Structural Performance of Polymeric Composite Members in a Transmission Line Tower

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Abstract: On transmission lines of different countries, the theft of redundant steel members from the transmission towers has been reported in recent years [1-4]. The removal of these members from the tower can result in the collapse of the tower, causing the suspension of electric service. An alternative to avoid this problematic is to replace some steel components by polymeric composite members. The integrity of the tower will be maintained if the polymeric composite members resists the mechanical stresses that occur along the tower due to the own weight of the structure and all the components installed inside the structure (conductors , insulators, fittings, etc.) and due to the wind striking the structure. To check the resistance of the polymeric composite members, simulations of stresses along the transmission tower were performed using COMSOL Multiphysics. The results show that the use of polymeric composite components in transmission line towers can be a good alternative to prevent theft of steel members from these towers.

Keywords: redundant members, polymeric composite members, critical load factor, transmission line tower.

1. Introduction

In general, the transmission tower body comprises three types of members which are: main members, those forming the tower silhouette; secondary members, and redundant members. These latter members decrease the unbraced length of the main member and provide intermediate support [5]. The unbraced length is the distance between two intermediate support members of a larger member as shown in Figure 1.

It is noteworthy that the redundant members in the bottom panel of the tower are the members most commonly stolen from the structure. It is due to they are the easiest to reach and are easier to transport; furthermore, when they are being removed an immediate failure of the tower does not occur. Figures 2 and 3 show a transmission line tower section with and without redundant steel members.

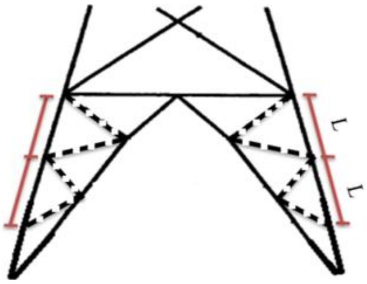


Figure 1. Leg sections of a lattice transmission tower, where L is the unbraced length and the dotted lines are the redundant members.

Figure 2. Tower with all its redundant steel members.

The removal of the redundant members from the tower has resulted in the collapse of the tower, causing the suspension of electric service and great economic losses. Currently, to avoid this problem, the towers are periodically inspected in order to immediately replace the missing members. However, the latter requires a constant investment, since steel members are stolen again, and thus the risk of failure of the tower follows being latent, if the members are not replaced promptly.

Figure 3. Tower without redundant members (stolen).

An alternative to avoid this problematic is to replace the steel components by polymeric composite members. The above is based on that the recycling economic value for a polymeric composite member is too low compared with the steel price. Thus, it is hoped that the theft of an unprofitable material will be discouraged; thereby the integrity of the transmission tower could be conserved.

To check the feasibility of this alternative, the resistance of the polymeric composite members to the mechanical stresses that occur along the tower due to the own weight of the structure and all the components installed inside the structure (conductors , insulators, fittings, etc.) and due to the wind striking the structure is evaluated.

2. Analysis Methodology

In transmission line towers, the sizing of the main members is governed mainly by its compressive strength [6]. When a load of wind hits the tower in any direction, it causes a tension force on the legs of the tower in the direction of wind flow. However, on the legs of the tower, which are not directly hit by these wind loads, a compressive force over the leg support is generated. So, a certain crushing on these legs occurs. Additionally, the forces generated by the self-weight of the structure and the other members (chains of insulators, conductors and earth wires) are projected toward the center of the earth and also cause compressive forces on the tower members. For this reason, the tension mode caused by wind loads is neglected, and consequently, strength analysis along the tower is carried out based on the compression mode.

Under compressive loads, the buckling is the main cause that can collapse a transmission line tower [7]. Therefore, the feasibility for using polymeric composite members instead of steel members as redundant members in transmission towers is performed by computing the critical buckling load using a linear buckling analysis.

The critical buckling load evaluation considers the conditions of normal loads corresponding to the weight of the conductors and associated hardware, and the wind force over the conductors and body of the tower. The first load (weigh) is simulated as a vertical load, and the second one (wind force), as a horizontal load. These loads are applied on the top corners of the transmission tower section being modeled for the analysis.

