INFLUENCE OF DESIGN PARAMETERS ON THE STRUCTURAL DESIGN OF GUYED TOWERS

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Abstract *The structural design of guyed towers requires increasingly greater knowledge of the design variables and the influence of each of them on the global behavior, since the behavior of these systems is so complex. This is due mainly to their non-linearities and slenderness, and to the increased demand for higher and more reliable towers as a result of the expansion of the telecommunications sector. Due to advances in numerical methods, more realistic simulations of the system in service can be run, and therefore the main variables that influence the behavior of these structures can be determined. The objective of this work is to evaluate the sensitivity of guyed towers to the influence of four important design parameters: pretension and angle of inclination of the guys, base width, and height of the sub-modules. The finite element method was used together with Taguchi's technique to determine the influence of each of these design parameters on the structure's response in terms of maximum values of the resulting displacements, Von Mises stresses, and forces on the guys. The results show that, in terms of maximum displacement, the design variable with the greatest influence is the angle of inclination of the guys, and that, in terms of the maximum Von Mises stress and the forces on the guys, the variable that had the greatest influence was the pretension. Thus, the use of the finite element method together with Taguchi's technique proved to be an effective and quick tool for analyzing the sensitivity of guyed towers.*

Keywords: *guyed towers, finite element method, design of experiments, Taguchi's technique.*

1. INTRODUCTION

Due to the advance of various sectors, such as telecommunications and energy, a great demand for high towers has arisen. For economic reasons, these towers must be light and slender. Guyed towers have been widely employed because they are the best economic solution for high towers (Ekhande and Madugla, 1988). However, this kind of structure has a complex behavior, due mainly to its slenderness and the interaction of the guys with the mast, in addition to the need for large areas for anchoring.

The structural analysis of guyed towers is complex, with one of the major issues being their guys. These structures are subjected to requirements that are not very well defined; therefore, these analyses are more uncertain when compared to other analyses performed on other structures (Gerstoft and Davenport, 1986).

There are several studies showing the behavior of guyed towers, with most of them involving wind loads. Guimarães et al. (2007), for example, performed a preliminary behavioral study of guyed towers subjected to static and dynamic wind loads according to the procedures described by the standard NBR 6123/1988. They verified that the critical loading condition was a dynamic wind at a 45º angle to the structure.

Determining the influence of project parameters on the behavior of guyed towers using finite element methods, experimental planning, and analysis of variance may lead to structures compatible with the new market demands.

The concept of robust design was initially proposed by Taguchi. This concept consists of improving the quality of the product or process through the investigation of interactions between controllable factors and noise factors using the experimental planning methodology (Doltsinis et al., 2005). In 1996, Lee et al. studied an optimization problem without the restriction of lattice structures, applying Taguchi's concept for numerical planning.

The purpose of this work was to evaluate the guyed towers' sensitivity to the influence of four major project parameters, which are guy pretension and angle of inclination, base width, and sub-module height. To do so, Taguchi's experimental planning technique was used. It indicates the order in which the numerical experiments must be performed. The numerical experiments were carried out using the finite element method, which allowed for the creation of numerical models for analyzing the structure. The sensitivity analysis of the design variables was carried out through the Analysis of Variance (ANOVA) technique. Nevertheless, it is important to emphasize that there are uncertainties inherent to finite element models, primarily because such models are approximate, but also because of uncertainties concerning, for example, properties of the materials and boundary and loading conditions. Therefore, planning and statistical analysis are essential tools for analyses performed using finite elements.

Lastly, it was verified that the angle of inclination of the guys was the design variable with the greatest influence on maximum displacements, and that pretension was the variable with the greatest influence on maximum Von Mises stress and tension on the guys.

Based on this work, it can be concluded that the use of the finite element method along with Taguchi's technique was shown to be an efficient and quick tool for the sensitivity analysis of guyed towers.

2. TAGUCHI'S TECHNIQUE

The experimental planning methodology proposed by Genechi Taguchi in the early 80's presents three main objectives: (1) to design products or processes that are robust in relation to environmental conditions; (2) to design and develop products that are robust in relation to the variability of its components; and (3) to minimize the variability of a nominal value. According to Taguchi, there are three stages of development for a product or process: system design, parameter design, and tolerance design. The use of statistical methods for experimental planning is particularly important in the last two stages. This contributes to more robust products and processes, which are insensitive to uncontrollable factors that may influence their performance (Montgomery, 2001).

