# Analysis and Design of a New Generation GFRP Wind Turbine Tower

**BY**
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# Abstract

The focus of the research program is to analysis and design of a new generation glass-fibre reinforced polymer (GFRP) wind turbine tower for full scale prototype testing. The study includes the finite element analyses of different tower section configurations, the parametrical study of different variables, the selection of appropriate configuration and dimensions, and the finalization of the section. The design section arrived from this study has the bottom outer diameter of 1350 mm, the top outer diameter of 800 mm, the constant inner diameter of 600 mm and uniform wall thickness of 11.25 mm. The tower is also analysed and compared with a steel tapered tower. The analysis results indicate that the tower is considered as a soft-soft tower and that, in general, the lateral deflection limitation is a governing factor in the design of GFRP wind turbine tower. The proposed section met all the design requirements and the fabrication drawings are provided for the further study of full scale test.

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The author would like to dedicate this work to his loving parents Md Abdus Sabur and Sofia Begum, without their support it would not be possible for the author to study overseas. Once again, the author is tempted to show due honour and respect to Dr. Nipon Rattanawangcharoen for sparing a substantial portion of his valuable time during the research period.

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## List of Symbols

| | |
|---|---|
| $E_1$ | Modulus of elasticity of composite in the fibre direction |
| $E_f$ | Modulus of elasticity of the fibre |
| $E_m$ | Modulus of elasticity of the matrix |
| $V_f$ | Fibre volume fraction |
| $E_2$ | Modulus of elasticity of composite perpendicular to the fibre direction |
| $G_{12}$ | The shear modulus of composite |
| $G_f$ | Fibre shear modulus |
| $G_m$ | Matrix shear modulus |
| $v$ | The Poisson's ratio of the composite |
| $v_f$ | The Poisson's ratio of the fibre |
| $v_m$ | The Poisson's ratio of the matrix |
| $\rho_2$ | Density of the composites |
| $\rho_f$ | Fibre density |
| $W_f$ | Fibre weight fraction |
| $\rho_m$ | Matrix density |
| $W_f$ | Fibre weight fraction |
| $S_{1T}$ | Ultimate tensile strength in the fibre direction |
| $S_{2T}$ | Ultimate tensile strength in the transverse fibre direction |
| $S_{1C}$ | Ultimate compressive strength in the fibre direction |
| $S_{2C}$ | Ultimate compressive strength in the transverse fibre direction, |
| $\sigma_{ij}$ | Ultimate shear strength |
| $\sigma_1$ | Stress in the fibre direction |

| | |
|---|---|
| $\sigma_2$ | Stress perpendicular to fibre direction |
| $I_{F\max stress}$ | Failure index for the maximum stress criterion |
| $I_{FTSai-wu}$ | Failure index for the Tsai-Wu failure criterion |
| $C_{ij}$ | Coupling Coefficients |
| $\rho$ | Air density |
| $\sigma_c$ | Critical buckling stress |
| $f_n$ | Tower natural frequency |
| $f_p$ | Rotor frequency |
| $f_{bp}$ | Blade passing frequency |
| $v_{avg}$ | Average wind velocity at hub height |
| $F_x$ | Thrust force in x direction due to rotation of rotor |
| $F_y$ | Force in y direction due to rotation of rotor |
| $F_z$ | Thrust force in z direction due to rotation of rotor |
| $M_x$ | Moment in x direction due to rotation of rotor |
| $M_y$ | Moment in y direction due to rotation of rotor |
| $M_z$ | Moment in z direction due to rotation of rotor |
| $e_m$ | Mass eccentricity for the rotor |
| $R$ | Rotor radius |
| $P_n$ | Mean pressure on rotor swept area |
| $C_{fb}$ | Pressure coefficient |
| $v_r$ | Rated wind spend |
| $A$ | The rotor swept area |

| | |
|---|---|
| $e_w$ | The eccentricity of wind turbulence force |
| $w$ | An extreme wind gradient over the rotor swept area |
| $P_{el}$ | The electrical power output of turbine |
| $k_b$ | Gust factor |
| $P_b$ | Mean pressure on rotor swept area |
| $\alpha$ | Exponential factor |
| $P_s$ | The stagnation pressure |
| $e_r$ | Rotor blade eccentricity |
| $m$ | Mass of the rotor blade |
| $\omega$ | Angular velocity of the rotor |
| $F_{x\ \text{shaft}}$ | Thrust force in shaft |
| $v_{avg}$ | Average wind velocity at hub height |
| $C_T$ | Thrust coefficient |
| $V_{design}$ | Design Wind Speed |
| $V_{hub}$ | Wind Speed at hub height |
| $V_{ref}$ | Wind speed at reference height |
| $B$ | Number of blades |
| $C_d$ | Drag coefficient |
| $A_{\text{proj},B}$ | Plan form area of blade |
| $v_{e50}$ | Reference wind velocity at hug height in 50 years recurrence period |
| $A_{\text{proj}}$ | Nacelle/turbine component area projected to wind direction |
| $C_f$ | Force coefficient |
| $F_{x\ \text{component}}$ | Wind force on turbine component |

