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Dynamic response due to cable rupture in a transmission lines guyed towers

Thiago B. Carlos[a]*, João Kaminski Jr.[b]

[a]*Department of Civil Engineering, University of Coimbra, Rua Luís Reis Santos, Coimbra 3030-788, Portugal*
[b]*Department of Structures and Civil Construction University of Santa Maria, Av. Roraima 1000, Santa Maria 97105-900, Brazil*

Abstract

The design of guyed lattice steel structures used in transmission lines (TL) is generally accomplished by static analysis, in order to simplify the dynamic actions, which are represented by "equivalent static loads". However, the static response to this type of structure is not always sufficient for design purposes, since such structures are lightweight, slender and that are always subject to dynamic nature action, except the own weight. Therefore, a dynamic analysis is critical to get a more precise result in terms of stresses on the bars and nodal displacements. In this context, this paper deals with the static and dynamic response evaluation of guyed lattice steel towers of TLs submitted to dynamic action of rupture cable. For this purpose, numerical models of isolated tower and completed stretch of TL were developed, including all components. The models are subjected to static analysis through "equivalent static loads" application coming from the rupture cable and dynamic analysis, in the time domain, using the Direct Integration Method (DIM) of equations of motion explicitly, with central finite differences for the problem solution. Finally, the results of static and dynamic analysis are compared, specifically the peak and final values (after the structure stops vibrating) with the static response values, in order to verify the dynamic amplification generated in the most realistic model against the results obtained from the model used in the usual design practice.

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Keywords: Guyed towers; transmission lines towers; dynamic analysis; cable rupture.

* Corresponding author. Tel.: +351-961-086-943; fax: +351-239-797-123.
E-mail address: thiago.carlos@student.dec.uc.pt

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1. Introduction

The main actions on transmission line structures (TL) are dynamic in nature, such as wind and cable rupture. Cable rupture, although occurring less frequently, is one of the actions that can lead the tower to collapse, including triggering the phenomenon known as the "cascade effect," in which many towers collapse in sequence. The rupture of a cable, or bundle of cables, generates forces in the towers that are longitudinal to the TL, whereas in the action of the wind, the forces in the towers can be longitudinal or transverse. In the design of a tower, these actions should be considered as dynamic actions, however, for simplicity, they are usually considered as "equivalent static". Currently, this is no longer justified because of the great advances in numerical and computational methods, making it possible to obtain the structure response through a dynamic analysis, which would lead to more realistic results and consequently the design of a more efficient and economical structure. The mechanical behavior of TL towers is usually is evaluated through a static and linear analysis. Determining the effects of the dynamic nature actions on TL towers is a complex task, given the range of variables involved and their randomness. The use of methods that result in more proximity to reality is essential to design the towers safely, seeking to maintain the efficiency and economy in their design. Thus, a dynamic numerical model for a careful evaluation of TL segments, which guarantees accurate results at element level, becomes necessary.

This research presents an numerical investigation on dynamic response in a transmission lines guyed towers subjected to cable rupture. The main purpose was to determine the dynamic response of lattice towers of guyed TLs subjected to cable rupture in terms of stress amplification in the discrete elements of the dynamic model versus the results obtained in the elements of the static model.

2. Cable rupture analysis

The response of a guyed tower, called S1E2, subjected to the cable rupture hypothesis, is obtained through two types of analysis: static and dynamic in the time domain. The methods defined for static and dynamic analysis are detailed below.

2.1. Static analysis

The static analysis was performed in the finite element program ANSYS© [1], considering a model with an isolated guyed tower. A hypothetical span of 500m in relation to the supposed adjacent towers was considered. In order to evaluate the static response of the isolated tower, "equivalent static loads" were used in order to simulate the rupture of a conductor cable or a lightning rod, according to the procedures prescribed in the NBR 5422 [2]. The "equivalent static loads", directly on the arms of the suspended guyed tower are as follows:

- A horizontal load, in the longitudinal direction to the TL, applied to the arm of the tower where the cable to be rupture is located, with a value equal to the traction in EDS (Every Day Stress) condition of the cable. The value to be taken for a conductor cable, equivalent to the static residual stress after rupture, is 16% of that of its Ultimate Tension Stress (UTS). For a lightning rod of the guyed tower studied, the value adopted for the horizontal load is of 11.75% of the UTS of this cable.
- Vertical loads applied on the tower arms to consider the weight of insulator chains, conductive cables and lightning rods.
- Self-weight of the structure, which is considered in the ANSYS© [1] program by applying a vertical acceleration of 1g ($g = 9.81$ m / s^2). The structure, consisting of steel profiles, has a specific mass $\rho = 7850$ kg / m^3. In this way, the program calculates the bars self-weight and distributes them to the nodes of the structure.

