

## COB-2023-1512 VULNERABILITY OF A GUYED LIGHTWEIGHT STEEL TOWER TO EXTREME LATERAL LOADS

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**Abstract:** *Lightweight structures exposed to strong earthquakes can experience significant displacements, vibrations, and plastic deformation accumulation, resulting in failure of critical components of the structure. To address the issues affecting the service life and ultimate limit state of these structures, this study proposes an initial evaluation of the vulnerability of tall steel structures to extreme lateral loads. The study proposes the use of a guyed metallic power transmission tower modeled in Abaqus to perform a Pushover analysis. Based on the pushover results, it is possible to estimate the damage limits for the given tower, addressing the significant gap in current standards and recommendations related to these limit states. Pushover analysis is utilized to identify failure mechanisms by analyzing the nonlinear behavior in the nodes of the elements, employing the perfect plasticity constitutive law to model steel properties. The study's results unveil the maximum strength of the tower in the Pushover analysis, providing insight into the structure's response to potential earthquakes. Additionally, the pushover analysis aids in defining the damage limits that can be employed when assessing the structural vulnerability to extreme seismic loads.*

**Keywords:** *Guyed tower, dynamic analysis, pushover.*

### 1. INTRODUCTION

Metallic power transmission towers play a fundamental role in the electricity supply infrastructure, enabling the safe and efficient distribution of energy by connecting long distances, such as consumption areas, to substations and power plants. In relation to the structural system, Chaves (2004) distinguishes the towers into two types regarding their structural system: self-supporting and guyed towers. The self-supporting towers are those whose equilibrium is ensured by their own structure, without the need for a substructure to contribute to their stability. The guyed towers are those that use tensioned cables anchored to the ground at their ends, which ensure the stability of the structure.

Abrupt vibration caused by the sudden release of energy accumulated by the deformation of the lithosphere, an earthquake propagates as seismic waves. Due to its manner of occurrence, earthquakes are considered transient phenomena, and the majority are of tectonic origin (Sánchez, 1994).

Earthquake engineering is an emerging area of study in the fields of civil engineering and geophysics, developed almost exclusively by English scientists in the 18th and 19th centuries, despite the fact that there were no major seismic activities in England, and it began to have major developments only during the 19th century 20 (Filiatrault et al., 2013).

Using the Abaqus software, which is excellent for performing finite element analyses, this article utilized this tool to predict the behavior of a metallic power transmission tower under dynamic earthquake loads, obtain natural frequencies, vibration modes of the structure, and pushover analysis. By analyzing the obtained results, it is expected to provide a contribution on the understanding of the behavior of this type of structure when subjected to extreme lateral loads as seismic events.

### 2. OBJECTIVE

The main objective of this paper is to conduct a comprehensive analysis of the structural response of a guyed power transmission tower, with a particular focus on utilizing pushover analysis. The key objectives are to determine and define the damage limit states for this specific type of structure, addressing a notable gap in existing standards and recommendations for these limits.

### 3. DESCRIPTION OF THE STUDY

### 3.1 Tower model

Using a structure adapted from the model used by Gani and Légeron (2010) according to Figure 1, the guyed tower was modeled with beam elements, and all nodes were labeled. The tower consists of a mast with a total height of 52.18 meters, composed of solid bars with a diameter of 6 centimeters. It is supported by four cables, each with a diameter of 22 millimeters, pre-tensioned at 120 MPa. The tower was meshed with 4520 elements, and the cables were subdivided into 20 elements each.

