Influence of Guy Rupture and Plasticity on the response of Guyed Telecommunication Towers

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Abstract. A large number of tall guyed towers consisting of a mast laterally supported by pretensioned cables have been recently built due to an increasing demand for taller antenna towers. The cables act as a supporting system, increasing the towers critical load and natural frequencies. Their influence depends on the number of guy levels and the distribution setup. However, many accidents have been reported involving guyed towers, being cable rupture one of the frequent causes of structural failure. Here, the sudden rupture of one or two, arbitrarily selected, cables on the linear and nonlinear response of the guyed tower under static and dynamic loads is investigated. Also, the elastoplastic behavior of the mast and cables is taken into account. For this, models consisting of a mast supported by different cable set ups are investigated. The analysis is conducted using the finite element software ABAQUS. The mast is modelled using three-dimensional beam-column elements and the cables using tension only truss elements. Thus, the tower-cables interaction leads to a highly non-linear behavior under static and dynamics loads. First, the critical load and natural frequencies of the structure are determined for the intact structure and for configurations missing one or two cables. Coincident buckling loads and vibration frequencies are observed due to the symmetric cable distribution around the tower. This symmetry condition may lead to interactive buckling and internal resonances, increasing the effect of the nonlinearities on the response of the structure. Then the nonlinear post-buckling behavior is studied using the Riks method and the influence of rupture and plasticity on the tower load carrying capacity is evaluated. Finally the influence of cable rupture and plasticity on the free and forced vibrations of the tower is investigated.

Keywords: Guyed towers, cable rupture, elasto-plastic behavior, buckling and post-buckling behavior, nonlinear vibrations.

1 Introduction

In the recent history, society has experienced many events and changes that promoted social, political and economic impacts. In the mid 20th century, the third industrial revolution has occurred with the development of electronics, information technology and telecommunications. Nowadays, it is said that we are living the fourth industrial revolution, also called Industry 4.0. The new revolution is driven by artificial intelligence, big data, data mining and internet of things, making electronic devices more and more connected to the internet over the years. This industrial revolution makes use of broadcast transmission which requires high transmission towers. A structural alternative to make this happen is guyed towers. These towers are subjected to many environmental events and even terrorism that can lead to oscillations and occasionally to cable rupture. These conditions modify structural behavior and should be investigated to improve design practice and mitigate structural damage and, in worst cases, collapse.

Madugula [1], in his book, discusses many topics regarding the analysis and design of guyed towers, such as dynamics of cables and mast, nonlinear dynamics effects of cables, wind loads, seismic effects, being one of rare books to focus specifically on guyed towers. He also presents a detailed literature review. Recently, Marques [2], Pezo et al. [3] and Sequeira [4] studied in detail the nonlinear static and dynamic nonlinear behavior of guyed tower focusing on their stability, safety and nonlinear phenomena. In [2] and [4] a detailed literature review is presented, including research papers, design codes and practical considerations.

This paper has as main goal to improve the knowledge of the influence of nonlinearities on the static and dynamic behavior of guyed towers. For this, a finite element model using the software ABAQUS [5] is developed. In particular, this work investigates and quantify the effect of loss of one or more cables on the nonlinear response, safety and load capacity of the structure. Initially, it is evaluated the buckling loads and natural frequencies of the intact and damaged structure. In addition, the buckling and the post buckling behavior and imperfection sensitivity is investigated. Since the damaged structure leads to large displacements, the effect of plastification of the mast and cables is analyzed. Finally, the nonlinear dynamic behavior of the structure is analyzed using times responses, phase space projections, Fast Fourier Transforms and spectrograms. The effect of plasticity on the nonlinear vibrations is also analyzed. The results show the strong influence of the loss of one or more cables on the response of the guyed tower.