The loads are considered in the model as concentrated vertical forces (Y direction) applied to the cable suspension nodes, located at the ends of the tower arms, as shown in Fig. 1. It should be noted that the vertical force of the conductor cables applied to the tower arms is the sum of the weight of these cables with the weight of the insulators chain, which is 1350 N. The vertical load applied at the point of suspension adjacent to the ruptured cable was halved, as there is no self-weight in the span with the ruptured cable. The S1E2 tower is analyzed for two different cable rupture hypotheses. The first, called H1, simulates the rupture of the conductor cable suspended by the upper arm (conductor 1). From the three conductor cables suspended by the tower, only the conductor cable 1 was selected for the analysis of cable rupture, because it is the highest, and therefore, the one that causes the greatest stresses in the tower. In the second hypothesis, called H2, the rupture is simulated for the lightning rod 1. Fig. 1 shows the values of the static loads that must be applied to the nodes of the numerical model to perform the static analysis of the S1E2 tower, considering the rupture hypotheses.

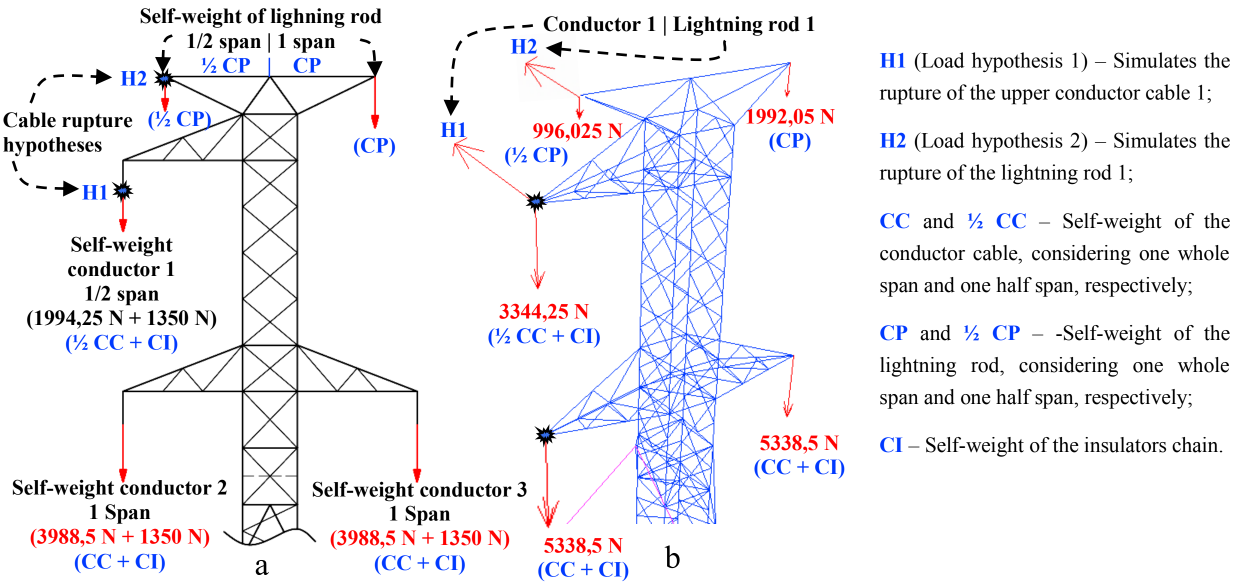

Fig. 1. (a) frontal view and (b) perspective view (b) of the top of the guyed tower, with the location of the cables self-weight loads and the equivalent static loads of cable rupture.

It is important to note that the equivalent static loads simulating the rupture of the conductor cable and the lightning rod are not applied simultaneously in the analysis of the structure. The span considered for simulation of the cable rupture in static analysis, in order to take into account the weight of the cable elements on the tower was 500 meters (half span).

