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Review Article

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Finite Element Analysis of Glass Fiber Reinforced Polymer Guyed Meteorological Towers: Structural Design and Operational Performance Assessment

Sami Alshurafa[1*], Hanan Alhayek[2] and Dimos Polyzois[2]

[1]*Department of Civil Engineering, University of Pittsburgh Johnstown, Pennsylvania, USA*

[2]*Department of Civil Engineering, University of Manitoba, Winnipeg, Manitoba, Canada*

***Corresponding author:** Sami Alshurafa, Associate Professor, Department of Civil Engineering, University of Pittsburgh Johnstown, Pennsylvania, USA

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Abstract

In recent years, there has been a surge in demand for long-lasting, low-maintenance, corrosion-resistant construction materials to replace steel towers. The current paper presents the results of a theoretical and experimental research project on composite meteorological towers. The theoretical work included developing various models to analyze an 81-meter tower using the finite element program ANSYS and designing the tower to meet the Canadian CSA-S37 Standard and the American specification EIA/TIA-222. The composite tower designed for this application was triangular, consisting of three identical cells joined together to form an equilateral triangle with sides measuring 450 mm. Several parameters were investigated, including the effect of three different laminates with varying stacking sequences of laminae orientations, different laminate thicknesses, cable size, cable spacing, and cable pre-stressing. An 8.6m tower segment was tested under both static and dynamic loads.

Keywords: GFRP; Guyed tower; ANSYS; Meteorological Tower; FEM

Introduction

Steel monopole towers are primarily used as supporting structures for the transmission of radio and telecommunication antennas and transmission lines. They serve as light standards in parks, parking lots, and roadways, as well as supporting traffic signs. Monopoles can be free-standing (radio and telecommunication towers) or guyed towers. Galvanizing protects the steel from corrosion. This method of galvanizing steel members is not always feasible because the size of the steel member to be galvanized is determined by the size of the existing galvanic bath. The galvanized coating on monopole steel structures has deteriorated significantly due to weathering. Such deterioration exposes the steel to the elements and reduces the cross-sectional area of the members over time. The Canadian Standard CSA-S037-01 (2001) "Antennas, Towers, and Antenna-Supporting Structures" and the American specification EIA/TIA-222-F (2003) "Structural Standard for Antenna Supporting Structures and Antennas" specify corrosion-prevention measures for steel towers, including galvanizing, epoxy coating, electric isolation, and cathodic protection. The search for an alternative material for constructing lightweight monopole towers was motivated by the desire to eliminate corrosion and provide a maintenance-free solution. Since there are no standards for composite towers, the new technology was based on the same standards as those governing the quality of construction of steel towers. Several research projects were conducted on the development of GFRP poles for use in electrical transmission

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and distribution networks (Polyzois et al., 1999, 2000 and 2007; Ibrahim and Polyzois, 1999. New technology for analysis, design, and fabrication new generation of multi-cell meteorological guyed GFRP towers was developed by Alshurafa and Polyzois, 2018, and 2019; Alshurafa et al. 2019, 2020, 2021, 2022, and 2023. This paper presents a summary of the results from the finite element analysis of an 81 m GFRP guyed communication tower and results from testing a 9 m tower segment. The FRP tower segment was erected in a vertical position and tested under dynamic loading to obtain natural frequencies of vibrations. Results obtained from a finite element analysis showed a good agreement with the experimental results. Moreover, new design guidelines were also developed in that study. The uniqueness of the work lies in the geometry of the tower, the application of the tower, and the fabrication process. The theoretical analysis was conducted to evaluate both the static behavior and the dynamic behavior (structural vibration) of an FRP 81m meteorological tower under severe loading conditions. This 81m FRP was a guyed tower consisting of 16 segments, as shown in Figure 1.