2 Guyed tower model

This model is composed by a mast with cables defining three symmetry planes. There are two levels of cables in each plane. Two configurations are considered for the cables: fan and parallel. In this model, there is one inferior cable missing. Figure 1 shows a model sketch of the guyed tower. The mast is 100 m high, and has a circular tube section with the external radius R 0,5 m and wall width of 0,025 m. It is made of steel of density 7.850 kg/m³, elasticity modulus equal to 2,1 . 10^{11} N/m² and Poisson coefficient of 0,3. The mast is fixed at the base and free at the top. It is modelled with three dimensional beam-column elements with a quadratic formulation, using the software ABAQUS [5]. The steel cables have a circular section with radius equal to 48 mm. Cable density is 7.850 kg/m³, elasticity modulus equal to 1,3 . 10^{11} N/m² and Poisson coefficient of 0,3. Cables are hinged at base and mast link. They are modelled as three-dimensional linear truss elements. Cables are prestressed in order to prevent from loosening, carrying a force of 125,0 kN each.

Elastic-perfectly plastic material behavior is considered for mast and cables. The mast has a uniaxial yield stress of 250 MPa and the cables of 690 MPa. Figure 2 shows the behavior of these materials.

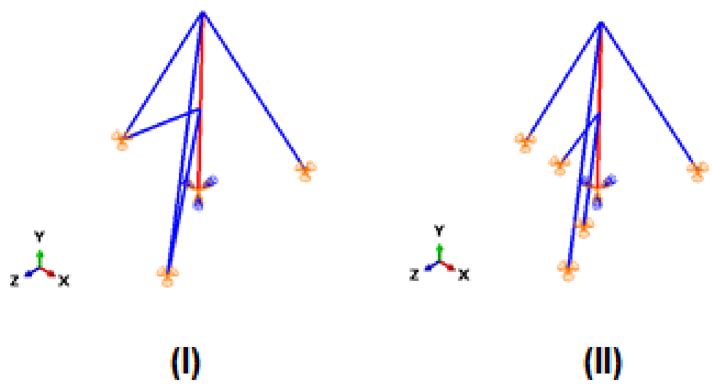

Figure 1. Model sketch without one inferior cable, fan (I) and parallel (II).

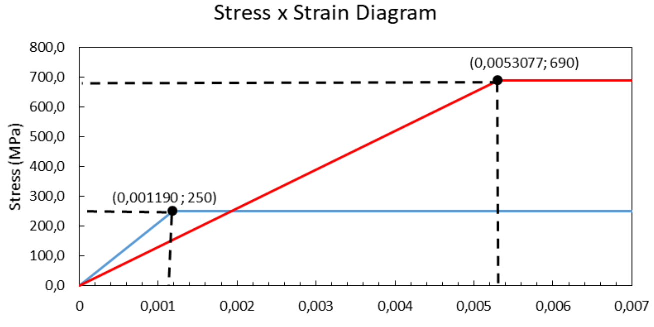

Figure 2. Stress x strain diagram of the materials.

3 Linear Analysis

First, a study of the global equilibrium of the model is carried out, considering the self-weight of the structure and the pre-stress tension in the cables, in order to determine the initial equilibrium position to be used in the following steps. Then, the critical load and natural frequencies of the structure are determined.

Table 1 shows the buckling loads and vibration frequencies in the model of tower without one inferior cable, in comparison of the tower with all cables. In first, we noticed that, as the symmetry disappear, the buckling loads and natural frequencies don't occur in pars, as it is seen in the original model. Also, the loss of a cable shows a decrease in the value, explained by the decrease of the stiffness of the structure. Another consideration is that the model with fan cable geometry presents value higher buckling loads than the alternative with parallel cables.

Table 1. Buckling loads and vibration frequencies of original model and model without one inferior cable.