This method uses an orthogonal array, which is a type of fractional factorial design consisting of a representative set of all possible combinations of experimental conditions. The use of Taguchi's technique may lead to a balanced comparison of process parameter levels and to a significant reduction in the total number of simulations (Padmanabhan et al, 2007).

In this work, the experimental planning method proposed by Taguchi was used to specify the numerical simulations. For each factor analyzed, two levels were considered. There are many factors, such as pretension guy and angle of inclination, that affect the structural behavior of guyed towers. However, there are other factors, such as mast configuration and guy placement, that were considered as fixed factors. Table 1 shows the design parameters and their respective levels to be used in the finite element method simulations.

Table 1. Design Parameters and their Respective Levels

Design Parameter	Levels	
	1	2
Pretension (%)	8	15
Angle of Inclination of the Guys (°)	20	30
Base Width (m)	0.70	1.00
Sub-Module Height (m)	0.70	1.00

Taguchi's orthogonal array for four factors and two levels is L8, which leads to eight simulations as shown in Tab. 2, in which the first column represents the simulation number and the following columns represent the design parameters, and the rows represent the simulations with the levels of each parameter to be analyzed.

Table 2. Taguchi Orthogonal Array (L8)

Experiment Number	Design Parameters			
	Pretension	Guy Inclination	Base Width	Sub-Module Height
1	1	1	1	1
2	1	1	1	2
3	1	2	2	1
4	1	2	2	2
5	2	1	2	1
6	2	1	2	2
7	2	2	1	1
8	2	2	1	2

After performing the experimental planning using Taguchi's technique, eight simulations were carried out using the finite element method (FEM) in order to predict the behavior of the guyed tower in terms of the maximum resulting displacement values, Von Mises stress, and tension on the guys when design parameter levels were changed. The FEM results were analyzed using the ANOVA statistical method. The aim of the study was to determine the parameters that influence the behavior of guyed towers, in order to obtain the impact of each design parameter on the system's responses obtained through FEM. Thus, the degree of importance of each parameter on the structural response of interest was also obtained.

3. FINITE ELEMENT METHOD

In this work, the finite element method was used by means of the ANSYS program. The steps to obtain a finite element model included domain definition, properties of the material, domain discretization, and boundary and loading conditions.

3.1. Domain Definition

To define the domain, a 30-module guyed tower was used (Fig. 1). Each module comprised 10 sub-modules. It also had a square cross section lattice mast, pyramidal base, and two torsion resistance devices.
Mast sections are ASTM A36 steel angles with equal legs, and the mast-supporting guys are 19-wire zinc-galvanized steel wire rope.