| | |
|---|---|
| $P$ | Design wind pressure |
| $N$ | Reynolds's number |
| $C_d$ | Drag factor for smooth pole structure |
| $A_s$ | Net projected area of tower |
| $A_i$ | Net projected area of tower including ice |
| $H_x$ | Height above ground |
| $C_g$ | Wind gust factor |
| $C_a$ | Roof wind speed up factor |
| $W$ | Wind load |
| $I$ | Ice load |
| $D$ | Dead load |
| $P_f$ | Factored Load |
| $P_s$ | Load in Service |
| $\alpha_D$ | Dead load factor |
| $\psi$ | Combination factor |
| $\alpha_w$ | Wind load factor |
| $\alpha_i$ | Ice load factor |
| $h^*$ | Reference height |
| $e_m$ | Mass eccentricity of the rotor system |

# Chapter 1 Introduction

Wind is a green and renewable natural resource with numerous benefits. Wind power is the conversion of wind energy into electrical power using wind turbines. Wind power is already a major source of energy across Europe. In 2012, installed wind power capacity in the European Union totalled 105 GW which is 7% of the EU's electricity. By 2020, 230 GW of wind capacity will be installed in Europe, consisting of 190 GW onshore and 40 GW offshore. This would produce 14-17% of the EU's electricity (European Statistics, 2012). Even though, Canada has one of the world's best wind resources, it is behind other countries in utilizing wind power. At the end of 2011, wind power generating capacity was 5.2 GW, providing only 2.3% of Canada's electricity demand. The Canadian Wind Energy Association has outlined a future strategy for wind energy that would reach a capacity of 55 GW by 2025; meeting 20% of the country's energy needs (Can WEA Wind vision 2025, 2008). Hence, significant research, experiment and development are required to meet the targeted goal set by Canadian Wind Energy Association.

Steel have been commonly used as the wind turbine tower for many years. A durable and cost effective construction material with sufficient strength, low transportation and low maintenance cost has become important to replace steel in the recent years. With the advancement in the technology, Fibre Reinforced Polymer (FRP) composite material is considered to be a competitive alternative for steel in the next decades. The main advantages of using FRP as an alternative over the conventional steel for wind turbine towers are:

- Higher strength-to-weight ratio in comparison to steel;
- Fewer problems relating to heat, conductivity, and climatic conditions than steel;

- More superior corrosion resistance than steel;
- Half the price of stainless steel, yet up to 5-10 times longer lasting than stainless steel in very corrosive environments (wateronline.com, July 2013);
- Lighter weight than aluminum or steel. FRP weight is approximately 2/3 that of aluminum or ¼ the weight of steel. This makes it cheaper to transport and erect;
- Recent resin improvements relative to heat, impact, and crack resistance are encouraging extensive use of FRP in comparison to metal;
- Good insulating material which can prevent electric short circuit compared to steel;
- Adhesive strength and elongation of resins can help absorb equipment vibration (wateronline.com, July 2013).

To ensure the FRP's proper use as a wind turbine tower material, extensive research and experimental works are required. Over the last fifteen years, the University of Manitoba in Winnipeg, Canada, has been conducting research in the development of FRP towers to be used as a wind turbine tower. To meet this goal, Ungkurapinan (2005) developed CFRP wind turbine towers, Alshurafa (2012) developed GFRP meteorological towers and the current research is a continuation of the past research to establish GFRP as a wind turbine tower material.