Mode	Fan				Parallel			
	Buckling Load (kN)		Vibration Frequency (Hz)		Buckling Load (kN)		Vibration Frequency (Hz)	
	Original	Without 1 Inferior Cable	Original	Without 1 Inferior Cable	Original	Without 1 Inferior Cable	Original	Without 1 Inferior Cable
1	9214,75	8719,50	0,9680	0,8167	9055,48	8178,20	0,9120	0,7099
2	9214,75	9243,60	0,9680	0,9695	9055,48	9249,68	0,9120	0,9188
3	21622,90	18183,00	1,5891	1,2756	20994,90	15239,70	1,3993	1,2269
4	21622,90	21694,90	1,5891	1,6020	20994,90	21329,90	1,3993	1,4215

Figure 3 shows the configurations of the first mode of buckling load of the model without one inferior cable, in the geometry fan and parallel.

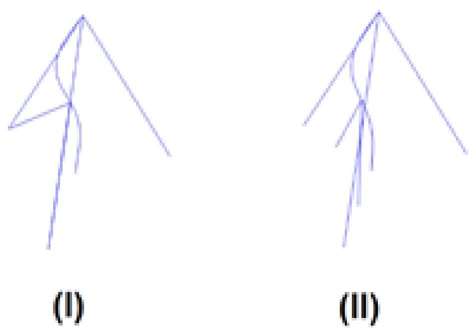

Figure 3. Configurations of the first mode of buckling load of the model without one inferior cable, fan (I) and parallel (II).

4 Static Nonlinear Analysis

Static nonlinear analyses follow, including post-buckling behavior and elasto-plastic material response. Under such conditions the tower load carrying capacity is evaluated. The post-buckling behavior is obtained using the Riks Method. Geometric imperfections are usually adopted in this kind of analysis. Here, the concept of modal imperfection is used. In order to facilitate the understanding of the graphs, a parameter α is adopted, Equation 1, where P is the load, L is the length of the mast, E is the elasticity modulus and I is the inertia momentum.

$$\alpha = \frac{PL^2}{EI} \tag{1}$$

Figure 4 shows the post critical behavior of the model missing one inferior cable for material elastic behavior and modal imperfection of 100%; results for the models with all cables are compared. It shows that the loss of a cable reduces considerably the value of the critical load. For example, the critical load of the type fan model when one lower cable is missing (Plim=2328,21 kN, α = 12,4) is 52% of the critical load of the original model (Plim=4461,01 kN, , α =23,35). The curves show an instable bifurcation, reaching a limit point followed by an expressive stiffness drop, indicating sensitivity to imperfections.

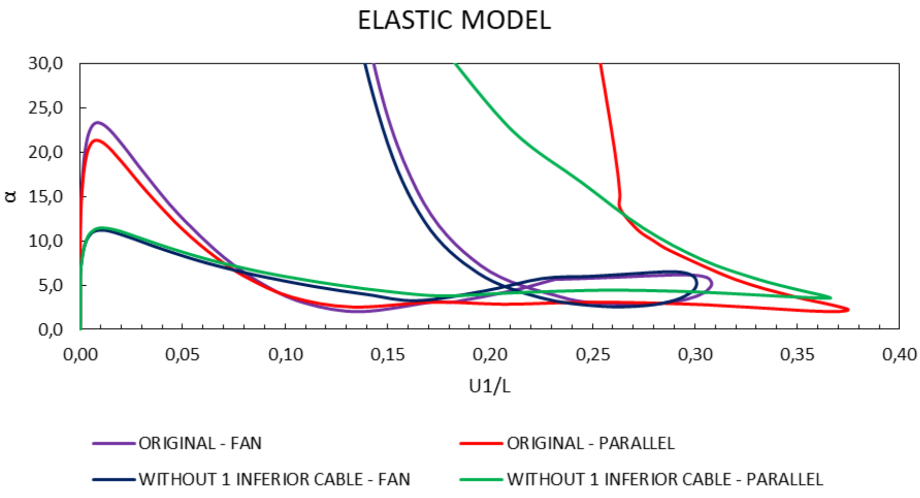

Figure 4. Post buckling behavior of the model without one inferior cable, elastic material – Modal Imperfection 100%

Figure 5 shows the post buckling behavior of the model without one inferior cable, both elastic and elastoplastic materials. It shows that, when elastoplastic material response is adopted, there is a decrease in the value of the critical load. For example, the critical value of the model, type fan and elastic material (Plim=2328,21 kN) has a decrease of 20% when elastoplastic material behavior is considered (Plim=1868,15 kN).