The analysis consists in determining the structural condition of 3 different sections of a tower for the following study cases:

a) Tower sections without the removal of the redundant steel members, namely, normal operation condition.

b) Tower sections with the absence of redundant members and of some secondary members in the bottom panel (Figure 3).

c) Tower sections with the installation of redundant polymeric composite members only in the bottom panel, in place of steel members.

Once determined the structural condition for each case, the obtained results are compared among them, and it is evaluated if polymeric composite members may or may not be a feasible alternative.

3. Use of COMSOL Multiphysics

COMSOL counts with the Structural Mechanics Module for performing linear buckling studies by the Solid Mechanics, Shell, Plate, or Truss interfaces, depending of the problem type to be solved. The Solid Mechanics and Truss seems to be more adequate for modeling towers. The Shell and Plate interfaces are mainly used to model thin structures [8].

However, we tried using the Truss interface, but it was not possible to model a tower having cross members, as they are commonly found in the transmission line towers. A singular equation error was generated during the problem solution. Hence, the Solid Mechanics was used for modeling the structural performance on towers with such a characteristic.

The tower type considered for the analysis is that shown in Figure 2, which is typically used on 230 kV transmission lines, in our country. The entire tower was not possible to model it, due to that the mesh representing the tower geometry was generated with wrong jointed triangular elements. It was attributed to the big amount of elements required to build the mesh. Therefore, it was only modeled different sections of the study tower including the zone where structural members are stolen. The sections modeled, with and without structural members, were the followings (Figure 4):

- Case 1: Tower bottom panel (Figure 4a).
- Case 2: Half of tower pyramidal body (Figure 4b).
- Case 3: Tower belt (Figure 4c).

The governing equations to estimate the critical load at which a structure becomes unstable are those implemented in COMSOL Multiphysics for a linearized buckling analysis [8]. As stated in COMSOL Multiphysics, this analysis is a predefined study type which consists of two study steps: one step in which a load is applied to the structure, and a second step in which an eigenvalue problem is solved for the critical buckling load. COMSOL describes this analysis in the following way:

- Consider the equation system to be solved for a stationary load **f**,

  $$K\mathbf{u} = (K_L + K_{LN})\mathbf{u} = \mathbf{f} \qquad (3.1)$$

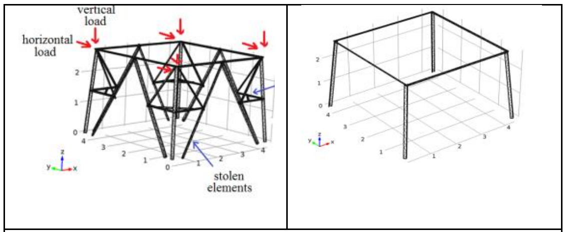
  where **u** is the displacement vector and K is the total stiffness matrix. K is split into a lineal part (K_L), and a nonlinear contribution (K_{NL}).
- In In a first approximation, K_{NL} is proportional to the stress in the structure and thus to the external load. So if the linear problem is solved first,

  $$(K_L)\mathbf{u}_0 = \mathbf{f}_0 \qquad (3.2)$$

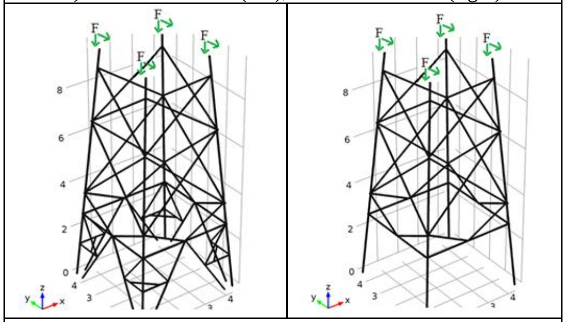
  where $\mathbf{f}_0$ is an arbitrary initial load level.
- Then the nonlinear problem is approximated as

  $$(K_L + \lambda K_{LN}(\mathbf{u}_0\ ))\mathbf{u} = \lambda\mathbf{f} \qquad (3.3)$$