## 1.1 Research Objectives

The focus of the research study is to arrive with a design of a 80 feet (24.3 m) high new generation ice bearing 10 kW power producing wind turbine tower using Glass Fibre Reinforced Polymer (GFRP). More specifically, the main tasks of this study include:

- The evaluation of the material properties of unidirectional composite layers using conventional formulas for the finite element analysis (FEA);
- The determination of the rotor loads for the 10kW turbine at the tower's top;
- The determination of the wind and ice loads for the 24.3-m high wind turbine tower;
- The development of the FEA models for eight-, ten-, and twelve-cell towers to investigate their structural behaviour under the wind, ice, and turbine loadings;
- The selection of an appropriate-cell section based on the tower serviceability limit and the tower weight and further customization from the fabrication point of view;
- The development of the FEA model for the proposed design section;
- The optimization of the proposed design cross-section;
- The nonlinear static analysis of the proposed tower including the tower deflection, the failure analysis and the buckling analysis;
- The free vibration analysis of the proposed tower;
- The prediction of the failure lateral loads for the proposed tower;
- The comparison between a steel and the proposed GFRP towers; and
- The preparation of the fabrication drawings.

## 1.2 Scope

The scopes of the study are:

- The wind turbine tower height is 80 feet (24.3 m);
- Fix-based support condition is used;
- 8-, 10-, and 12-cell cross sections are considered;
- Fibre volume ratio investigated for 45%;

- The tower is designed for 10 kW production capacity;
- The wind turbine is designed to be erected in St. Jones, Newfoundland, Canada.

### 1.3 Outline of Thesis

This thesis contains five chapters and seventeen appendixes. The first chapter outlines of a general introduction and a list of objectives and the scopes of the study. The second chapter provides an overview of wind turbine towers, past research on multi-cell FRP wind turbine towers, the formulas required for determining the material properties of the FRP composites, the material failure criteria and the buckling of unidirectional composite. The third chapter contains the tower design requirements as well as the standards for determining the designed loads. The fourth chapter presents the design of a 10 kW wind turbine tower. The final chapter contains the discussions, conclusions of the present study and the recommendations for the future work.

# Chapter 2 Background

This chapter presents an overview of wind turbine towers, a brief review of the literature relating to the FRP wind turbine towers, properties of composites, the material failure criteria and buckling of unidirectional lamina.

## 2.1 Wind Turbine Towers

The wind turbine tower places the wind turbine at a certain elevation where desirable wind characteristics are found. It houses many electrical components, connections and the control protection systems and provides access area to the wind turbine. Most importantly, the wind turbine tower supports the wind turbine that carries the loads generated from the turbine.

### 2.1.1 Types of Wind Turbine Towers

There are mainly two types of wind turbine towers commonly used for the horizontal-axis wind turbines: guyed towers and monopole towers, Figure 2.1.

A guyed tower is a tower supported by guy wires. The use of guy wires lowers the initial cost of the tower because it requires less tower material. However, the maintenance costs for the guy wires add more costs to the operation for large scale towers. Therefore, the guyed towers are popular for small wind turbines. The main disadvantages of the guyed towers are owed to the fact that they are not easily climbable for inspections or repairs and that they require more land than monopole towers. The guyed tower can either be a lattice or tubular type.

(a) ( b) (c) (d)

**Figure 2.1:** Common types of wind turbine tower: a) Guy-latticed wind turbine tower b) Guyed tubular wind turbine tower c) Monopole tubular tower d) Monopole lattice tower (Image source: www.freedigitalphotos.net, July 2013)

A monopole wind turbine tower is also named a free standing tower. It is the most common type of wind turbine towers. The monople tower can also be latticed or tubular type. Many tubular towers are either tapered or stepped with larger diameter at base. The thickness of the wall can also varies along the height of the tower to save the material while satisfying the structural requirements.

## 2.2 Past Research on FRP Wind Turbine Towers

Research studies to achieve a light weight wind turbine tower with FRP are not new. Several FRP tower patents have been filed including the one by the University of Manitoba.

Livingston et al. (2002) developed and tested the components of an 80-m tower for a 1.5 MW turbine using space frame carbon fiber-reinforced polymer (CFRP) tubes (Figure 2.2).They reported the tower weight and cost less than 20 and 25 percent ,respectively, in comparison to steel tower. The program ended, however, in 2005, without a commercial product.

**Figure 2.2:** Composite space frame wind turbine tower (Livingston et al. 2002)

European Laboratory for Structural Assessment (Gutiérrez et al. 2003) conducted an experiment on the 1/3 scaled GFRP wind turbine (Figure 2.3). The full scale tower was 50 m high with 3.5 m uniform diameter cross section. The composite tower design met both the serviceability and the limit load design criteria; however it was reported that the production did not meet the quality assurance. The lay-up and fibre volume fraction of the skins was not sufficient to guarantee the generation of the required material properties. More importantly the shear transfer between the concrete base and the inner and outer skins of the composite tower was very poor.

