DEVELOPMENT OF METEROLOGICAL TOWERS USING ADVANCED COMPOSITE MATERIALS

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Abstract

The present paper deals with the results from a theoretical and an experimental research program on the development of composite meteorological towers. The theoretical work consisted of developing various models to analyze an 81 m tower using the finite element program ANSYS and to design this tower in accordance with the Canadian Standard CSA-S037. The composite tower developed for this application had a triangular shape comprised of three identical cells jointed together to form an equilateral triangle, each side measuring 450 mm. The cells were designed to be fabricated through the filament winding method using a collapsible mandrel designed and fabricated specifically for this project. Unfortunately, the filament winder was not available at the time and the cells were fabricated using four layers of unidirectional glass fibre mats with a sequence [90°, 0°, 0°, 90°] and a weight of 1285g/m^2. Each layer was saturated with a mixture of 105 epoxy resin and 205West System hardener. The mechanical properties of the composite layers were obtained through testing of several coupons. Various parameters were investigated theoretically, including: the effect of three different laminates that contained a variety of stacking sequence of laminae orientations; various thicknesses for each laminate; the effects of fibre volume fractions; and, various sizes and location of guy cables. An 8.6 m tower segment was tested under static and dynamic load to verify the theoretical model. In addition, a comparative analysis was carried out between an 81 m composite tower and a steel tower both designed to resist identical loading conditions. The test results confirmed the validity of the theoretical model.

1 Introduction

1.1 Project Description

Steel monopole guyed towers are mainly used as supporting structures for transmission of radio and telecommunication antennas, and transmission lines. Monopoles can be free standing, such as power transmission towers, or guyed, such as radio and telecommunication towers. The Canadian Standard CSA-S037 [1] and the American Specification TIA-222F [2] require that additional corrosion preventing measures, such as galvanizing, epoxy coating, electric isolation, or cathodic protection, be taken to prevent corrosion of steel towers.

Monopole steel structures have shown significant deterioration of the galvanized coating caused by weathering. Such deterioration exposes the steel area to weather and causes a decrease of the cross sectional area of the members over time. The main advantage of using FRP as alternative materials over conventional steel for meteorological towers is their resistance to corrosion and their high strength-to-weight ratio. The current research project involved both theoretical and experimental work. This paper presents a summary of the results from the finite element analysis of an 81 m FRP guyed tower as well as a summary of the results from the testing of an 8.6 m segment. The 81 m tower examined in this paper was made up of 16 segments, as shown in Fig. 1, and had a uniform cross section consisting of three identical composite cells bonded together to form an equilateral triangle, as shown in Fig. 2.

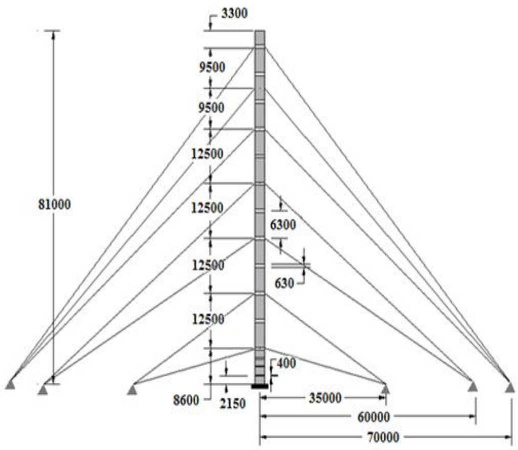

Fig.1 - Tower Elevation (Units are in mm)

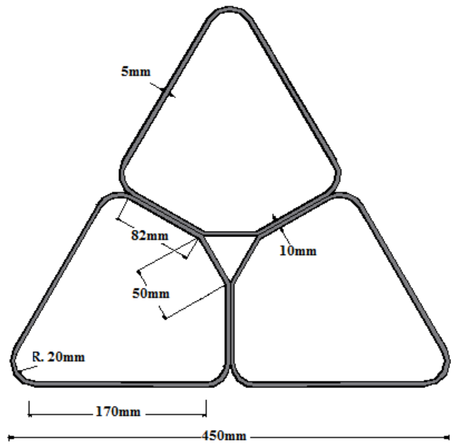

Fig. 2- Tower Cross Section (Units are in mm)

Due to equipment limitations, the largest segment that was possible to fabricate was 2.15 m and the largest tower that could fit in testing laboratory was 8.6 m. Thus, this test specimen was made up of four 2.15 m sections, each of which consisted of three cells, as shown in Fig. 2. The individual cells were inter-connected using sleeve joints, as shown in Fig. 3. Each composite cell was fabricated using four layers of glass fibre matting for a total thickness of 5 mm with a sequence of [90°, 0°, 0°, 90°] impregnated in epoxy resin. No 45° fibre matting was used since the anticipated shear stresses due to bending at the ends of the test segment were quite small and deflection criteria would govern the design.