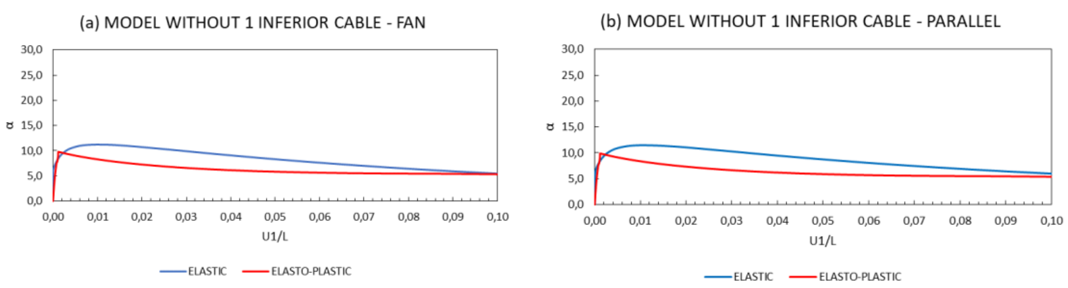

Figure 5. Post buckling behavior of the model without one inferior cable, elastic and elasto-plastic material behavior, fan (a) and parallel (b) cable geometry – Modal Imperfection 100%.

5 Dynamic Nonlinear Analysis

The main objective of this section is to understand the nonlinear dynamic behavior of the guyed tower and the effect of a missing cable. The analysis follows under forced damped vibration. A harmonic line load is applied along the mast, in direction X, defined by a load magnitude F_0 and excitation frequency Ω close to the structure resonance (Equation 2):

$$F(t) = F_0 * \sin(\Omega t) \tag{2}$$

The Newmark-β integration method is adopted with parameters alpha = 0, beta = 0,03025 and gamma = 0,6, as recommended by Hilber et al. [6]. An important step is defining the damping attribute. Rayleigh proportional damping ξ is adopted with the value of 1%. The results are shown as displacements and velocities. Also, the Fast Fourier Transform and spectrograms are presented. Figure 6 shows the velocity x displacement in direction X for a load magnitude of 10 kN/m. It shows that, the model without one cable has values of velocity and displacement higher than the model with all cables and symmetry is lost. Figure 7 shows the Fast Fourier Transform and spectrogram for the same case. The highest peak corresponds to the first natural frequency of the structure, closer to the resonance frequency.

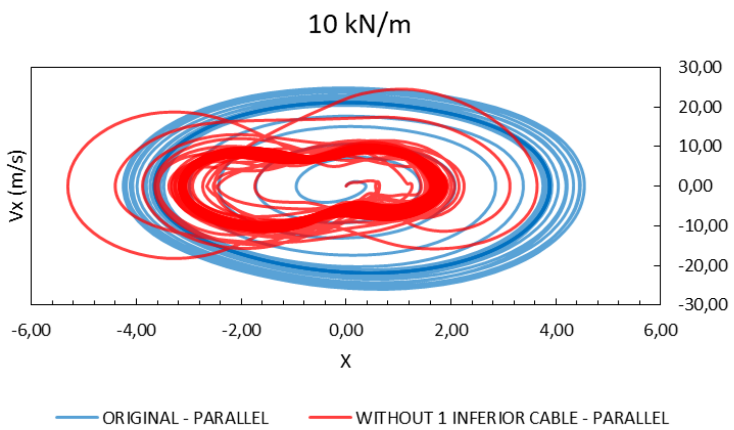

Figure 6. Forced vibration under harmonic load of amplitude 10 kN/m. Elastic behavior.

