Effect of the cable system on the static and dynamic stability of Guyed Towers

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Abstract. This paper aims at understanding the influence of the cable setup on the static and dynamic stability of the guyed towers. For such, simplified models consisting of mast and cables at different inclinations and guys level are studied. The effect of these structural characteristics is studied through a nonlinear finite element model. First, the influence of the configuration of the guys on the linear vibration frequencies and buckling load of the mast is investigated considering the initial deformations and internal forces due to self-weight and cable pretension. Coincident buckling loads and vibration frequencies happen for an even cable distribution around the tower. This symmetry condition may lead to interactive buckling and internal resonance, increasing the effect of the geometric nonlinearities on the response of the structure. Second, the nonlinear static and dynamic frequencies and buckling loads are determined for the different guys configurations. The results show that the towers exhibit highly nonlinear responses, even at low load levels. Thus, the geometric non-linear behavior must be considered in the design stage. In addition, the results indicate the necessity of further investigation of the nonlinear dynamic response of these structures for guys setup and mast dimensions used in actual towers.

Keywords: Guyed Tower, Natural Frequencies, Non-linear Vibrations, Post-critical Behavior.

1 Introduction

In the last years, the increasing use of guyed towers, mainly to support telecommunications and transmission antennas, has lead to structures that are slender and taller each day. However, these structures show high sensitivity to imperfections and stability control is still an engineering challenge. The number of accidents with partial or total tower collapse strengthens this statement. To deal with the highly nonlinear behavior of guyed towers, design codes with strong restrictions regarding displacements and behavior of these structures are required. Alternatively, nonlinear dynamic structural analyses can provide insight to a safer design of guyed towers.

This study presents a parametric investigation of the influence of physical and geometric characteristics of the cables on the natural frequencies and on the critical load of the structure. In addition, the paper discusses the effects of geometric nonlinearities on the static and dynamic structure response.

To take into account different tower models and loading conditions, finite element models are developed using the commercial software ABAQUS®. Different models of towers are idealized as frame systems, which are investigated under static and dynamic loads.

2 Synthetic model

This work investigates different types of stationary towers with a cylindrical central mast and multiple cables using the finite element method. Synthetic models are developed representing n a simplified way the main components of the structure.

2.1 2D Guyed Tower

The starting point of this study is the two-dimensional tower with one level of guys proposed in the work of Del Prado et. al. [1], [2]. The aim of this study is to gain insight into the post critical behavior of this type of structure.

Figure 1 presents the tower geometry and the finite element model. The column base is clamped in all directions and cable anchoring restricts the displacements in all directions. The discretization of the cables follows with 2D truss elements. The tower column is discretized using three-node 2D beam elements, each node having three degrees of freedom. Column and cable elements have constant cross section. The cable material is defined in such a way that it does not carry compression. Cables are submitted to initial tension, which is held constant throughout the analyses. The model properties are taken from Del Prado et. al. [1], [2] and are reproduced in Table 1.

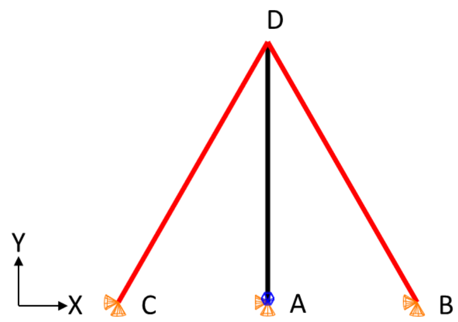

Figure 1: 2D Guyed Tower representative scheme

Table 1: Physics and geometrics proprierties of elementos of the bidimensional model of guyed tower

Properties	Circular tube column	Cable
Internal Diameter (D)	0,475 m	-
Outside Diameter (d)	0,500 m	1.8 E-02 m
Length (L)	100 m	115.47 m
Cross Section Area (*A*)	1,914E-02 m²	2.54E-04 m²
Inertia (*I*)	5,691E-02 m⁴	-
Young's Modulus (*E*)	1,18E+11 N/m²	1.0E+11 N/m²
Density (ρ)	7850 kg/m³	7850 kg/m³
Prestressing Force	-	10 kN

For this model, it is possible to notice a significant influence of the cables on the post-critical behavior with a sharp decrease in the load carrying capacity of the structure. The minimum post-critical load is associated with a fold bifurcation, Figure 2.