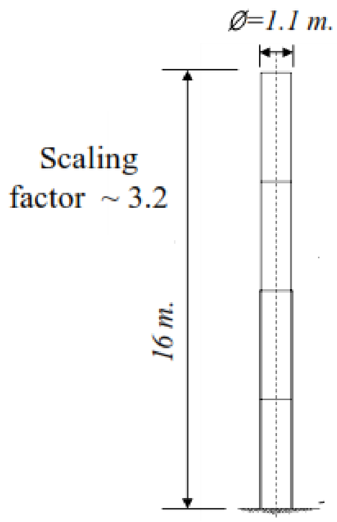



**Figure 2.3:** Prototype specimen of 50 m long tower (Gutiérrez et al., 2003)

At the University of Manitoba, Ungkurapinan (2005) carried out experiments on multi-cell CFRP wind turbine towers. His works was patented later in 2011 (US Patent No. 7866121). In his study, he included the design and fabrication of a robotic filament winding machine that was used to fabricate a single and a multi-cell composite segment and tower specimens. Both experimental and theoretical studies were conducted to investigate the structural performance of the multi-cell composite wind turbine towers. The experimental program was carried out in three phases. In the first phase, two tests of a single cell specimen under a lateral loading were performed. The second phase contained two tests of a single cell specimen in compression. The third phase of the experimental investigation involved two tests of an eight-cell jointed CFRP towers subjected to a lateral loading. Summary of the results are as follow.

***Phase I: Single cell under a lateral load***

The load-deflection relationship was found to be linear behavior up to the point of local buckling. A sudden drop in the load was observed after local buckling occurred. The failure mode was local buckling on the compression side near the fixed base. There was no other sign of failure, such as cracking or crushing of the resin or fiber during the tests at any part of the specimens.

***Phase II: Single cell under a compression load***

Specimens failed by local buckling. It was found that the FEA results had a strong correlation with the results obtained from the experimental program. The average ratio of the experimental-to-theoretical failure load was 0.891 with a coefficient of variation of 0.48 percent.

***Phase III: Multi-cell towers under a lateral load***

The load-deflection relationship was found to be linear up to 84 percent of the ultimate load. At higher load levels a nonlinear behavior was observed due to the accumulation of the damage and the progressive failure on a micro scale of the tested specimens. The specimens failed by local buckling on the compression side near the base. The experimental results were validated by numerical analysis on ANSYS. It was found that Tsai –Wu failure criterion value obtained from the analysis was less than unity at the ultimate load which indicated that the failure did not occur from a material failure. An attempt to repair one of the towers and retest it was unsuccessful. The repaired tower was able to reach the ultimate capacity of the original tower but the deflections were too large.

From the validated finite element model, he conducted an FEA of a 50-m high, eight-cell 750 kW CFRP wind turbine tower (Figure 2.4) and concluded that the serviceability limit for lateral deflection was the controlling factor in the design of the FRP wind turbine towers and not the local buckling or material failure.

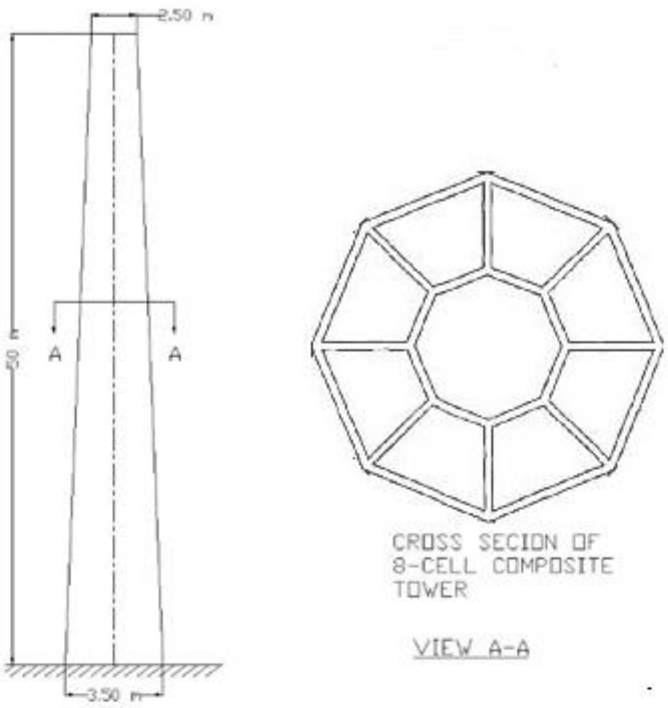



**Figure 2.4:** 50-m CFRP 750 kW wind turbine tower (Ungkurapinan, 2005)

Ching et al (2012) patented a manufacturing procedure to arrive with a composite wind turbine (Figure 2.5) that can have a tensile modulus of 20 GPa to approximately 200 GPa, while keeping the tower weight low (US Patent No. US8192572). This improved tensile modulus of the composite wind turbine tower also results in an increase in the tower frequency range, which makes the tower less prone to the excitation modes under varying turbine operational and wind loads.