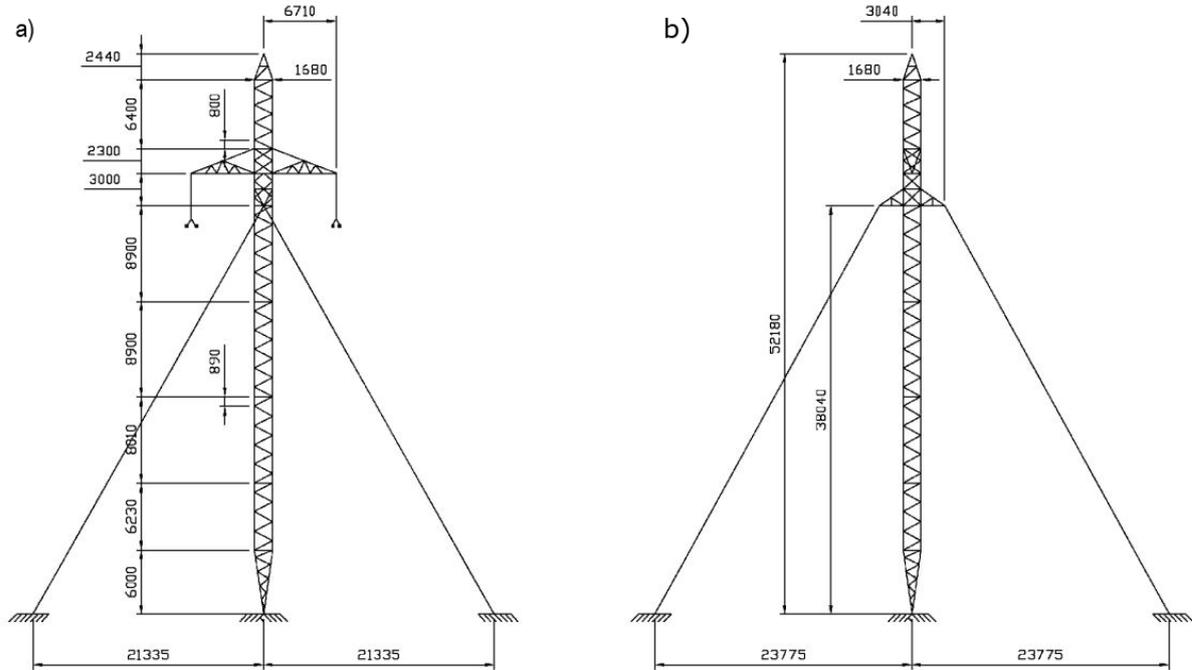


Figure 1. Tower model: a) transverse view; b) longitudinal view. All dimensions in millimeters.

The physical properties of the materials used to build the model, such as modulus of elasticity ( $E$ ), Poisson coefficient ( $\nu$ ) and density ( $\gamma$ ) are shown in Table 1.

Table 1. Physical properties of materials.

Physical properties	Tower	Cable
$E$ (GPa)	200	186
$\nu$	0.3	0.3
$\gamma$ (kg/m <sup>3</sup> )	7500	7500

### 3.2 Natural frequencies

The tower's natural frequencies and vibration modes were obtained through free vibration analysis in Abaqus. Table 2 presents the natural frequencies of the first five vibration modes.

Table 2. Natural frequencies.

Vibration mode	Natural frequency (Hz)
$f_1$	2.0186
$f_2$	3.145
$f_3$	4.211
$f_4$	5.4807
$f_5$	5.6877

Figures 2 to 6 graphically present the first five vibration modes of the natural frequencies shown in Table 2.

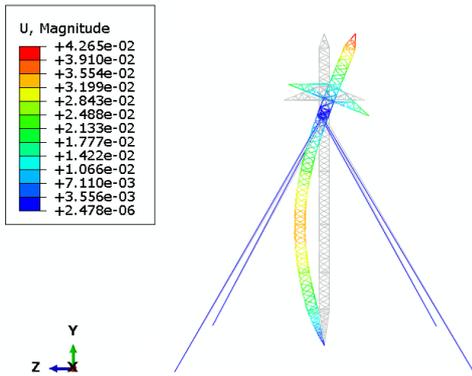


Figure 2. 1<sup>st</sup> vibration mode  $f_1 = 2.0186$  Hz.