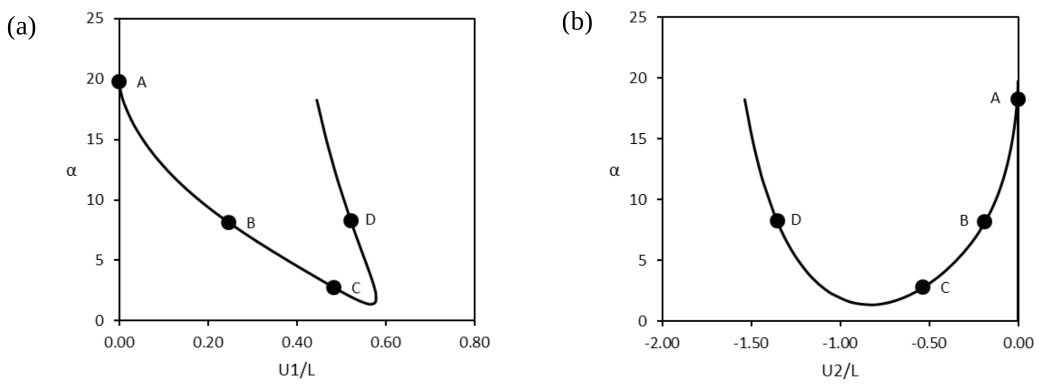

Figure 2: (a) Post-critical paths as a function of the lateral displacement. (b) Post-critical paths as a function of the vertical displacement

2.2 3D Tower model with one level of guys

The synthetic model of the 3D tower with one level of guys, identified here as reference model, is the base for the studies. In this model the cables are connected to the top of the column and are spaced equally defining an angle of 120º between each pair, resulting in three planes of symmetry. Figure 3 shows the model geometry and boundary conditions.

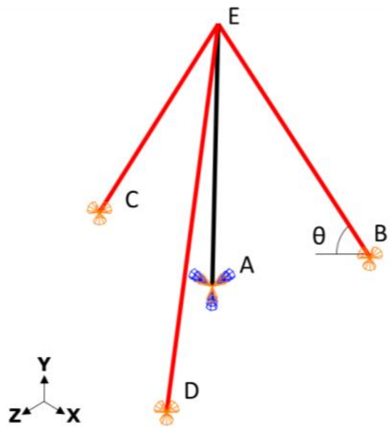

Figure 3: Guyed tower model with one level of cables.

The column is modeled with 3D beam-column elements with three nodes and six degrees of freedom per node. Cables are modeled with 3D truss elements with two nodes and three degrees of freedom each node. Inertial and damping effects are included in the formulation of the truss element. However, as in Guimarães et. al, [3], no hanging effects are considered. The initial tension in the cable follows the procedure recommended by CSA [4], and should be in the range 8% to 15% of its failure load. In this work, a pretension of 10% of the cable failure load is adopted.

As in the 2D model, self-weight is included in the analyses. The column is clamped at its base in all directions and cable anchoring prevents end displacements. The Table **1** provides the geometric and physical properties of the reference model.

Table 1: Geometric and physical properties of the reference model

Properties	**Tubular column**	**Cable**
External diameter (*D*)	0,95 m	-
Internal diameter (*d*)	1 m	-
Length (*L*)	100 m	115.47 m
Cross section (*A*)	7,658E-02 m²	2.84E-04 m²
Inertia (*I*)	9,105E-02 m^4	-
Young's modulus (*E*)	2,1E+11 N/m²	1.3e+11 N/m²
Density (ρ)	7850 kg/m³	7850 kg/m³
Failure load	-	-
Initial load	-	10% of failure load kN

2.3 Tower with multiple levels of guys

Four synthetic models with more than one level of guys are studied. Two of these models have two levels of guys, which divide the tower into two segments of equal length. These two models differ in the anchoring position of the cables to the ground and result in parallel and fan geometries. The other two models have three levels of guys, which divide the tower in three segments of equal length. Again, the parallel and the fan cable geometries are investigated. Figure 4 presents the four models.