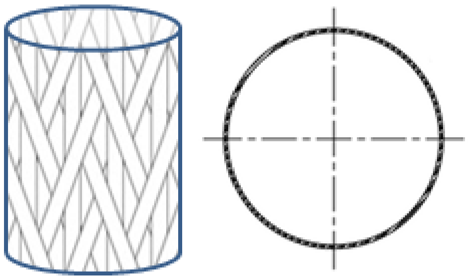


**Figure 2.5:** Sectional view and fibre orientation of the patented composite wind turbine tower (US Patent No. US8192572)

Lim et al (2013) re-designed an existing 80-m, 2 MW wind turbine steel tower with a 100-m GFRP tower. The designed tower weighed 270 tons which was 60% less than that the existing steel tower. The manufacturing cost of the arrived composite tower was found to be 33% less than that of the steel tower.

## 2.3 Laminate Composites

### 2.3.1 Material Properties

Laminate composites are made up of two main individual constituent materials: the matrix and the reinforcement. The matrix material surrounds and supports the reinforcement materials by maintaining their relative positions. For FRP, fibre is the reinforcement and the mixture of resin and hardener is the matrix. There are several types of fibre commonly used such as glass, carbon, aramid fibres but the ones that are used in the wind turbine industry is the E-Glass fibre because it is a good electrical insulator. In this particular study, the wind turbine tower segment is made up of layers of unidirectional E-Glass fibre with the West System epoxy resin and hardener as the matrix. Table 2.1 summarizes the material properties of the unidirectional fibre and the resin and hardener (Burachynsky, 2006).

**Table 2.1:** Properties constituents of unidirectional lamina (Burachynsky, 2006)

| Material Properties | E-Glass Fibre | West System Epoxy 105 Resin/205 Hardener |
|---|---|---|
| Tensile modulus, GPa | 72.4 | 2.81 |
| Tensile strength, GPa | 2.4 | 0.054 |
| Poisson's ratio | 0.27 | 0.3 |
| Shear modulus, GPa | 30 | 1.38 |
| Density, $g/mm^3$ | 0.0025 | 0.0016 |

Alshurafa (2012) tested and determined all the required properties for GFRP composite using the above fibre and matrix properties for the 40.6% fibre volume ratio. It was found that all the testes results are in consistent with the rule of mixture for finding composite's properties (Chamis, 1983). The comparisons of the test results and the plots of the material properties calculated from the formulas are shown in Figure 2.6 to Figure 2.10.

Based on the rule of mixture (Chamis, 1983), the properties of FRP layer can be determined using the fibre and the matrix properties as follow:

- The modulus of elasticity in the fibre direction, $E_1$ , can be calculated using the rule of mixtures