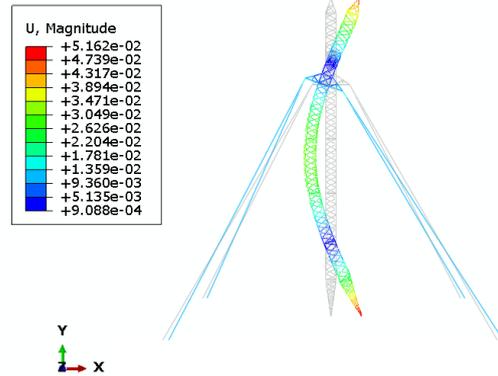


Figure 3. 2<sup>nd</sup> vibration mode  $f_2 = 3.145$  Hz.

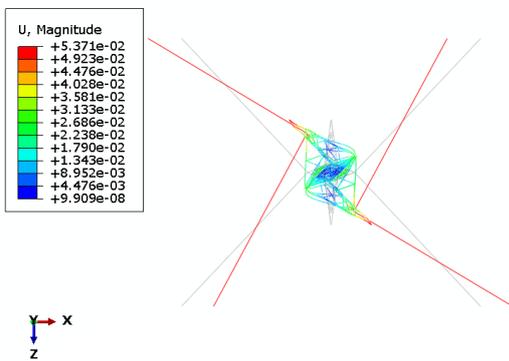


Figure 4. 3<sup>rd</sup> vibration mode  $f_3 = 4.211$  Hz.

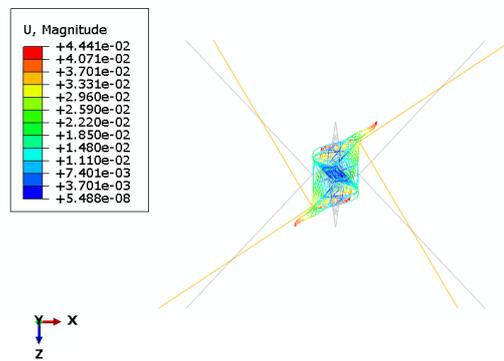


Figure 5. 4<sup>th</sup> vibration mode  $f_4 = 5.4807$  Hz.

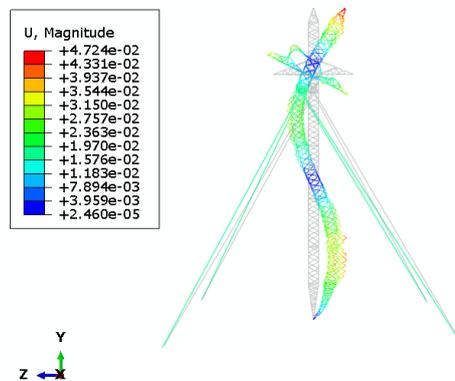


Figure 6. 5<sup>th</sup> vibration mode  $f_5 = 5.6877$  Hz.