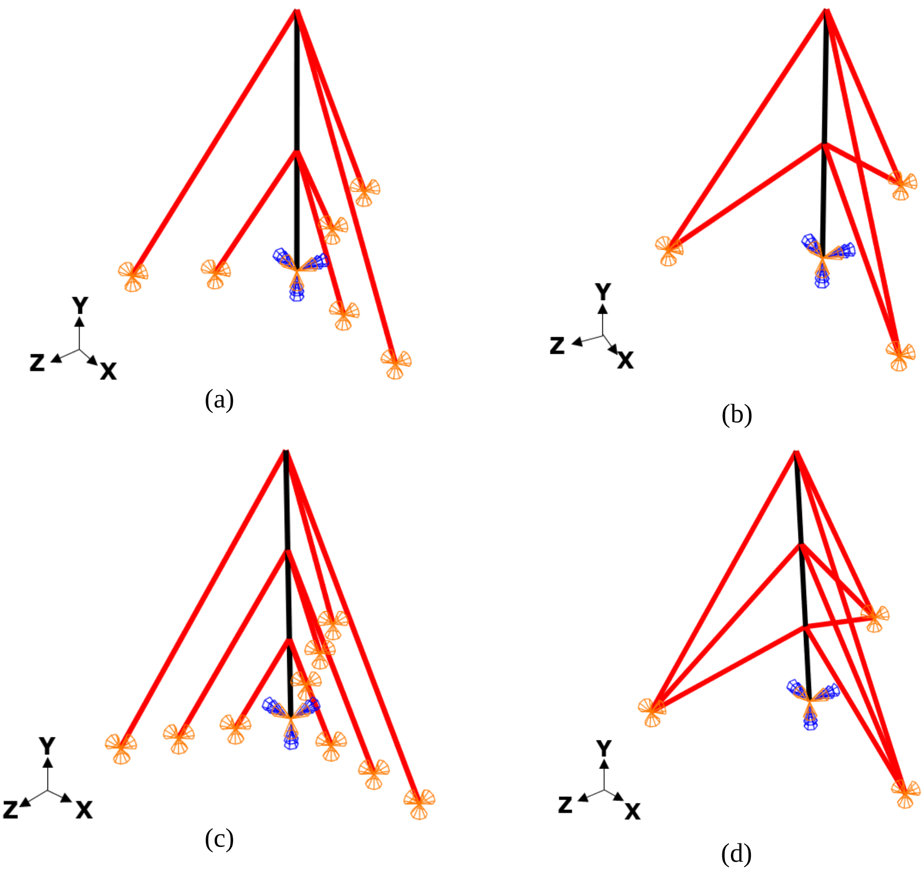

Figure 4: (a) Models with two levels of parallel guys; (b) Models with two levels of guys with the same anchoring points; (c) Models with three levels of parallel guys and (d) Models with three levels of guys with the same anchoring points.

3 Static Nonlinear Analysis

Static analyses evaluate the influence of the cable characteristics and of the structure self-weight on the system critical load. This first assessment is followed by a stability analysis and the investigation of the post critical behavior of the structure. The post critical equilibrium path is obtained through the modified Riks method, to see Dassault Systems [5], Ramm [6], Crisfield [7], Simons and Powell [8]. This method obtains stable and unstable equilibrium paths in addition to passing through load and displacement limit points, Tafreshi [9]. Initial geometric imperfections are introduced in the system in the form of isolated or combined buckling modes.

The first analysis is the buckling load for the model with one level of guys. As expected, due to system symmetry, the first two bifurcation loads are the same, indicating the possibility of modal interaction. Table 2 provides the first four bifurcation loads for the finite element model. The same occurs for the models of towers with more cables, where the critical loads are presented in pairs, Table 4, indicating the possibility of modal interaction. Then, the post-critical trajectory is analyzed, noting that with the increase in the number of cables there is a gain in the system's carrying capacity. Along with this gain, an increasing sensitivity to imperfections is observed, Figure 5. This hypothesis is based on the increase in the initial inclination of the post-critical response.