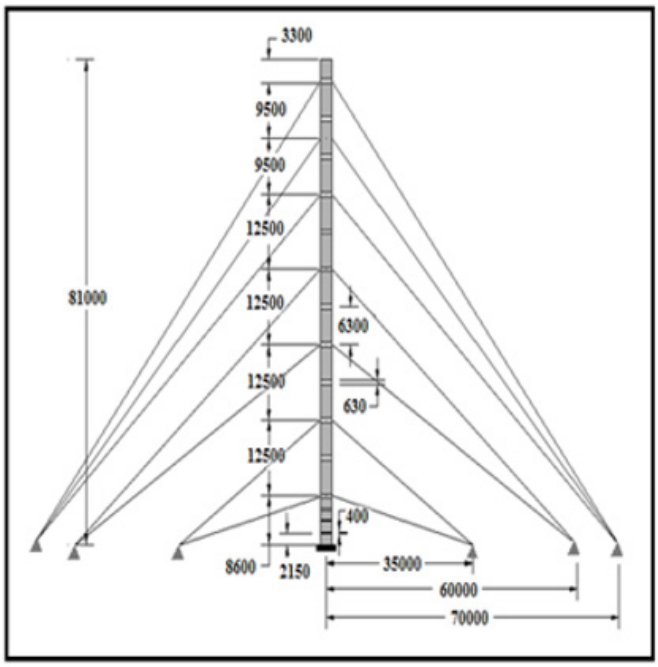


Figure 1: Tower elevation.

All segments had the same cross-section. The bottom segment consisted of four sections each having a length of 2.15m. The top segment had a length of 3.1m, while the remaining eleven segments had a length of 6.3m each. Typically, the bottom 8.6m tower segment would be a single section. The reason for breaking this up into four 2.15m segments was to reflect the actual component of the tower that was fabricated and tested in the lab. Due to equipment limitations, the largest segment that was possible to fabricate in the lab was 2.15m, and the largest tower segment that could fit in the test laboratory was 8.6m. Each of the tower segments consisted of three individual cells bonded together to form an equilateral triangle as shown in Figure 2. Several tower parts were fabricated, assembled into a single tower segment, and tested under static and dynamic loading to confirm the theoretical analysis and design. This paper will present a summary of the results obtained from the finite element analysis of the 81m tower and the 8.6m tower fabricated segment.

Finite Element Analysis

The 81m FRP guyed tower was designed based on the ultimate limit state and the serviceability limit state requirements as specified in the CSA-S037-01 (CSA, 2001) Standard. The factored and service wind loads applied on the 81m FRP guyed tower are shown in Figure 3. These loads were used in the finite element analysis of the 81m guyed tower as well as that of the 8.6m FRP tower segment tested in the lab. Two elements of the ANSYS (2006) library were used to analyze the FRP tower. The elements chosen were SHELL 99 and LINK10. The SHELL 99 element is a 100-layer shell structure and has six degrees of freedom at each node, three translations, and three rotations. ANSYS SHELL 99 element was selected to model the FRP composite tower because of its ability to predict failure using three different failure criteria, the capacity of the element to account for large deflection, cross-section deformation, and the option of handling an unlimited number of layers with constant and uneven thickness. The ANSYS LINK10

element with the tension-only option was chosen to model the guy wires. This element is a three-dimensional element having the unique feature of a bilinear stiffness matrix resulting in a uniaxial tension-only or compression-only element. Each composite cell consisted of four layers of glass matt fiber for a total thickness of 5mm with a sequence of [90 ◦ /0 ◦ /0 ◦ /90 ◦]. The material properties were obtained from coupons with unidirectional fibers tested under tension, compression, and shear. As shown in Figure 4, the maximum deflection of the 81m tower obtained from the FEA was 176.7mm without pre-stressing the cables under the service loads given in Figure 3.

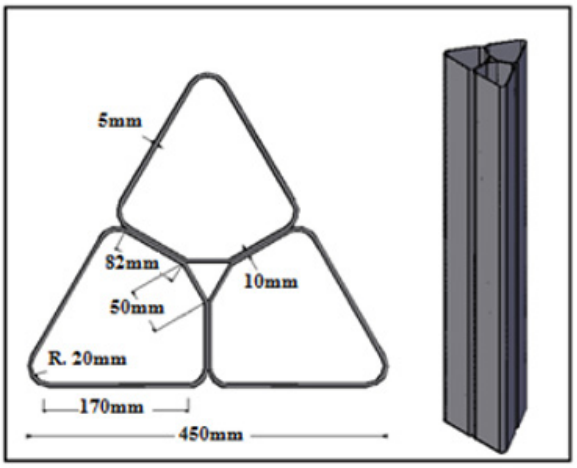


Figure 2: A section consists of 3 cells bonded together to form an equilateral triangle.