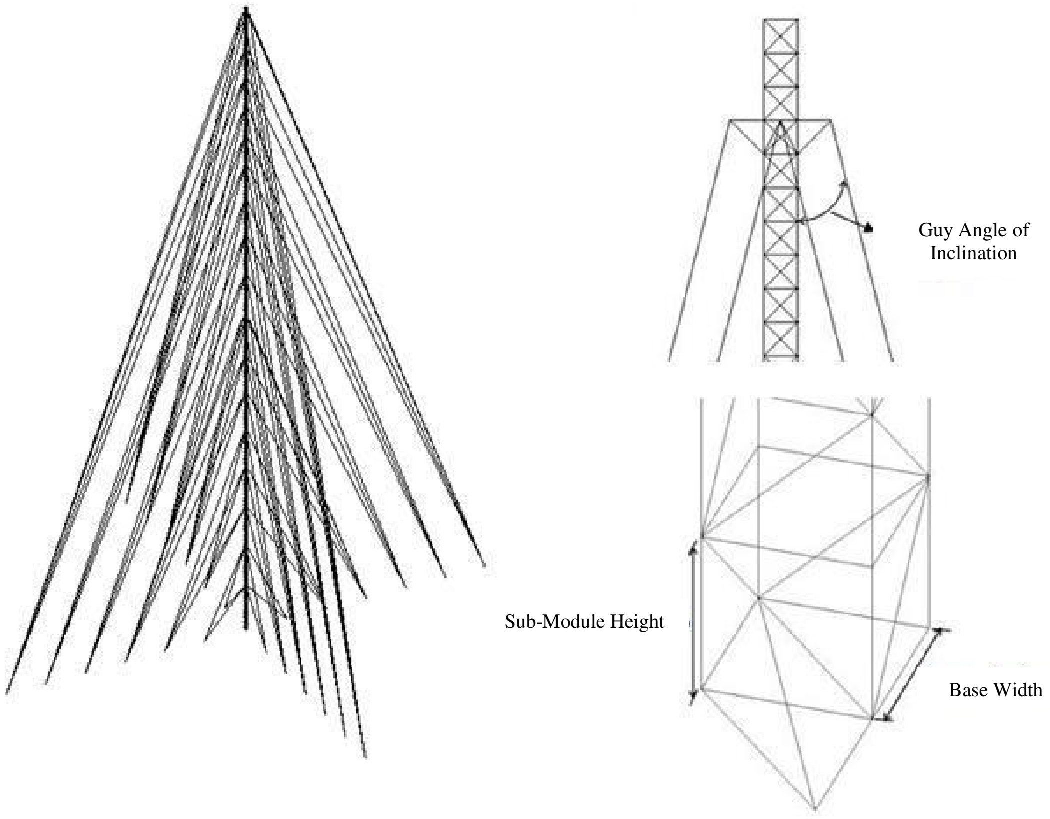


Figure 1. Geometry of the analyzed guyed tower.

3.2. Properties of the Materials

For modeling, structural materials were considered to be isotropic, homogeneous, and linearly elastic. The properties of the material used are showed in Tab. 3, where: ‘E’ is the Young’s modulus, ‘fy’ is the yield strength, ‘fu’ is the tensile strength, ‘α’ is the specific weight, and ‘ν’ is the Poisson’s ratio.

Table 3. Properties of profiles and wires used in the guyed tower

Steel Angles with Equal Legs (NBR 8800/2008 and ASTM A36/1997)

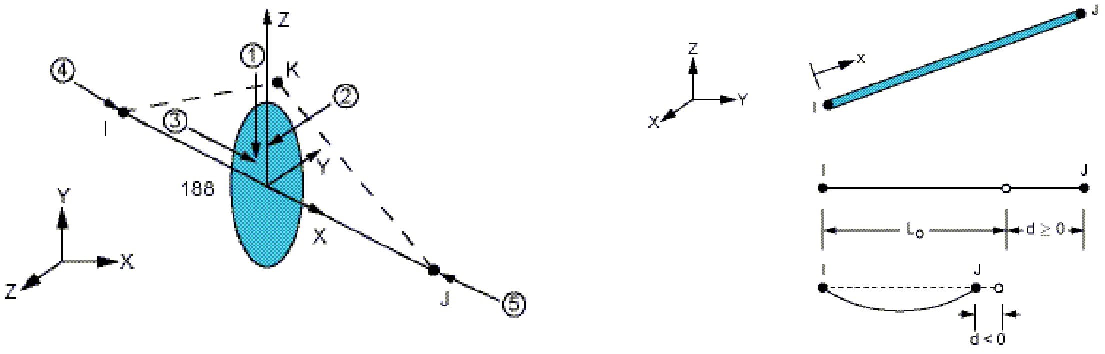
Steel	ν	E	fy	fu	α
		GPa	MPa	MPa	kg/m3
ASTM A36	0.3	205	250	400-550	7,850

Wire Rope (CIMAF)

Wire Rope	Diameter	E	Mass/Length	Breaking Load
	mm	GPa	kg/m	kN
1×19	13	147	0.521	127

3.2. Domain Discretization

In this step, the elements to be used in the discretization of the mast and guys were defined. For the mast, finite element BEAM 188 (Fig. 2a) was used. Based on Timoshenko's beam theory, it has six degrees of freedom per node. For the guys, finite element LINK 10 (Fig. 2b) was used. It has three degrees of freedom and allows the application of pre-deformations.



(a)

(b)

Figure 2. Elements used in domain discretization. a) BEAM 188 and b) LINK 10. Source: ANSYS®

In the end, a mesh composed of 42,092 elements and 81,577 nodes was obtained for any value of design parameter, according to Fig. 3.