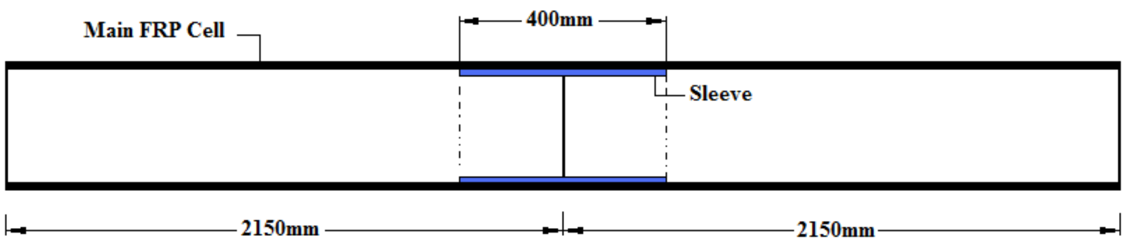

Fig. 3 - Tower Cells Interconnected With Sleeves

1.2 Literature Review

A number of projects have been carried out at the University of Manitoba over the last 15 years on the development of FRP poles for use in electrical transmission and distribution networks by Polyzois et al. [3, 4, 5]; Ibrahim and Polyzois [6]; and, Ibrahim et al. [7]. Polyzois et al. [8] also investigated the minimum joint length required to develop the full capacity of jointed FRP poles. Based on their test results, the authors recommended a minimum joint length of 1/10 of the length of a segment being jointed. Polyzois et al. [9] expanded the research on composite poles to include composite wind turbine towers and composite meteorological towers. Polyzois and Ungkurapinan [10] received a North American patent for their composite wind turbine tower technology.

Research on the development of meteorological towers began by Ochonski [11] who experimented with filament wounding latticed towers. He fabricated an 8.53 m FRP guyed latticed tower and tested it under static loading using a multiple point load arrangement that simulated a uniformly distributed wind loading. The same FRP tower segment was also 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 his experimental results. While the technology developed by Ochonski is quite promising, the high cost associated with the fabrication of the specimens necessitated a search for an alternative type of a meteorological tower, one that would be less expensive to fabricate and yet satisfy current standards.

2 Finite Element Method (FEM)

The design of the 81 m FRP monopole guyed tower was designed based on the ultimate strength limit state and the serviceability limit state requirements as specified in the CSA-S037-01 Standard [1]. The factored and service wind loads applied on the 81 m FRP guyed tower are shown in Fig. 4. These loads were used in the finite element analysis of the 81 m guyed tower as well as that of the 8.6 m FRP tower segment tested in the lab. Two elements of the ANSYS [12] 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 by means of three different failure criteria, the capacity of the element to account for large deflection, cross section deformation, and the option of handling 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 5 mm with a sequence of [90˚,0˚,0˚,90˚].

The material properties used in ANSYS program were obtained from coupon testing manufactured from the same material of the fabricated tower segment having a fibre volume fraction of 40.6% with unidirectional fibers tested under tension, compression and shear. As shown in Fig. 5, the maximum deflection of the 81 m tower with non-prestressed guy cables under the service loads shown in Fig. 4 obtained from the FEA was 176.7 mm. The maximum tensile and compressive stresses obtained from the FEA in the direction perpendicular to the fiber were 13.65 MPa and -13.71 MPa, respectively. In the direction parallel to fibers, the maximum tensile stress was 28.64 MPa and the maximum compressive stress was 25.10 MPa. The stresses were obtained under the factored loads shown in Fig. 4 taking into account the dead weight of the tower and the attached guy cables.