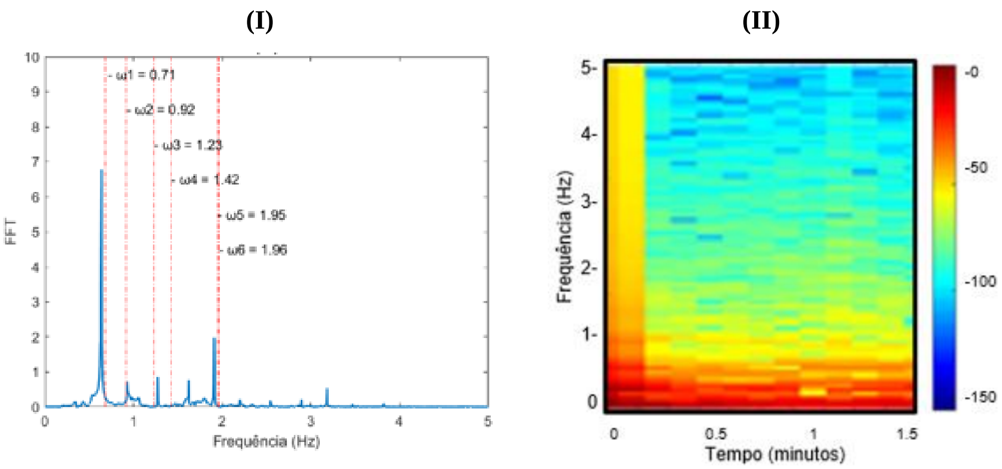

Figure 7. Forced vibration under harmonic load of amplitude 10 kN/m. Elastic behavior. Fast Fourier Transform (I) and spectogram (II).

To evaluate the effect of mast plastification on the dynamic behavior of the tower, the harmonic load amplitude was adopted as 20 kN/m. Figure 8 shows the von Mises uniaxial equivalent stress for the model without one inferior cable, limited by the yield stress of the mast (250 MPa).

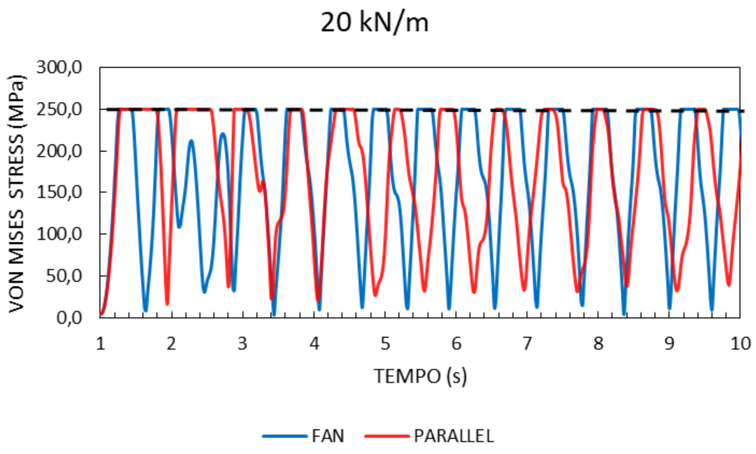

Figure 8. Forced vibration analysis. Elasto-plastic behavior. Von Mises stresses at the tower base.

6 Conclusions

Cable rupture produces a decrease in the buckling load and vibration frequency of the structure. The post-buckling behavior shows an unstable bifurcation mode and a minimum post critical value associated with large displacements. Also, it was observed that, as the modal imperfection increases, the buckling load decreases considerably. Regarding the non-linear dynamic behavior, it was shown that the increase in the magnitude of the load, increases considerably de values of displacements and velocities. In many cases chaotic motions are present, as detected by the Fast Fourier Transform. Finally, the consideration of the elastoplastic material behavior together with cable rupture produces interesting results, reducing the load capacity and safety of the structure. The results show that this kind of structure is highly sensitive to physical and geometric nonlinearities and cable rupture, indicating that these effects should be considered in the design phase of the tower.

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Authorship statement

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