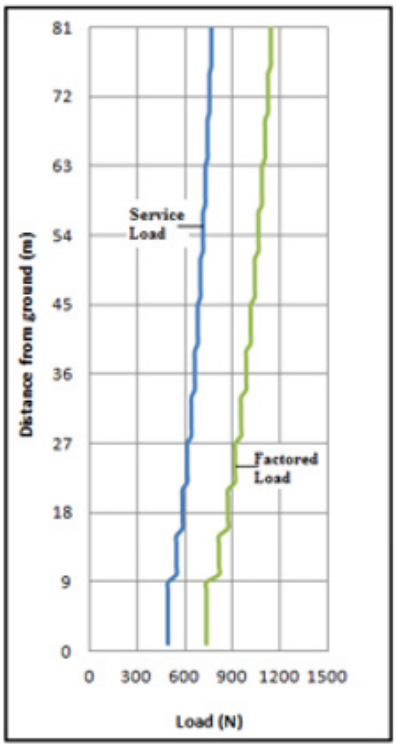


Figure 3: Wind Loads on Tower.

The maximum tensile and compressive stresses obtained from the FEA in the direction perpendicular to the fiber were 13.65MPa and -13.71MPa, respectively. In the direction parallel to fibers, the maximum tensile stress was 28.64MPa and the maximum compressive stress was 25.10MPa. The stresses were obtained under the factored loads shown in Figure 3 and considering the dead weight of the tower and the attached guy cables. An 8.6m tower segment comprising the bottom section of an 81m tower was also analyzed using the FEA. The maximum deflection obtained from the FEA of the bottom 8.6m segment of the 81m FRP tower was 54.2mm while the maximum deflection of the single 8.6m segment was 52.1mm, as shown in Figure 5. It was also found, from the finite element modal analysis, the first flexural of natural frequencies of vibrations of an 8.6m FRP tower segment had a damped natural frequency of .

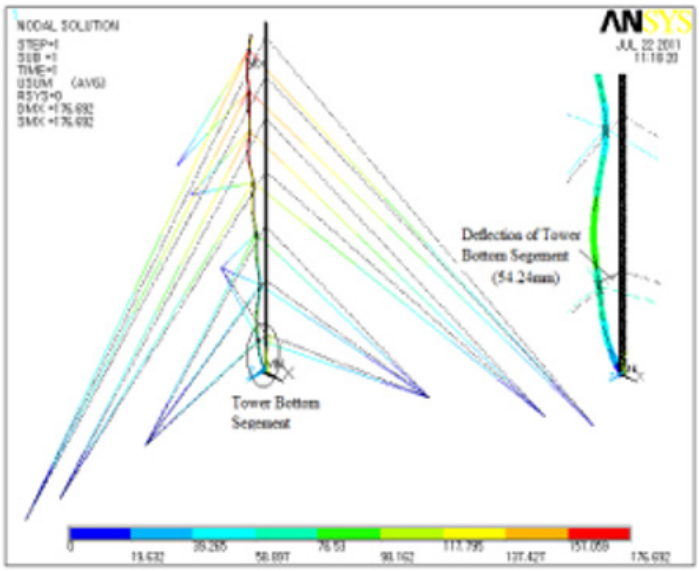


Figure 4: Deflections of 81 m FRP guyed tower obtained from FEA.