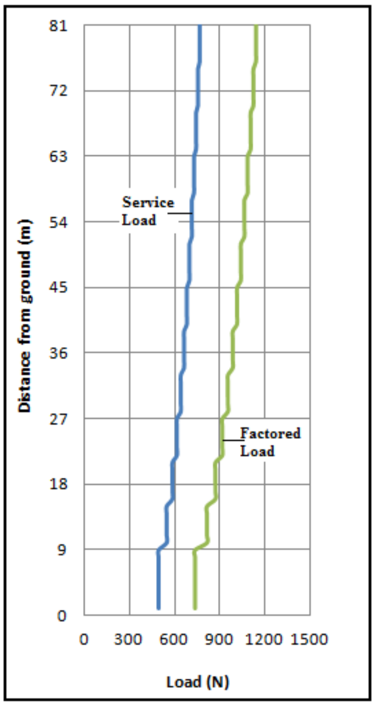

Fig. 4 - Wind Loads on Tower

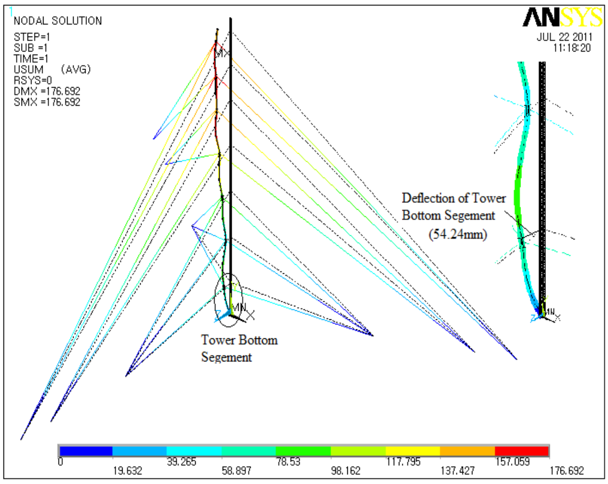

Fig. 5- Deflections of 81 m FRP guyed tower obtained from FEA

Mechanical properties corresponding to a fibre volume fraction of 65% were also used in the ANSYS finite element program to analyze the FRP tower in order to assess the structural behaviour of the same tower. The deflection of the 81 m tower without pre-stressed guy cables is shown in Fig. 6. According to the finite element results, the increase in fibre volume fraction from 40.6% to 65% resulted in a decrease in the maximum deflection from 176.7 mm (Fig. 5) to 152.8 mm (Fig. 6), a reduction of 13.5 % when the cables were not pre-stressed. By increasing the fibre volume fraction to 65%, the mass of the tower was also increased by

27%. As a result, increasing the volume of the fibre fraction leads to an increase in the stiffness of the tower mast resulting in a reduction in the lateral deflections.

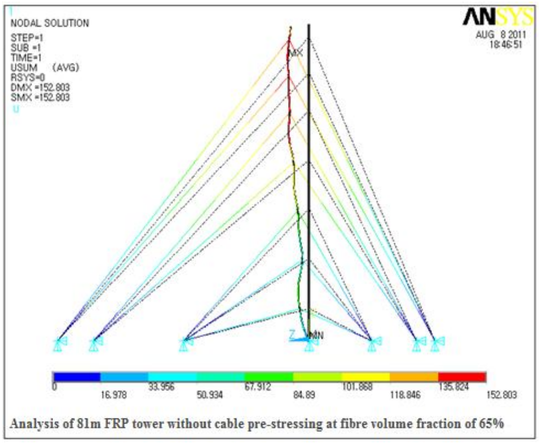

Fig. 6- Deflected shape of composite tower with fibre volume fraction of 65% and without pres-stressing the cables

An 8.6 m tower segment comprising the bottom section of an 81 m tower was also analyzed using the FEA. The maximum deflection obtained from the FEA of the bottom 8.6 m segment of the 81 m FRP tower was 54.2 mm while the maximum deflection of the single 8.6m segment was 52.1 mm, as shown in Fig. 7. It was also found, from the finite element modal analysis, the first flexural of natural frequencies of vibrations of an 8.6 m FRP tower segment had a damped natural frequency of f_d=6.1 Hz.

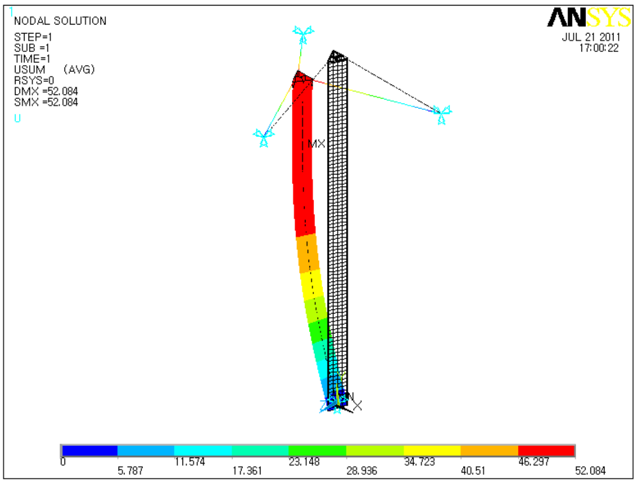

Fig. 7 -Deflections of 8.6m FRP guyed tower obtained from FEA

3 Experimental Programs

3.1 Material testing

A total of 15 unidirectional standard coupons of FRP were fabricated and tested according to ASTM standards D3039 [13], D3410 [14] and D5379 [15] in tension, compression, and shear to determine the material properties required in the FEA. The mechanical properties obtained from these tests are listed in Table 1. The volume fraction of the fibre in the composite material was 40.6 %, determined through a burn-off test.