### 3.3 Pushover analysis

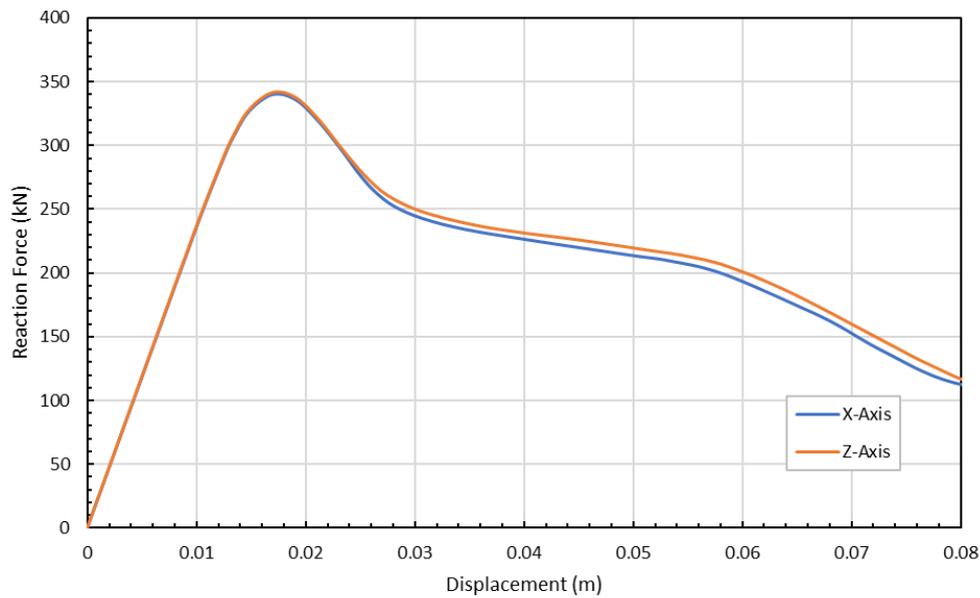
According to FEMA 356, the Nonlinear Static Procedure, often called pushover analysis, uses simplified nonlinear techniques to estimate seismic structural deformations. The analysis is performed by subjecting the structure to gravitational loads and a monotonic lateral loading of increasing pattern, representing the configuration of lateral loads acting on the structure. Due to the increasing lateral loads, the elements start to yield sequentially, resulting in a stiffness reduction at each step. This fact leads to the analysis being also known as a sequential yield analysis (ASCE, 1996).

The pushover analysis aims to assess the expected performance of the tower. It estimates the force demands and deformations caused by earthquakes through an inelastic static analysis, and then compares these results with the available capacities of the structure. The analysis provides an approximate demonstration of the internal force distribution that arises when the structure is subjected to inertial forces beyond the elastic range, which can no longer be resisted. (Krawinkler; Seneviratna, 1998).

In order to determine the most vulnerable direction to seismic events for the structure, pushover analysis was conducted in each direction. To perform the analysis, a uniform displacement of one meter was applied to all the nodes on the face under consideration, excluding the base node that is fixed to the ground.

#### 4. RESULTS

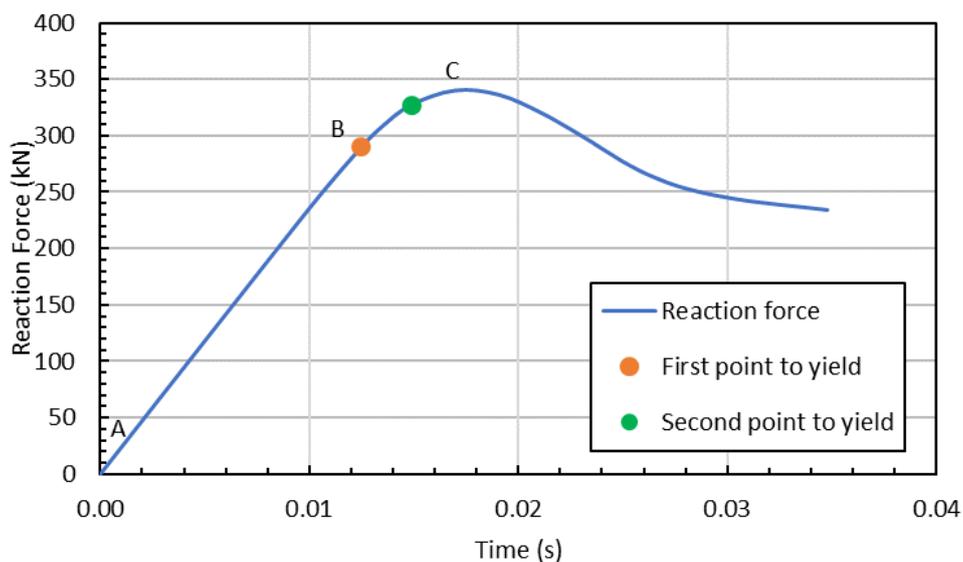
After applying the displacements in both directions, the Graph 1 was plotted, showing the displacement of the top of the structure on the X-axis and the sum of the reactions of the base nodes of the tower on the Y-axis for both cases.