  $$E_1 = E_f V_f + (1 - V_f) E_m \quad (2.1)$$

  $E_f$ : Modulus of elasticity of the fibre

$E_m$ : Modulus of elasticity of the matrix

$V_f$ : Fibre volume fraction

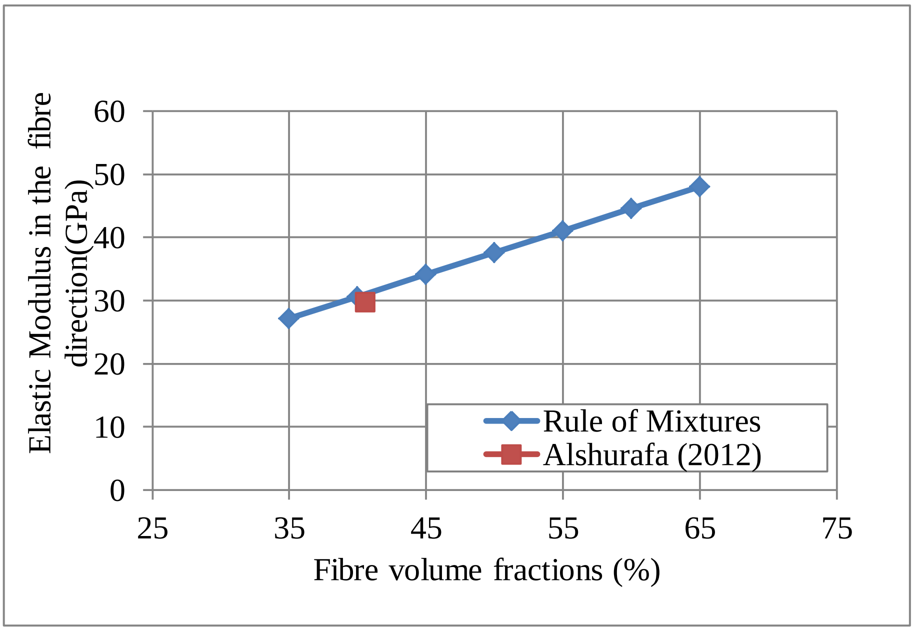



**Figure 2.6:** Elastic Modulus $E_1$ at various fibre volume ratios

- The modulus of elasticity in the direction perpendicular to the fibre, $E_2$, can be evaluated from following inverse rule of mixture

$$\frac{1}{E_2} = \frac{V_f}{E_f} + \frac{1-V_f}{E_m} \tag{2.2}$$

Hopkins and Chamis (1988) presented a modified equation for calculating $E_2$ as follows,

$$E_2 = E_m[(1 - V_f) + \frac{\sqrt{V_f}}{1-\left(1-\frac{E_m}{E_f}\right)\sqrt{V_f}}] \tag{2.3}$$

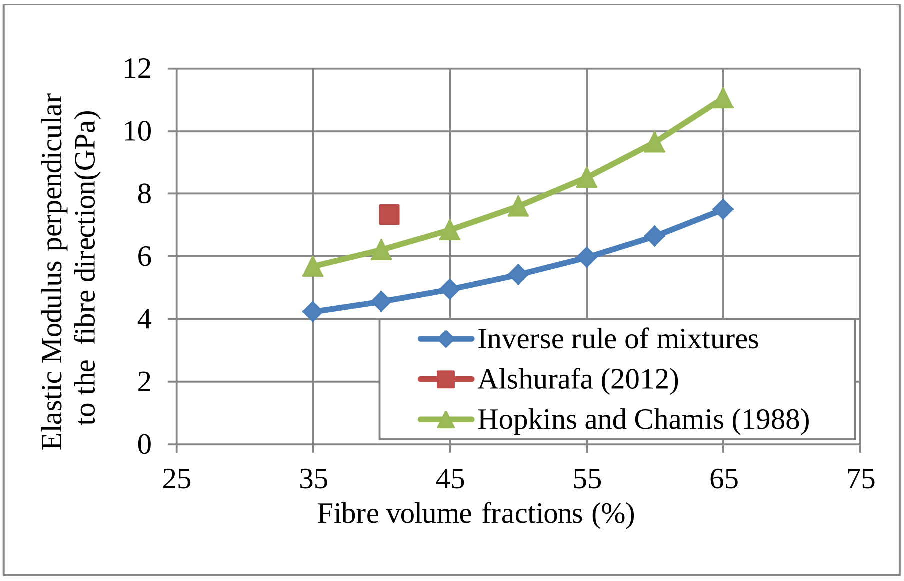



**Figure 2.7:** Elastic Modulus $E_2$ at various fibre volume ratios

- The major Poisson's ratio, can be determined from

$$v = v_f V_f + v_m V_m \tag{2.4}$$

$v_f$ : The Poisson's ratio of the fibre

$v_m$ : The Poisson's ratio of the matrix

$V_m$ : The voulme ratio of the matrix

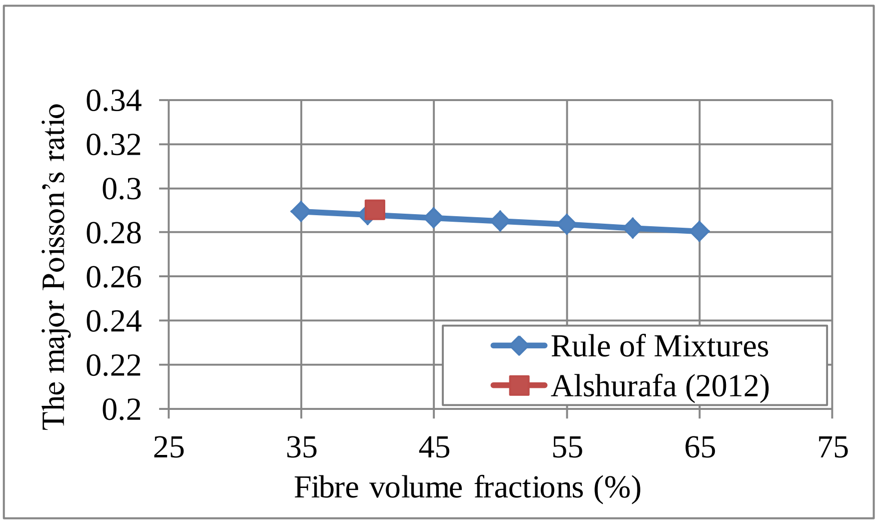



**Figure 2.8:** Major Poisson's ratio at various fibre volume fractions

- The shear modulus, $G_{12}$, can be determined from following inverse rule of mixture