Table 3: Bifurcation load (kN) for five different cable diameters, ϕ.

		Critical Load (kN)					
ϕ (mm)	ρ_{cable} (kg/m³)	Modes					
		1	2	3	4	5	6
19	7850	**3482.19**	**3482.19**	9616.61	9616.61	13582.40	13582.40
22	7850	**3510.96**	**3510.96**	10441.90	10441.90	16128.60	16128.60
29	7850	**3522.32**	**3522.32**	10925.70	10925.70	21499.90	21499.90
38	7850	**3476.40**	**3476.40**	11050.30	11050.30	22537.10	22537.10
48	7850	**3407.71**	**3407.71**	11102.70	11102.70	22843.90	22843.90

In addition to the number of cables, another factor that influences the static response of the structure is its configuration. Tower models with the same number of cables, but with different configurations, have different critical load values, Table 4. Towers with parallel cables present lower critical loads than those with fan cables.

Table 4: Bifurcation load (kN) for five different configurations and levels of cables.

Critical Load (kN)					
Mode	**1 Level**	**2 Parallel Levels**	**2 Fan Levels**	**3 Parallel Levels**	**3 Fan Levels**
1	3407.71	9038.95	9197.18	14809.90	16366.30
2	3407.71	9038.95	9197.18	14809.90	16366.30
3	11102.70	20934.50	21540.90	19323.60	20028.10
4	11102.70	20934.50	21540.90	19323.60	20028.10
5	22843.90	25386.50	28843.30	38339.30	38115.90
6	22843.90	25386.50	28843.30	38339.30	38115.90

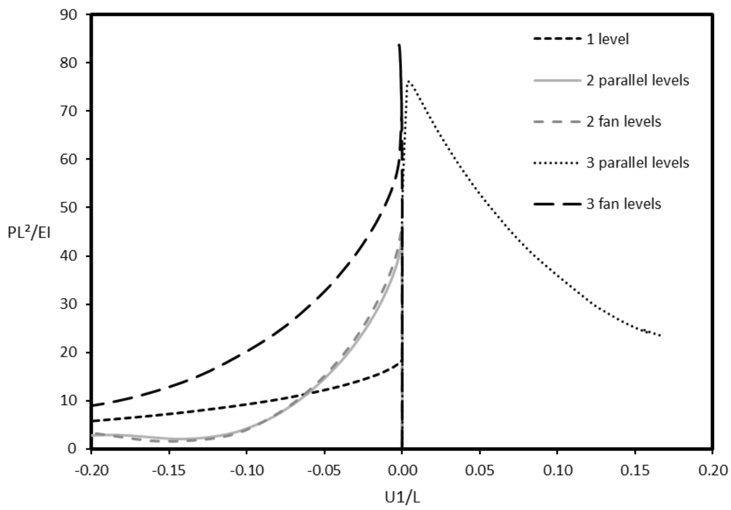

Figure 5: Post critical analysis showing an unstable response for different configurations and number of levels of guys. Nondimensional load x normalized horizontal displacement of the top node.

4 Nonlinear Dynamic Analysis

The nonlinear behavior of guyed towers is even more pronounced under dynamic loading. The study of the dynamic behavior of the synthetic tower models is divided in two parts. In the first part, the natural frequencies and vibration modes are obtained through the solution of an eigenvalue problem. This step gives the resonant frequencies of the structure. With this information, it is possible to develop an analysis of the effect of the initial conditions and harmonic loads on the non-linear structural response. In a second step, the structures are analyzed under damped forced nonlinear vibrations.

The dynamic analyses are performed with the "Dynamic implicit" ABAQUS module. This module executes the transient and permanent system analyses with or without damping. Time integration uses the Hilber-Hughes-Taylor, HTT-alpha method, Dassault Systems [5], with the parameters alpha=0, beta=0.3025 and gamma=0.6 to avoid error propagation Hilber, Hughes and Taylor [10], Wood, Bossak and Zienkiewicz [11],. Structural damping is also present and is introduced as a material property, by the Rayleigh damping. The column and cables have a modal damping of $\xi = 1\%$, Chowdhury and Dasgupta [12].