Parameters		**Units**	**Average Value**	**Coefficient of Variation (%)**
Elastic modulus in the fibre direction	E_1^{tu}	GPa	29.67	1.43
Elastic modulus in the transverse fibre direction	E_2^{tu}	GPa	7.13	2.88
Shear modulus	G_{12}	GPa	2.11	7.80
Poison’s ratio	v_{12}^{t}	-	0.29	5.70
Ultimate tensile strength in the fibre direction	F_1^{tu}	MPa	587.46	2.89
Ultimate tensile strength in the transverse fibre direction	F_2^{tu}	MPa	21.27	5.25
Ultimate compressive strength in the fibre direction	F_1^{cu}	MPa	267.15	5.25
Ultimate compressive strength in the transverse fibre direction	F_2^{cu}	MPa	71.05	2.90
Ultimate shear strength	F^{su}	MPa	27.20	5.4

Table 1- Material Properties from Coupon Testing with Fibre Volume Fraction of 40.6%

3.2 Static and Dynamic Testing of an 8.6 m FRP Tower Segment

In order to validate the finite element model developed in this research program, an 8.6 m FRP tower was fabricated and tested under static load, as shown in Fig. 8, and under dynamic loading, as shown in Fig. 9.

Fig.8-Static Loading Through of Whiffle Tree System

Fig.9- Dynamic test of FRP Tower Segment

To simulate a uniformly distributed lateral load on the tower, the static load was applied vertically upward using a whiffle tree system, as shown in Fig. 8. The deflections at quarter points and at mid-span of the tower were monitored by a four Linear Variable Displacement Transducers. The strains were monitored through 30 strain gauges mounted on various locations on the tower specimen. The specimen was loaded to a maximum load of 12.67 kN, corresponding, approximately, to 80% of the its theoretical ultimate capacity. The test results for strain and deflection, along with the FEA results, are shown in Figs. 10 and 11. The maximum deflection at mid-span was 49.1 mm. This deflection is less than the deflection of 60.0 mm obtained from the FEA at that location. The difference of 22.2% indicates that the

FEA overestimates the deflections. This is understandable given the fact that the FEA is based on a number of assumptions which underestimate the stiffness of the tower.