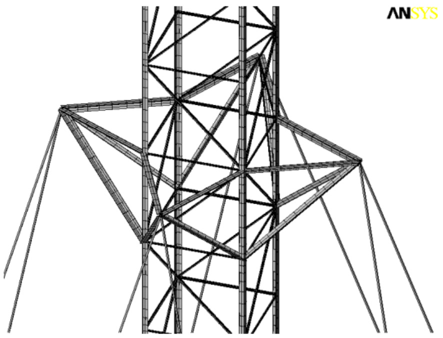
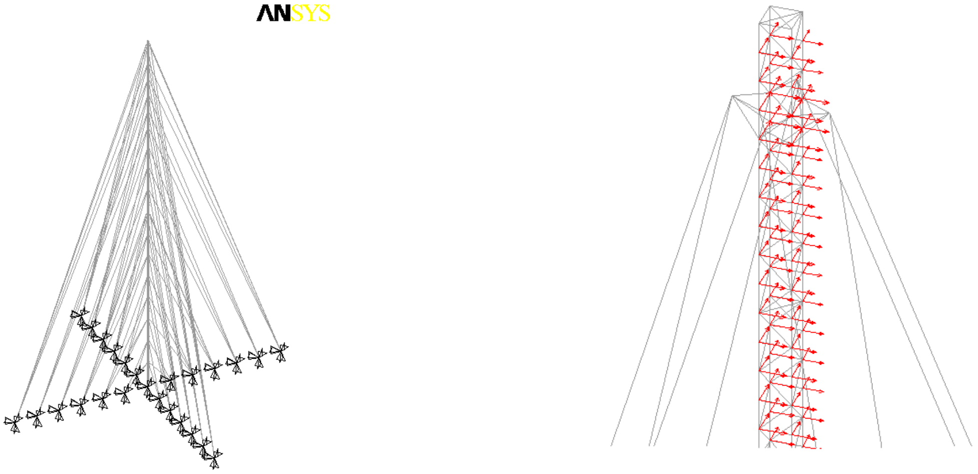


Figure 3. Mesh used.

3.3. Boundary and Loading Conditions

The boundary conditions (Fig. 4a) were restricted to displacements in every guy anchorage point on the mast and the ground. For the mast, they were restricted to displacements of its base.



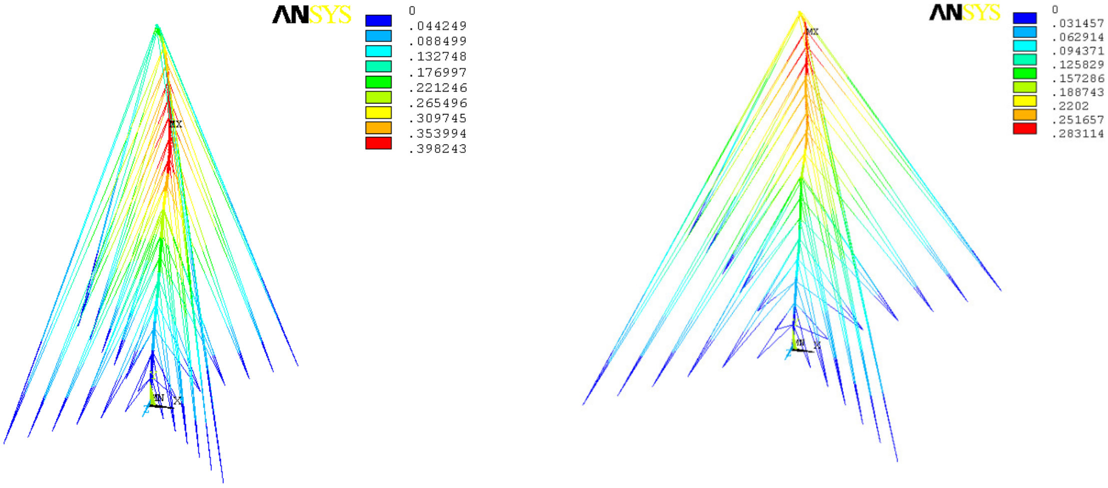
(a) (b)

Figure 4. Representation of boundary (a) and loading (b) conditions

In Brazil, the main design factor for guyed towers is wind. For this reason, this work used the following loading conditions (Fig. 4b): wind at 45º (NBR6123/1988), guy pretension, percentage of the wire rope resistance capacity (CSA S37-94), and self weight of the structure, through the specific weight of the rods (α) and mass per unit length of the guys (Tab. 3).