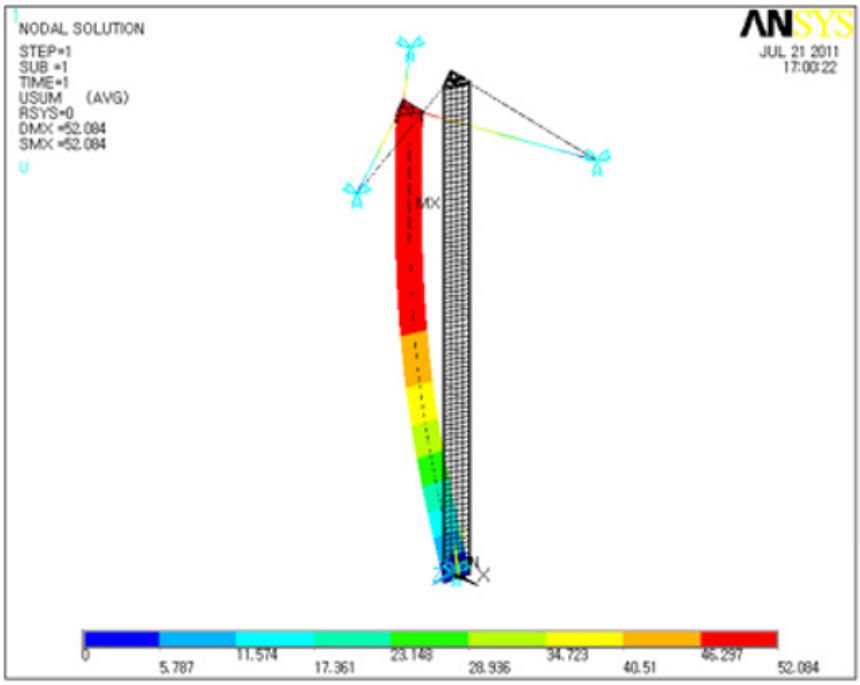


Figure 5: Deflections of 8.6m FRP guyed tower obtained from FEA.

Deflection Analysis with and without Pre-Stressing Cables

To examine the effect of pre-stressing on the performance of the composite tower, the guy cables were pre-stressed to 10% of their breaking strength, as required by Canadian Standard CAN/CSA S307-01. The ANSYS finite element was used to analyze the 81m tower under four conditions: the tower with and without ice and with and without cable pre-stressing. The recommended radial ice thickness for Winnipeg, Manitoba of 12.5mmm was used as given in Overhead Systems CAN/CSA-C22.3 NO. 1-06 Standard (CSA, 2006). The material properties used in ANSYS were obtained from coupon testing having a fiber volume fraction of 40.6%. The deflections obtained from the four cases are summarized in Table 1.

Table 1: Maximum deflection of the tower under service wind load.

Type of Tower Analysis	No Cable Pre-stressing (mm)	With Cable Pre-stressing (mm)
Tower without ice	176.7	69
Tower with ice	99.8	41

The maximum deflection of the tower under service wind loading without pre-stressing the guy cables was 176.7mm. The same tower was analyzed with guy cables pre-stressed to 10% of the breaking strength of cables or 11.96kN. This pre-stressing was equivalent to an initial strain in the cables of 0.000472. The maximum deflection of the tower in this case was 69.0mm, as shown in Figure 6. Similarly, the maximum deflection of the iced tower under service wind loading without and with pre-stressed guy cables was 99.8mm and 41.0mm, respectively. The results demonstrate the importance of pre-stressing the cables.

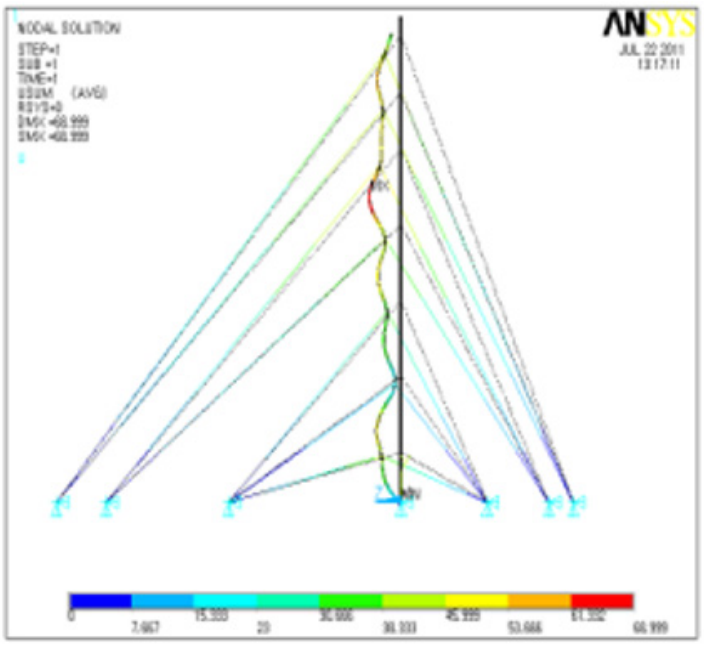


Figure 6: Deflection of 81m FRP tower with cable pre-stressing subject to win.