2.2. Dynamic analysis

The dynamic response of the structure in the time domain is obtained through a numerical routine developed in FORTRAN and adapted from Kaminski Jr. *et al.* [3] to allow the analysis of guyed lattice steel towers of TL. The routine uses the Direct Integration Method (DIM) of the equations of motion, explicitly, using central finite differences. Dynamic analysis simulates a complete segment of TL. According Menezes et al. [4], the DIM present a relatively simple formulation which can be used to obtain the response in the bars, cable elements and insulation of an TL as function of time, even allowing to treat physical and geometrical non-linearities with relative ease, besides the advantage of not requiring the assembly of the overall stiffness matrix, since the integration is performed at element level.

2.2.1. Simulation of the cable rupture

In order to inform the cable rupture simulation to the numerical routine, the total time of 40 seconds for the analysis of the complete TL segment was defined. The self-weight loads of the towers and cable elements are gradually applied, from 0 to 100% of their value, for a time interval of 5 seconds (t = 0 to 5 s). At this same time, the initial deformation is applied to give the desired prestressing to the guy-wires, also gradually. The time interval of 5 to 20 seconds is used to dampen any vibration induced in the numerical model. The rupture of the selected cable element occurs at the time instant of 20 seconds (t = 20 s) and the remaining 20 seconds of the analysis are consumed in obtaining the dynamic response of the structure in time. The cable elements selected to rupture, both from the cable conductor and the lightning rod, are located near tower 2, in the span 2 of the line, between the towers 1 and 2, as shown in Fig. 2. Tower 2 is the one that is further away from the end nodes, and therefore, selected for stress and displacement analyses.

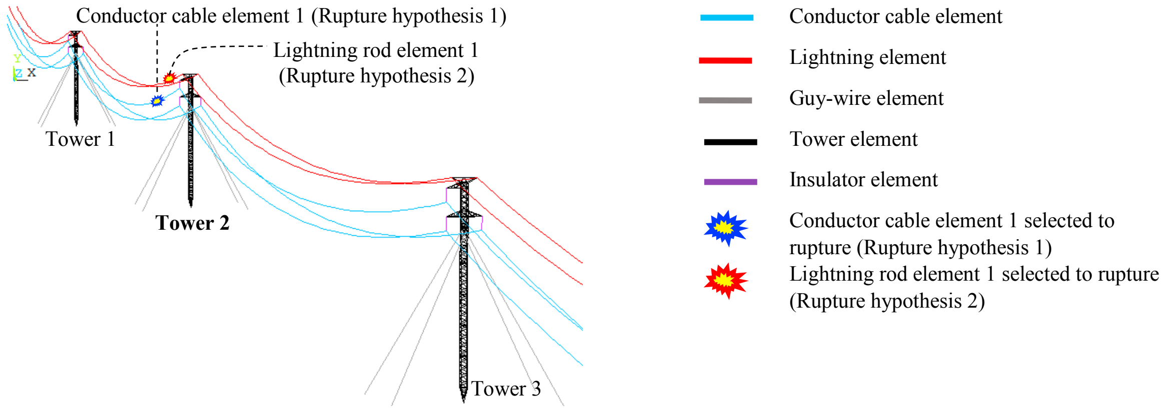

Fig. 2. 3D view of the complete TL model with the elements selected to rupture in the dynamic analysis.

Due to internal hypostaticities that occur in the space truss elements when using DIM, dummy bars with an axial stiffness such as to avoid instability of the structure and to not significantly alter the results. The process of calibration and evaluation is described in Carlos [5] and provided the stability of the numerical model. In addition, the numerical method response was evaluated through frequency analysis, which had satisfactory results, confirming the accuracy of the method.

3. Numerical examples

The reference model used to verify the reason of the stress amplification in the dynamic model, is a static model, composed of an isolated tower identical to those that make up the complete segment of the dynamic model.

3.1. Towers, insulators chains and elements selected for monitoring

The towers S1E2 for the numerical simulation are of suspension with asymmetrical triangular disposition of the conductor cables and two lightning rods. They are lattice steel structures, with a total height of 43.5 meters. The central mast has a square cross section, measuring 130 x 130 cm. Each tower has four guy-wires. The silhouette and the bars defined for the monitoring of the static and dynamic analysis are detailed in Fig. 3.