4. RESULTS

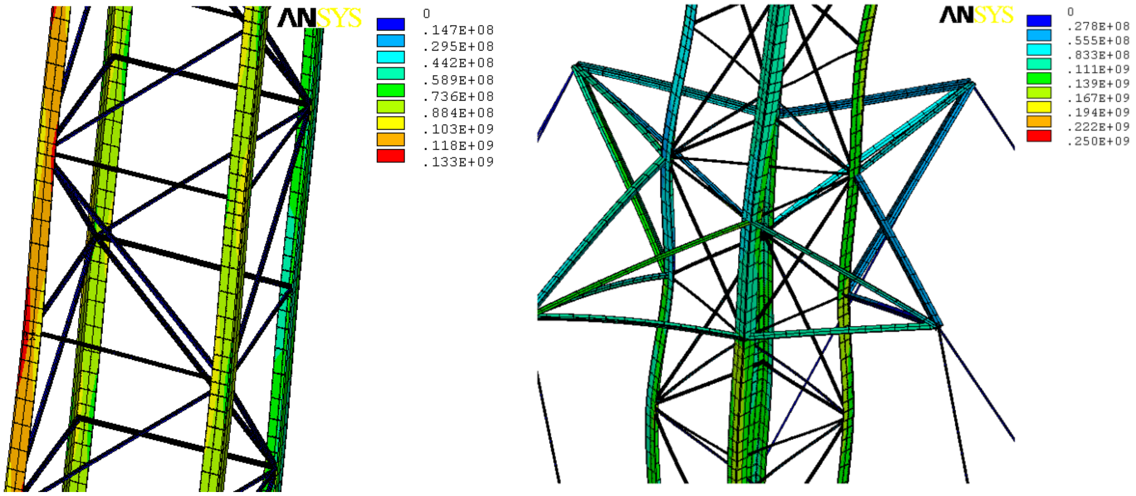
In order to analyze the structural response in terms of the maximum resulting displacement values, Von Mises stresses in the mast and tension in the guys, eight simulations were performed by changing the values of guy pretension and angle of inclination, base width, and sub-module height. These simulations were performed following Taguchi's Orthogonal Array shown in Tab. 2.



(a) (b)

Figure 5. Resulting displacement [m]. a) Simulation 1 and b) Simulation 8.

As shown in Fig. 5, a significant change in the distribution and intensity of the resulting displacement occurred when design parameters were changed. A significant change was also seen for the maximum Von Mises stress in the mast (Fig. 6).

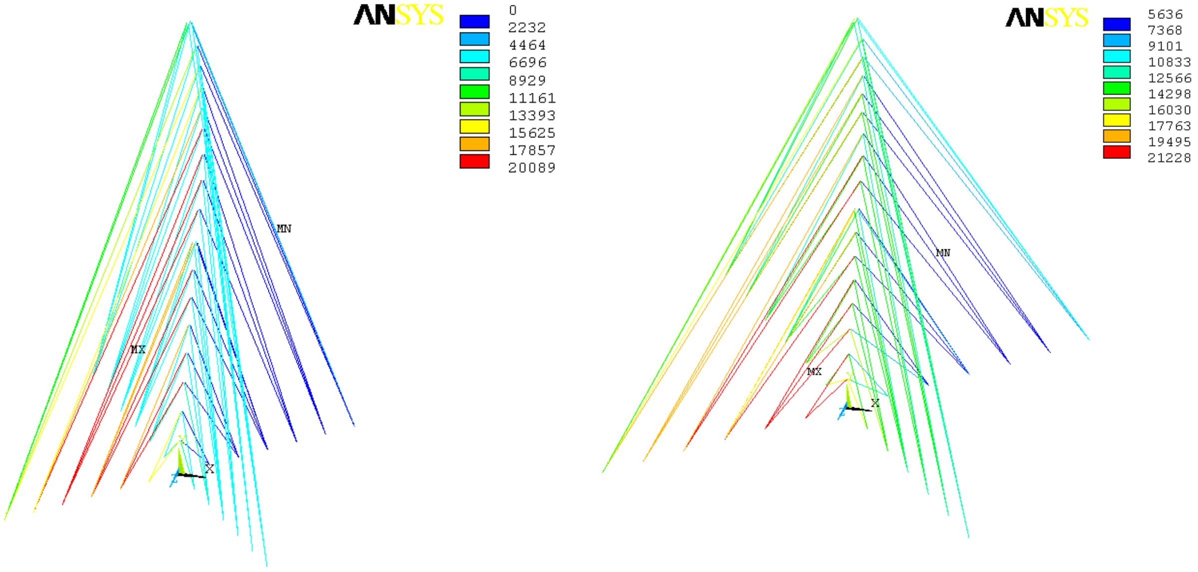


(a)

