaviour.

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