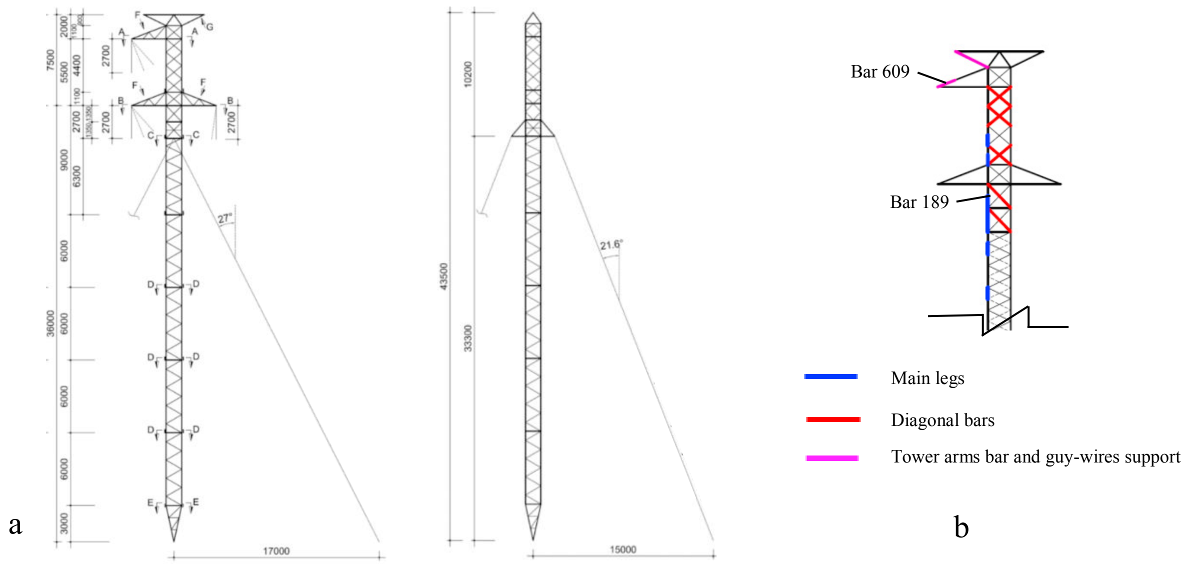

Fig. 3. (a) geometric configuration (front and side view) of the tower S1E2; (b) bars selected for monitoring in the static and dynamic analyses of the tower S1E2 (dimensions in millimeters).

3.2. Numerical model for static analysis

For the static analysis of the isolated guyed tower, analyzed in the ANSYS© [1] program, a numerical model consisting of space truss elements was considered in all the tower bars. In the modeling of the guy-wire elements, space truss elements were used, capable of acting only on the traction. Fig. 4 illustrates the static example with the location of the points of application of the equivalent static charges relative to the hypothesis of rupture of the conductor cable 1, as well as the position of the restriction nodes (foundations) and the tower arm nodes.

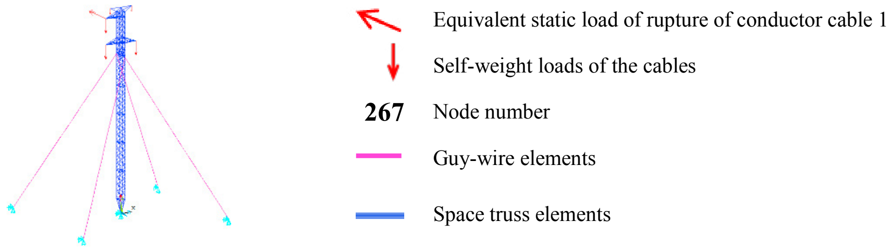

Fig. 4. Perspective view of the guyed tower with the location of the applied loads, the restriction nodes (foundations) and the arms nodes.

3.3. Numerical model for dynamic analysis

The numerical model used for the dynamic analysis consists of a complete segment of TL, composed of three guyed towers, four spans of conductor cables and lightning rods 500 m long, totaling a segment of 2000 m. At the ends of the TL segment (x = 0 m and x = 2000 m) the cables are supported on rigid nodes, that is, with all the degrees of freedom to translation (X, Y and Z) restricted.

4. Results

The results of the analyses are compared to each other, as for the peak and final axial forces (after the structure stops vibrating) generated in the bars, caused by the dynamic effect of the cable rupture and the values of the forces generated from the static response. This allowed to verify the dynamic amplification generated when using the most realistic model compared to the static model. That is, the ratio between the maximum stress obtained in the bar in dynamic analysis (dynamic peak) and the stress in the same bar, when obtained in static analysis, are evaluated. In dynamic analysis, in the time interval of 0 to 5 seconds, the elements self-weight is gradually applied and kept constant for 15 seconds until t = 20 s, together with the application of the prestressing on the guy-wires, observing the compressed state of the bars. Immediately after this instant, the rupture of the conductor cable is induced and the bar 189, located above the corbel that supports the guy-wires, undergoes an increase in the compression force. Such increase is quite significant, with an increase of approximately 240%, of the initial stress (with its self-weight only) for the final stress (after cable rupture). In relation to the effect caused by the dynamic action of rupture of the conductor cable 1, the bar 189 undergoes an amplification of stress of the order of 40%. The axial forces on the tower bar 189 and 609 obtained by dynamic and static analysis are shown in Fig. 5 (a) and (b), respectively.