Graph 1. Pushover curve.

Through the graph, the peaks of the reactions generated in the structure were identified, with the X-axis showing reactions of approximately 340 kN, and the Z-axis obtaining reactions of 341.5 kN. Consequently, it was determined that the X-axis is the most susceptible direction to seismic forces in the structure.

The displacement for the Pushover analysis was applied over one second, and Graph 2 indicates the initial time instants for the analysis in the X-axis, when the elements started to undergo yielding.



Graph 2. Reaction force over time.

In Graph 2, the segment between points "A" and "B" corresponds to the linear elastic part of the structure. Point "B" indicates the yield point of the steel bars of the tower. The segment between points "B" and "C" represents the deformation due to stiffness loss and hardening. Point "C" indicates the ultimate capacity of the structure, and beyond that, the structure experiences a loss of strength according to FEMA 356. Figures 7 and 8 indicate the first two bars that underwent yielding.

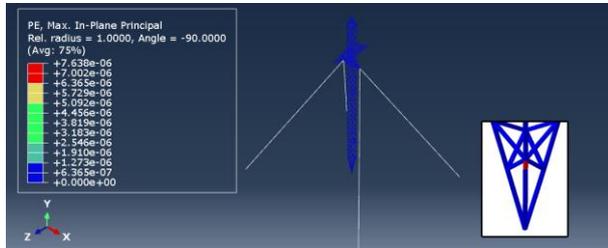


Figure 7. First point to yield.

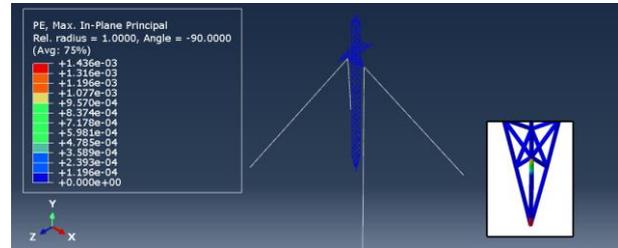


Figure 8. Second point to yield.

In the first point, yielding occurs at a time instant of 12.5 milliseconds, corresponding to a displacement of 12.5 millimeters. The second point undergoes yielding at 14.84 milliseconds, with a displacement of 14.84 millimeters. At the end of the Pushover analysis, after applying the entire displacement, the deformed shape of the structure was as shown in Figure 9, the figure is scaled three times larger to allow for a clearer visualization of the deformations.