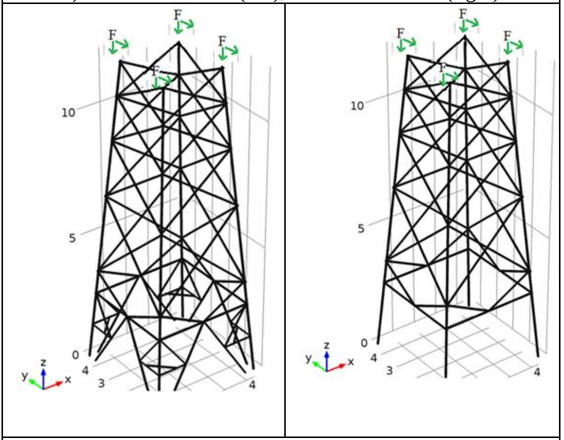
  where λ is called the load multiplier.
- An instability is reached when this system of equations becomes singular so that the displacements tend to infinity. The value of the load at which this instability occurs is determined by, in a second study step, solving an eigenvalue problem for the load multiplier λ.



a) with all members (left), without members (right)



b) with all members (left), without members (right)



c) with all members (left), without members (right)

Figure 4. Made models to analyze the structural performance of a transmission line tower with and without redundant members.

$$(K_L + \lambda K_{LN}(\mathbf{u}_0))\mathbf{u} = 0 \qquad (3.4)$$

COMSOL Multiphysics [8] reports a critical load factor, which is the value of λ at which the structure becomes unstable. The corresponding deformation is the shape of the structure in its buckled state. The level of the initial load used is immaterial. If the initial load actually was larger than the buckling load, then the critical value of λ is smaller than 1.

According to the above equations, the parameters required to evaluate the structure stability are load under which the structure is subjected and both Young's modulus as well as Poisson's ratio of structure members. The initial condition of the structure is no displacement along all its members. The boundary conditions are the load applied on the top corners or ends of the structure and the fixed constraints on the low ends of tower legs. The applied loads are given as transverse horizontal and vertical loads, represented as Fy and Fz in Figure 4. This is in order to simulate the actual loads actuating on the structure. The load values are taken from a research work about the structural performance of transmission line towers [9]. These values are Fy= 25.5 kN and Fz =16.0 kN.

The Young's modulus and Poisson's ratio values for tower steel members are 200x10^9 Pa and 0.33, respectively. For the polymeric composite members, considered to replace the stolen steel members, the values assumed are 30x10^9 Pa for Young's modulus and 0.32 for Poisson's ratio. These values correspond to one of the composite materials with the best mechanical properties found in the market.

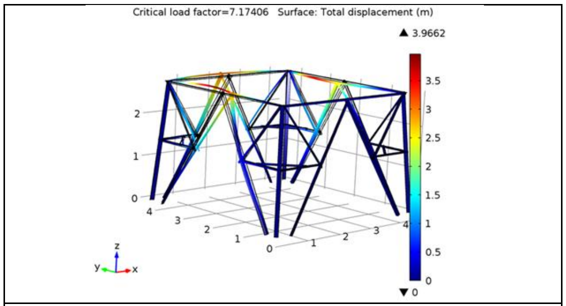
The performance of each case simulated in COMSOL, following the analysis methodology described in section 2, is determined based on the critical load factor obtained from the linear buckling analysis.

7. Results and Discussion

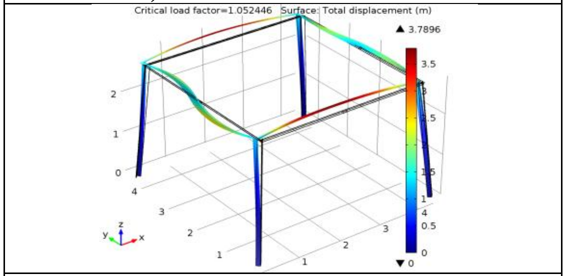
The results obtained from COMSOL, in terms of critical load factor (F_{CL}), are presented in Table 1. Figures 5-7 show the total displacements for the different simulated cases. The performance for each case is evaluated based on its critical load factor. A critical load factor lower than 1 means that the structure is in an elastic instability condition (buckling). Under this condition any additional load may affect the integrity of the structure. If the critical load factor is greater than 1, it means that there is no buckling risk under the load in which the structure is subjected.

Table 1. Critical load factor values obtained for the different models simulated with COMSOL.