(b)

Figure 6. Von Mises stress [Pa]. a) Simulation 1 and b) Simulation 2.

Regarding tension on the guys (Fig. 7), their intensity did not undergo major changes; however, the location of the maximum tension changed when design parameters were changed.



(a)

(b)

Figure 7. Tension on the guys [N]. a) Simulation 1 and b) Simulation 8.

Through analysis of the results, the structural response variables seen to have greater sensitivity to changes in design variables are Von Mises stress and the resulting displacements, since both variables had significant changes in their distributions and intensities throughout the eight simulations.

Table 4. Analysis of variance (ANOVA)

Parameter	Level	Expt. no.	y			S/N		
			y_1 (cm)	y_2 (MPa)	y_3 (KN)	S/N_1	S/N_2	S/N_3
Pretension (%)								
level 1	8	1	39.8243	133	20.089	32.00296	42.47703	26.05917
		2	58.2074	219	20.254	35.29956	46.80888	26.13022
		3	17.2394	107	14.36	24.73044	40.58768	23.14309
		4	23.3832	110	14.508	27.37808	40.82785	23.23215
level 2	15	5	33.263	219	22.25	30.43923	46.80888	26.9466
		6	44.809	196	22.462	33.02731	45.84512	27.02897
		7	19.2547	206	21.118	25.69074	46.27734	26.49306
		8	28.3114	250	21.228	29.03923	47.9588	26.53818
Guy Inclination (º)								
level 1	20	1	39.8243	133	20.089	32.00296	42.47703	26.05917
		2	58.2074	219	20.254	35.29956	46.80888	26.13022
		5	33.263	219	22.25	30.43923	46.80888	26.9466
		6	44.809	196	22.462	33.02731	45.84512	27.02897
level 2	30	3	17.2394	107	14.36	24.73044	40.58768	23.14309
		4	23.3832	110	14.508	27.37808	40.82785	23.23215
		7	19.2547	206	21.118	25.69074	46.27734	26.49306
		8	28.3114	250	21.228	29.03923	47.9588	26.53818
Base Width (m)								
level 1	0.7	1	39.8243	133	20.089	32.00296	42.47703	26.05917
		2	58.2074	219	20.254	35.29956	46.80888	26.13022
		7	19.2547	206	21.118	25.69074	46.27734	26.49306
		8	28.3114	250	21.228	29.03923	47.9588	26.53818
level 2	1	3	17.2394	107	14.36	24.73044	40.58768	23.14309
		4	23.3832	110	14.508	27.37808	40.82785	23.23215
		5	33.263	219	22.25	30.43923	46.80888	26.9466
		6	44.809	196	22.462	33.02731	45.84512	27.02897
Sub-Module Height (m)								
level 1	0.7	1	39.8243	133	20.089	32.00296	42.47703	26.05917
		3	17.2394	107	14.36	24.73044	40.58768	23.14309
		5	33.263	219	22.25	30.43923	46.80888	26.9466
		7	19.2547	206	21.118	25.69074	46.27734	26.49306
level 2	1	2	58.2074	219	20.254	35.29956	46.80888	26.13022
		4	23.3832	110	14.508	27.37808	40.82785	23.23215
		6	44.809	196	22.462	33.02731	45.84512	27.02897
		8	28.3114	250	21.228	29.03923	47.9588	26.53818

However, to determine the influence of design factors on the structural response, the use of the analysis of variance (ANOVA) was required. Thus, in this work, Pareto ANOVA was used. It quantifies the influence of each design parameter on the structural response. In order to compare the structural system behavior, the mean square deviation was used. It combines the effects of the mean and the standard deviation of the results. Taguchi recommends a logarithmic transformation of the signal-to-noise ratio in the analysis of the results in order to increase design robustness. The signal (MSD) is given by:

$$MSD = y^{-2} \tag{1}$$

where 'y' is the measure of the structural response to be analyzed.