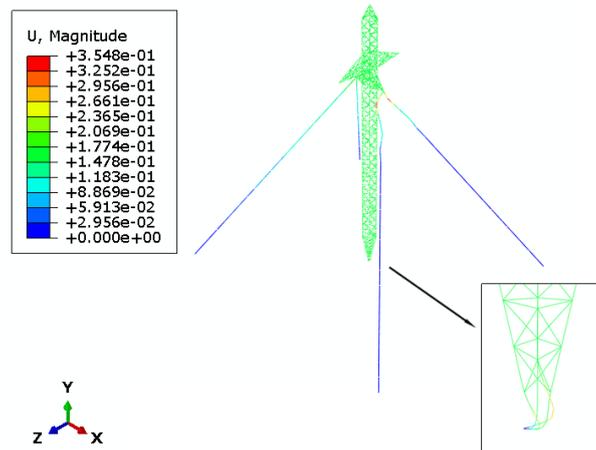
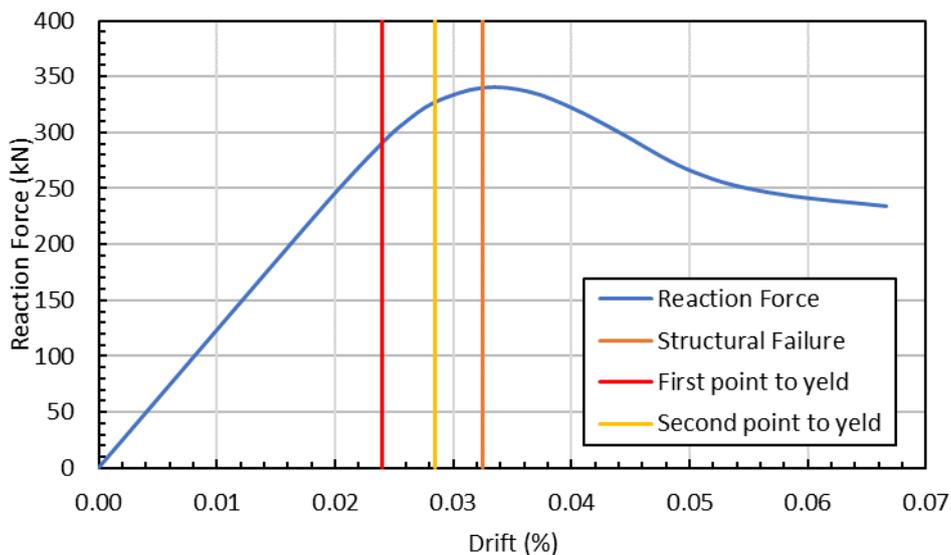


Figure 9. Deformed shape of the structure at the end of the Pushover.

The subsequent steps for assessing the seismic vulnerability of this type of structure involve conducting Incremental Dynamic Analysis (IDA), in which dynamic analyses are performed using a set of seismic acceleration time histories to induce vibrations in the structure. In the post-processing of the incremental analysis, it becomes possible to calculate fragility curves that provide the probability of the structure exceeding a specific damage state when subjected to earthquakes of a certain intensity. To calculate these fragility curves, it is initially necessary to define damage states that represent different limit states, ranging from the interruption of the tower's operation and usage to its complete collapse. The definition of these damage states is typically derived from the results of pushover curves, as evaluated in this paper. Consequently, three damage limit states were defined based on the lateral drift observed in the pushover curves, representing Uninterrupted communication, Communication failure, and structural collapse, respectively.

Graph 3 shows the limit states that were defined from the pushover analysis, where the drift was calculated as the ratio between the top displacement and the total height of the tower. As the first point starts to yield, the drift value is 0.024%; for the second point, it is 0.028%; and for the maximum strength, determining the failure of the structure, the drift was 0.032%.



Graph 3. Limit states produced as a result of pushover analysis.

## 5. CONCLUDING REMARKS

In conclusion, the Pushover analysis revealed that the X-axis is the most vulnerable direction to seismic forces in the structure, with reactions reaching approximately 340 kN. Graph 2 showed the initial time instants of yielding for the X-axis, with the first two points yielding at 12.5 milliseconds (12.5 mm displacement) and 14.84 milliseconds (14.84 mm displacement). The deformation pattern of the structure after the Pushover analysis was illustrated in Figure 9. From the pushover analysis, it was possible to identify the limit drifts that could be used in the future as damage limit states when obtaining fragility and seismic vulnerability curves for the studied tower. It is worth noting that the tower's foundation, being connected to the ground at a single point, proved to be the most vulnerable part of the tower when assessing its response to lateral loads. It can be anticipated that this tower model exhibits limited ductility under lateral loads because the failure of isolated elements near the base of the tower has the potential to induce the global structural collapse of the entire structure. For this reason, it is observed that the damage limits based on drift, as found from the pushover curve, were much lower than those observed in previous studies (Bilginer, O. et al., 2023), indicating the fragile behavior of the structure, which collapses under low levels of lateral displacement.

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