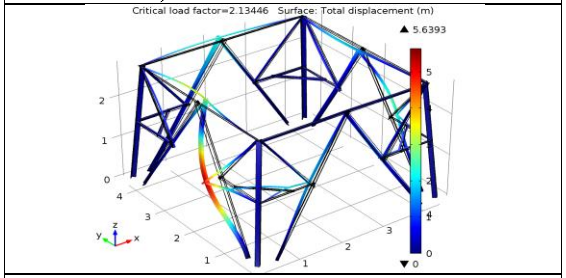
	Critical load factor (F_{CL}) values		
Model	With steel redundant members	Without redundant members	With polymeric material redundant members
Case 1	7.17	1.05	2.13
Case 2	2.51	0.73	1.03
Case 3	2.27	0.80	1.03



a) With redundant steel members

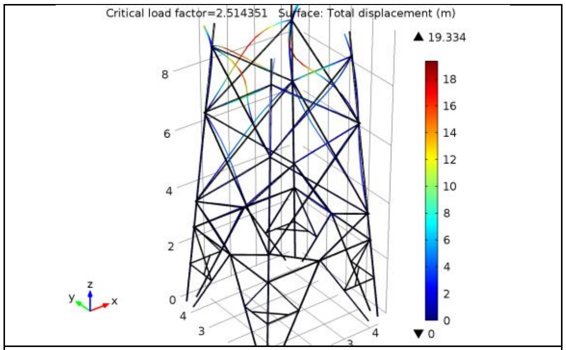


b) Without redundant members

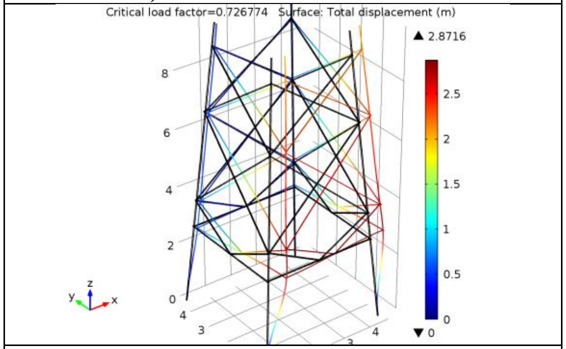


c) With redundant polymeric composite members

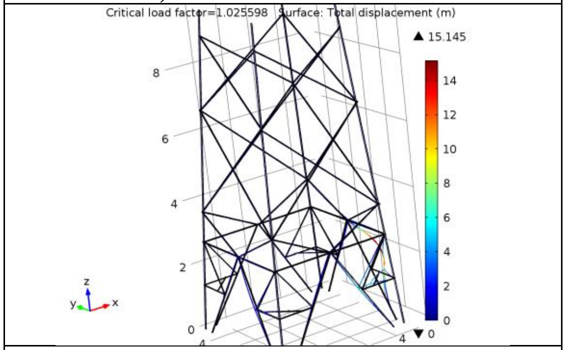
Figure 5. Displacement obtained with COMSOL for Case 1: Tower bottom panel.



a) With redundant steel members



b) Without redundant members

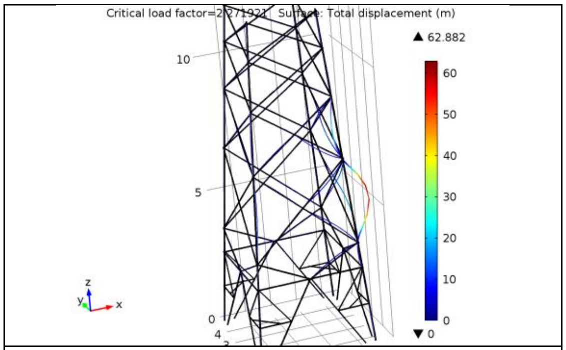


c) With redundant polymeric composite members

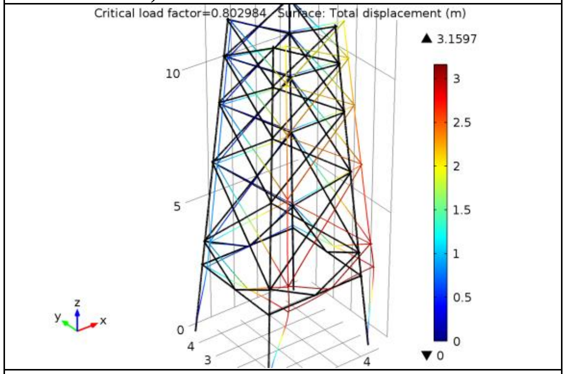
Figure 6. Displacement obtained with COMSOL for Case 2: Half of tower pyramidal body.