First, through the dynamic analysis, it is observed that the eigenvalues occur in pairs due to the symmetries of the model, leading to possible internal resonances. When comparing the values of natural frequencies for the different models it is observed that a tower with three levels of cables can triple the fundamental frequency in relation to that of one level, Table 6. Regarding the configuration of cables for structures with the same number of levels, the fan configuration results in higher frequencies than the parallel configuration.

Table 6: Natural frequencies for the different levels and configuration of cables.

	Frequency (Hz)				
Mode	**1 Level**	**2 Parallel Levels**	**2 Fan Levels**	**3 Parallel Levels**	**3 Fan Levels**
1	0,3926	0,9119	0,9679	1,1771	1,2956
2	0,3926	0,9119	0,9679	1,1771	1,2956
3	1,1577	1,3998	1,5898	1,5669	1,7449
4	1,1577	1,3998	1,5898	1,5669	1,7449
5	1,9265	1,9476	1,9668	2,3744	2,6551
6	1,9265	1,9476	1,9668	2,3744	2,6551
7	3,2672	3,4108	3,5287	3,3139	3,3504
8	3,2672	3,4108	3,5287	3,3139	3,3504
9	5,2946	5,3538	5,3563	5,3504	5,3988
10	5,2946	5,3538	5,3563	5,3504	5,3988

Next, a harmonic force is applied with a forcing frequency close to the lowest natural frequency of each of structure with three levels of cables. An integration step of one hundredth of the fundamental period of the structure is used and the integration is performed during approximately 290 forcing periods. Then, the fast Fourier transform of the steady-state response is obtained, Figure 6. The presence of sub- and super-harmonic resonances is detected, whereby the model with the parallel configuration presents strongerr nonlinearities.

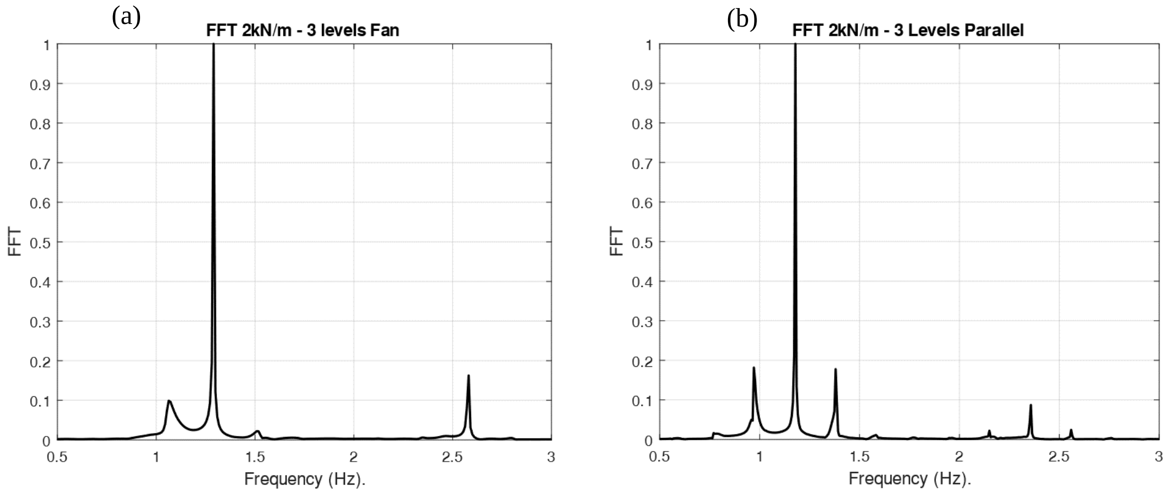

Figure 6: Frequency spectrum of the guyed tower with three levels of guys: (a) fan configuration and (b) parallel configuration

5 Conclusions

The results show that guyed towers exhibit highly nonlinear response, even at low load levels. Thus, the geometric nonlinear behavior must be considered in the design stage. In addition, the results indicate the necessity of further investigation of the nonlinear dynamic response of these structures for guys setup and mast dimensions used in actual towers.

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