Experimental Program

Material Testing

A total of 15 unidirectional standard coupons of FRP were fabricated and tested according to current ASTM standards to determine the material properties to be used in the theoretical model. The physical properties obtained from the tested coupons were the tensile modulus, the ultimate tensile strength, the compressive modulus, the ultimate compressive strength, the shear strength, the density of FRP, and the volume fraction of fibre and resin matrix. The test results are shown in Table 2.

Static and Dynamic Testing of an 8.6m FRP Tower Segment

To validate the finite element model developed in this research program, the bottom 8.6m segment of an 81m FRP tower was fabricated and tested under static and dynamic loading in the structural laboratory of the University of Manitoba, as shown in Figures 7 & 8. The load in the static test was applied vertically upward on the tower using a whiffle tree method. The loading arrangements of the whiffle tree applied on the tower were considered to simulate a uniformly distributed lateral load. The

tower specimen was also erected in the vertical position, as shown in Figure 8, to perform a dynamic test in the first flexural mode. The tower was displaced laterally at mid-height to a predetermined amount and was released, allowing it to vibrate freely. A maximum deflection of 49.13 mm was recorded at the mid-span of the 8.6m specimen under a total static load of 12.67kN. This deflection is less than the deflection obtained from the finite element model at that location. The deflection difference between the finite element results at mid-section and that from experimental results was 22.2%. The maximum longitudinal tensile stress at 12.67kN was 36.6MPa. The maximum longitudinal compressive stress at 12.67kN was 29.7MPa. The value of the natural frequency obtained from free vibration test data was found 5.50Hz, this value was less than the value of 6.098Hz obtained from the modal finite element analysis.



Figure 7: Arrangements of whiffle tree applied on tower.



Figure 8: FRP tower segment before release.

Table 2: Material Properties from Coupon Testing.

Parameters	Units	Value
E_1^{tu}	GPa	29.67
E_2^{tu}	GPa	7.13
G_{12}	GPa	2.11
v_{12}^{t}	-	0.29
F_1^{tu}	MPa	587.46
F_2^{tu}	MPa	21.27
F_1^{cu}	MPa	267.15
F_2^{cu}	MPa	71.05
F^{su}	MPa	27.20

Conclusions

The findings presented in this paper provide compelling evidence that FRP can be effectively used in the fabrication of guyed towers. The current research program involved the analysis, design, and construction of a meteorological tower made up of individual cells made of fiberglass matting that were bonded together to form an equilateral triangle. A finite element analysis was used to determine the tower's dimensions and the thickness of the cell walls, which were then chosen using limit states design criteria outlined in the current CSA S037-01 Canadian Standard. The detailed conclusions derived from this research program are summarized below: Several tests were conducted based on ASTM Standards to determine the mechanical properties of the FRP materials coupons. The fibre volume fraction of the FRP used to fabricate the tower segment was 40.6% determined from a burn-off test.

a. Various finite elements models were developed to determine the best lay-up sequence that would result in small deflections, minimized stresses, and reduced the overall weight of the tower. The best lay-up sequence consisted of four layers of glass fibre matting for a total thickness of 5mm with a sequence of [90 ◦ /0 ◦ /0 ◦ /90 ◦].

b. The maximum theoretical deflection obtained from the 8.6m FRP tower was compared well with the theoretical results obtained from the bottom segment of the full-scale 81m FRP tower. An 8.6m FRP tower was fabricated, assembled, and tested in static loading.

c. The deflections obtained through testing of the 8.6m tower segment were smaller than those results obtained from the FEA. As expected, the maximum deflection was recorded at the mid-span. The deflections obtained from the FEA and the experimental testing under a service wind loading of 3.94kN were 19.31mm and 15.66mm, respectively. These deflections correspond to L/445 and L/549, respectively, where L is the length of the tower segment. The deflections obtained from the finite element model and tested under a service loading compared well with the finite element results; and therefore, validated the developed model.

d. The small difference of 8.5% of the natural frequencies of the tower segment obtained from the test and the FE modal analysis confirms the strength of the finite element model as an analysis tool for composite towers.

Acknowledgment

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Conflict of Interest

There is no financial interest, nor any conflict of interest exists.

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