When the S/N ratio is used for analyzing results, there is a greater possibility of producing a more consistent result. This is used for measuring the structural response deviation in terms of the maximum resulting displacement values (y_1), Von Mises stress in the mast (y_2) and tension in the guys (y_3) (Tab. 4), where the S/N ratio is given by:

$$S/N = -10log\,(MSD) \tag{2}$$

and the mean S/N ratio (Tab. 5) is given by:

$$\overline{S/N} = \frac{1}{8}\sum_{i=1}^{8}(S/N)_i \tag{3}$$

Table 5. Mean S/N ratio

Parameter	Level	S/N_{1i}	S/N_{2i}	S/N_{3i}
Pretension (%)				
level 1	8	29.85276	42.67536	24.64116
level 2	15	29.54912	46.72254	26.7517
Guy Inclination (º)				
level 1	20	32.69227	45.48498	26.54124
level 2	30	26.70962	43.91292	24.85162
Base Width (m)				
level 1	0.7	30.50812	45.88051	26.30515
level 2	1	28.89376	43.51738	25.0877
Sub-Module Height (m)				
level 1	0.7	28.21584	44.03773	25.66048
level 2	1	31.18604	45.36016	25.73238
$\overline{S/N}$		29.70094	44.69895	25.69643

The S/N_{ji}: correspond to the S/N_i values, where 'j' indicates each one of the structural responses ($y_{1.}\ y_{2.}\ y_3$).

The sum of squares due to the total mean variation is given by:

$$SS = \sum_{i=1}^{8}((S/N)_i - \overline{S/N})^2 \tag{4}$$

The SS values for each of the structural responses are: SS_1 = 23.6562, SS_2 = 13.0921 e SS_3 = 4.3983. The sum of squares due to the total mean variation for each parameter (SS_i) is given by:

$$SS_i = \sum_{i=1}^{2}((S/N)_i - \overline{S/N})^2 \tag{5}$$

The values of the design parameters and of their contributions to the guyed towers' response are showed in Tab. 6, in which the percentage of individual contribution of each design parameter can be given by:

$$C = 100.SS_i/SS \tag{6}$$

Table 6. Contribution of design parameters

Design Parameters	SS_{1i}	SS_{2i}	SS_{3i}	C_1 [%]	C_2 [%]	C_3 [%]
Pretension	0.0461	8.1898	2.2272	0.19	62.56	50.64
Guy Inclination	17.8960	1.2357	1.4274	75.65	9.44	32.45
Base Width	1.3031	2.7922	0.7411	5.51	21.33	16.85
Sub-Module Height	4.4110	0.8744	0.0026	18.65	6.68	0.06

Where indexes 1, 2, and 3 indicate each one of the structural responses (resulting displacements, Von Mises stress in the mast and tension in the guys).

As shown in Tab. 6, the design parameters affect each structural system response in a different manner. However, it can be noted that the angle of inclination was the most important factor in terms of maximum resulting displacements, and the value of the pretension in the guys was the most important in terms of Maximum Von Mises' stress and tension in the guys. Therefore, these factors can be used in optimization processes to create a more efficient structural system.

5. CONCLUSION

This work used the finite element method along with Taguchi's technique in order to determine the sensitivity of guyed towers to the influence of four major design parameters (guy pretension and angle of inclination, base width, and sub-module height). ANOVA was also used for analyzing the influence of design parameters on structural response in terms of maximum resulting displacement values, Von Mises stress in the mast and tension in the guys. Through the results obtained, it was possible to observe that the angle of inclination of the guys is the most influential factor (approximately 75.65%) on the structural response in terms of the resulting displacements. However, for the Von Mises stress in the mast and tension in the guys, the most influential factor is guy pretension, being approximately 62.56% for the stress response and 50.64% for tension in the guys. Even so, it was possible to observe that tension in the guys is the structural response with the smallest variation in its intensity as a result of changes in design parameters due to experimental planning. Thus, the combination of FEM with Taguchi's technique and ANOVA is seen as an interesting tool for sensitivity analysis of design parameters. The information on structural sensitivity regarding specific parameters can be used for creating a more efficient structure.

6. ACKNOWLEDGEMENT

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