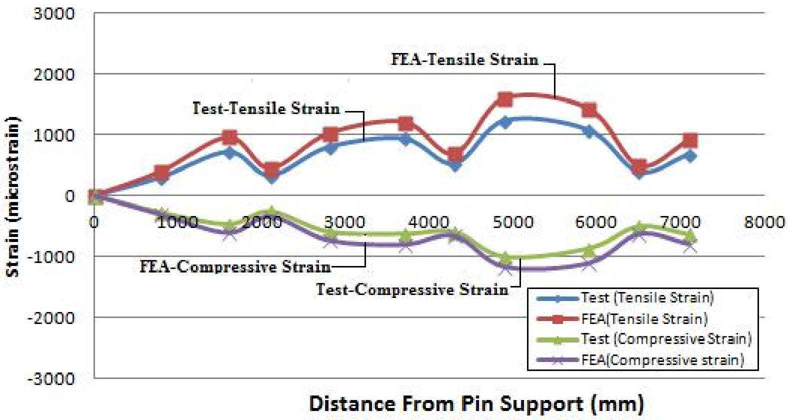

Fig. 10 - Strain variation along the FRP tower segment at 12.67kN

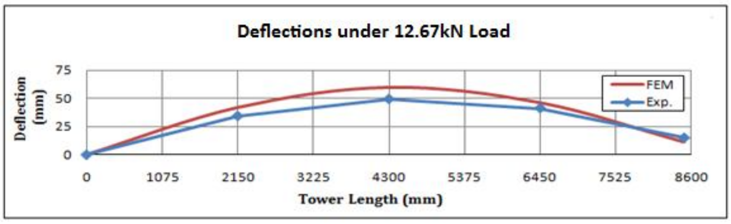

Fig. 11 - Deflection of Tower Specimen at 12.67kN

The maximum longitudinal tensile and compressive stresses at 12.67 kN were 36.6 MPa and 29.7 MPa, respectively. Theses stresses were about 6.3% and 11.1% of the maximum longitudinal tensile and maximum longitudinal compressive stresses, respectively, obtained from coupon testing. The lower stiffness of the tower in the FEA prodused maximum longitudinal tensile and compressive stresses that were 29.6% and 16.8% higher than the tensile and compressive stresses obtained through static testing, respectively. The tower specimen was also erected in the vertical position, as shown in Fig. 9, 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. The value of the natural frequency obtained from free vibration test was 5.5 Hz. This value was less than the value of 6.1 Hz obtained from the modal FEA.

4 Conclusions

The research results presented in this paper provide convincing evidence that FRP can be effectively used for the fabrication of guyed towers. The present research program involved the analysis, design and fabrication of a meteorological tower composed of individual cells fabricated from fibre glass matting bonded together to form an equilateral triangle. The dimensions of the tower and the thickness of the cell walls were determined from a FEA and were chosen on the basis of limit states design criteria, as stipulated in the current CSA-S37 Standard. The FEA showed that the tower was more flexible than the test specimen and yielded results for deflections and stresses that were higher than the test results.

5 Acknowledgment

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6 References

[1] Canadian Standard Association (CSA), "Antennas, Towers and Antenna-Supporting Structures: CSA-S37-01", Mississauga, Ontario, Canada, 2001.

[2] Telecommunication Industry Association (TIA), "Structural Standards for Steel Antenna Towers and Antenna Supporting Structures: ANSI/TIA-222G", Virginia, USA, 2005.

[3] Polyzois, D., Raftoyiannis, I., and Ibrahim, S., "Finite Element Method for the Dynamic Analysis of Tapered Composite Poles", *Journal of Composite Structures*, **43**, 25–34, 1998.

[4] Polyzois, D., Ibrahim S, and Raftoyiannis I., "Performance of Fibre-Reinforced Plastic Tapered Poles Under Lateral Loading", *Journal of Composite Materials*, **33(10)**, 941–59, 1999.

[5] Polyzois, D., Ibrahim, S., Burachynsky, V., and Hassan, S., "Fibre Reinforced Plastic Poles for Transmission and Distribution Lines: An Experimental Investigation", *Journal of Composite Manufacturing*, **16(4)**, 1–7, 2000.

[6] Ibrahim, S., Polyzois, D., and Hassan, S., "Development of Glass-Reinforced Plastic Poles for Transmission and Distribution Lines", *Canadian Journal of Civil Engineering*, **27**, 1–9, 2000.

[7] Ibrahim, S., and Polyzois, D.,"Ovalization Analysis of Fibre-Reinforced Poles", *Journal of Composite Materials*, **45**, 7-12, 1999.

[8] Polyzois, D., Raftoyiannis, I., and Philopulos D., "An Experimental Survey of the Static and Dynamic Behaviour of Jointed Composite GFRP Tapered Poles", *Journal of Mechanics of Advanced Materials and Structures*, **14:3**, 203-212, 2007.

[9] Polyzois, D., Raftoyiannis, I., and Ungkurapinan, N., "Static and Dynamic Characteristics of Multi-Cell Jointed GFRP Wind Turbine Towers", *Journal of Composite Structures*, **90**, 34-42, 2009.

[10] Polyzois, D., and Ungkurapinan, N., "Composite Wind Tower Systems and Methods of Manufacture", Patent No.: US7866121B2, 2011.

[11] Ochonski, A., "Development of Latticed Towers Using Advanced Composite Materials", Ph.D. Dissertation, University of Manitoba, Canada, 2009.

[12] ANSYS, "*ANSYS User's Manual Version 10*", Swanson Systems Inc., Houston, USA, 2005.

[13] American Society for Testing and Materials (ASTM), "Standard Test Methods for Tensile Properties of Polymer Matrix Composite Materials: ASTM-D3039/D 3039M", West Conshohocken, PA 19428-2959, USA, 2007.

[14] American Society for Testing and Materials (ASTM), "Standard Test Methods for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading: ASTM-D3410/D 3410", West Conshohocken, PA 19428-2959, USA, 2003.

[15] American Society for Testing and Materials (ASTM), "Standard Test Methods for Shear Properties of Composite Materials by the V-Notched Beam Method: ASTM-D5379/ D 5379M", West Conshohocken, PA 19428-2959, USA, 2000.