7.1 Case 1: Tower bottom panel

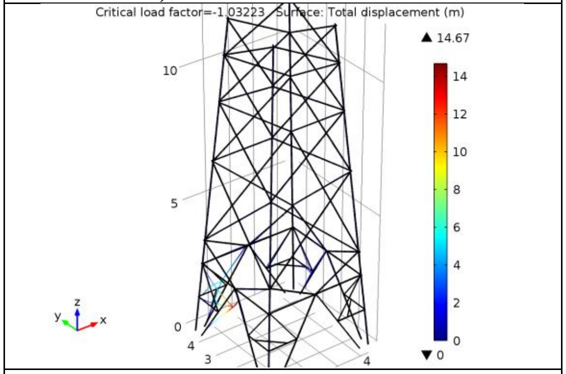
The bottom panel with all its steel members shows a reliability 7.17 times (F_{CL} = 7.17) with respect to the simulated load condition. Its reliability decreases to 1.05 times when redundant and diagonal members are removed, which represents a significant reduction in its stability, since this latest value is very close to a critical condition. The installation of redundant and diagonal members made of composite material instead of steel members may keep the reliability of the structure, as shown by the critical load factor (2.13) obtained for this condition. The displacements in the polymeric composite members (Figure 5c) help to hold the bottom panel stability.



a) With redundant steel members



b) Without redundant members



c) With redundant polymeric composite members

Figure 7. Displacement obtained with COMSOL for Case 3: Tower belt.

7.2 Case 2: Half of tower pyramidal body

The simulation of the structure with all its steel members gives a critical load factor of 2.15 (Table 5).This value means that the structure stability is not compromised. As it can be seen in Figure 6a, the major displacements take place in the diagonal members belonging to the pyramidal body that are closest to points where the loads apply (members in color red).

However, when the members in the bottom panel are stolen, the stability of the tower is at risk, according to the value of obtained critical load factor (F_{CL}=0.72), which is less than 1. The simulated displacements in the structure (Figure 6b) indicate that some main and diagonal members in the pyramidal body suffer buckling. Under this scenario, the structure can collapse.

The use of composite members in the bottom panel, instead of stolen steel members, results in a critical load factor of 1.03 for the simulated structure. This value of the factor means that no structure member suffers buckling, and thus the structure is not in an elastic instability condition. In Figure 6c, it can be observed that the composite members installed in the bottom panel eliminate buckling in the main and diagonal members of the pyramidal body of the structure.

7.3 Case 3: Tower belt

The results are similar to those obtained for the case 2. Namely, the structure keeps its stability if the steel members in the bottom panel are not stolen. In contrary case, the structure can meet a structurally unstable condition. Likewise, the use of composite members in the bottom panel may also keep the mechanical reliability of the structure. The displacements in the structure (Figure 7) show also that the redundant steel members in the bottom panel are not the most stressed, but without them, the structure can fail.

7. Conclusions

The feasibility of use composite material redundant members in the bottom panel of transmission line towers was evaluated using COMSOL. The evaluation was performed by a linear buckling analysis.

Based on the results obtained from the simulations performed in COMSOL, it can be concluded the following:

- Composite materials with Young´s modulus greater than 30 GPa may be a viable option for replacing steel in redundant and diagonal members used in the bottom panel of a transmission line tower.
- In a transmission tower integrated with all its steel members, according to the design requirements, the of mechanical failure risk at normal load conditions (wind force and weight both of the structure and of associated components) is little probable.
- The lack of redundant and diagonal members in bottom panel of a transmission line tower, due to vandalism, can cause buckling in diagonal and main members of pyramidal body of the tower. Therefore, the tower may collapse.
- The use of suitable composite material members in the bottom panel, in instead of steel members, may be an alternative capable of keeping structural stability of a transmission line tower.

8. References

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