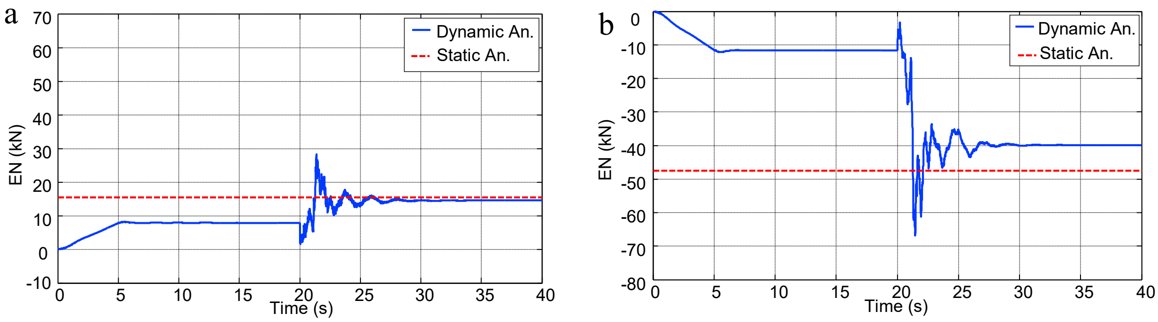

Fig. 5. Axial stress in the bar 189 (a) and bar 609 (b) of tower 2 for the static and dynamic simulation of the rupture of the conductor cable 1.

The bar 609 is the most requested and only presents compression, before and after the cable rupture. As in bar 189, bar 609 undergoes amplitude variation between the initial and final axial stress. After the 20 seconds of analysis, the span of the ruptured cable no longer exerts the self-weight forces that maintained the balance of the tower in the line, having longitudinal stresses by the remaining cable of the adjacent gap being generated and consequently an increase of traction in the bar 609. In the initial stresses of the bar (0 to 20 seconds), significant differences are observed when compared to the stress obtained with the static model, in which initially it is drawn in the dynamic analysis, whereas in the static analysis, where the actions in time are not taken into account, it is compressed. However, the final stress of the bars is quite close to that statically determined and does not approach the permissible load value. The bar 609 is the one with the highest dynamic peak. This variation results in an amplification of stresses of approximately 82% when compared to the result obtained in static analysis, being this, among the bars analyzed, the bar that obtained the largest dynamic amplification. The results of the bars selected for the analyses can be seen in Table 1.

Table 1. Results obtained for the bars of tower 2

Bars	Stresses by static analysis (kN)	Stresses by dynamic analysis (kN)		Dynamic amplification
		Final stress	Dynamic peak	
189	-47,57	-39,88	-66,79	40,4%
609	15,52	14,49	28,23	81,9%

5. Conclusions

In general, in the dynamic analysis of the complete TL segment, considering the conductor cable rupture, the results were very close to those determined in static analysis, in terms of residual axial forces in the bars (after the structure stops vibrating). However, when analyzing the peak stresses, we observe very significant dynamic amplifications, exceeding the normal stresses obtained in the static analysis, showing the importance of the dynamic analysis in the cable rupture hypothesis in TLs.

The largest dynamic amplifications were observed in the bars of the arm that supports the cable that ruptures, being quite significant.

The results of the static and dynamic analysis of the models in the hypothesis of rupture of the lightning rod 1, were inferior to the results obtained in the rupture of the conductor 1. Therefore, in this case, the rupture of the lightning rod is not determinant in the design of the tower analyzed and is not the most critical situation for evaluation among the models.

Finally, it is observed that the load used in the towers design practice, for the cable rupture hypothesis, generates a response very close to that in the final state of the structure (after the structure stops vibrating), however, for the consideration of the dynamic effect of cable rupture, the static model does not adequately represent such request, since the peak stresses occurring during the structure vibration show quite significant amplifications.

Acknowledgements

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