$$\frac{1}{G_{12}} = \frac{V_f}{G_f} + \frac{V_m}{G_m} \tag{2.5}$$

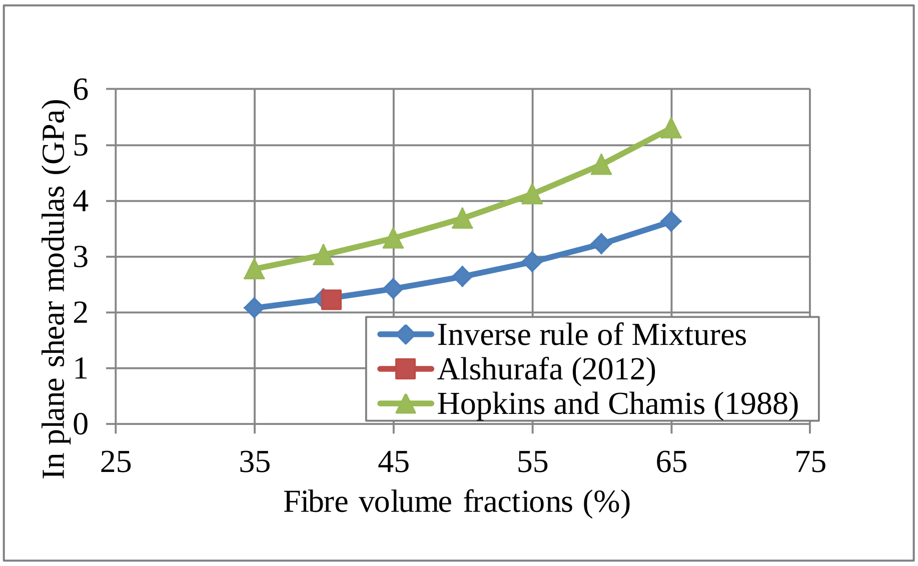



**Figure 2.9:** In plane shear modulus, $G_{12}$ at various fibre volume fractions

$G_{12}$ can also be obtained from the modified equation developed by Hopkins and Chamis (1988) as follows:

$$G_{12} = G_m[(1 - V_f) + \frac{\sqrt{V_f}}{1-\left(1-\frac{G_m}{G_f}\right)\sqrt{V_f}}] \tag{2.6}$$

$G_f$ : Fibre shear modulus

$G_m$ : Matrix shear modulus

- The density of the composites, $\rho_2$, is defined as

$$\rho_2 = \rho_f \frac{V_f}{W_f} \tag{2.7}$$

$\rho_f$: Fibre density

$W_f$: Fibre weight fraction

$$W_f = \frac{\rho_f v_f}{\rho_f v_f + \rho_m (1 - V_f)} \quad (2.8)$$

$\rho_m$ : Matrix density

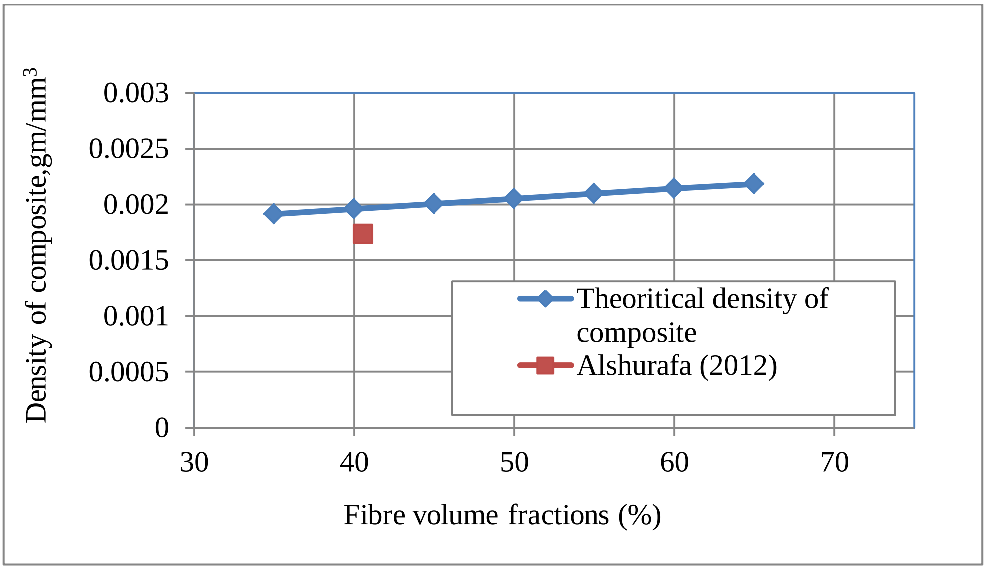



**Figure 2.10:** Composite density as a function of fibre volume fraction

In this thesis, 45% fibre volume for GFRP composite is used, the corresponding material properties are calculated using the rule of mixtures and presented in Table 2.2.

**Table 2.2:** GFRP composite properties for 45% fibre volume ratio

| | |
|---|---|
| Modulus of elasticity in the fibre direction, $E_1$, GPa | 34.125 |
| Modulus of elasticity in the direction perpendicular to the fibre, $E_2$, GPa | 6.8521 |
| Poisson's ratio, $\nu$ | 0.2865 |
| Shear modulus, $G_{12}$, GPa | 3.330 |
| Density of the composites, $\rho_2$, g/mm$^3$ | $2.005 \times 10^{-3}$ |

### 2.3.2 Mechanical Properties of Composite

To obtain the mechanical properties of the GFRP material, several standard tests are required. However, scope of the current study does not include an experimental work. Also noted that in the scope of the current study, the wind turbine tower will be designed using GFRP with fibre volume fraction of 45%.Therefore,for a conservative analysis, the mechanical properties of GFRP with fibre volume fraction of 40.6% obtained from coupon testing by Alshurafa (2012) will be used .The test results are summarized in Table 2.3.

**Table 2.3:** GFRP composite properties for 40.6% fibre volume ratio based on coupon testing

| | |
|---|---|
| Ultimate tensile strength in the fibre direction, $S_{1T}$ , MPa | 587.46 |
| Ultimate tensile strength in the transverse fibre direction, $S_{2T}$ , MPa | 21.27 |
| Ultimate compressive strength in the fibre direction, $S_{1C}$ , MPa | 267.15 |
| Ultimate compressive strength in the transverse fibre direction, $S_{2C}$ , MPa | 71.05 |
| Ultimate shear strength, $S_{ij}$ , MPa | 27.20 |

## 2.4 Failure Theories of Laminated Composites

Commonly used strength-based failure theories for the analysis of laminate composites can be classified into two major categories, i.e., non-interactive failure criteria and interactive failure criteria. The maximum stress criterion is considered to be a non-interactive failure criterion while the interactive failure criterion is Tsai-Wu. In this study, the maximum stress and the Tsai-Wu criteria will be used. In the following expressions, $S_{iT}$ and $S_{iC}$ ($i =$ 1, 2, 3) are the tensile and the compressive strength of the lamina along the material direction $i$, respectively. $S_{ij}$ $(i \neq j,\ i, j = 1,\ 2,\ 3)$ are the shear strength of laminas in the $ij$ plane. $\sigma_i$ , $\sigma_{ij}$ ($i$ = 1, 2, 3) are the normal and the shear stresses in the material principal axes.

### 2.4.1 The Maximum Stress Criterion

Matrix cracking

$$\sigma_2 \geq S_{2T} \text{ for } \sigma_2 > 0 \text{ and } |\sigma_2| \geq S_{2C} \text{ for } \sigma_2 < 0 \quad (2.9)$$

or,

$$\sigma_3 \geq S_{3T} \text{ for } \sigma_3 > 0 \text{ and } |\sigma_3| \geq S_{3C} \text{ for } \sigma_3 < 0 \quad (2.10)$$

Fibre breakage,

$$\sigma_1 \geq S_{1T} \text{ for } \sigma_1 > 0 \text{ and } |\sigma_1| \geq |S_{1C}| \text{ for } \sigma_1 < 0 \quad (2.11)$$

$I_{F\max stress}$ is defined as the ratio of maximum stress to the maximum strength of the material. If the failure index for the maximum stress criterion, $I_{F\max stress} \geq 1.0$, the structure is unsafe.

### 2.4.2 Tsai-Wu Criterion

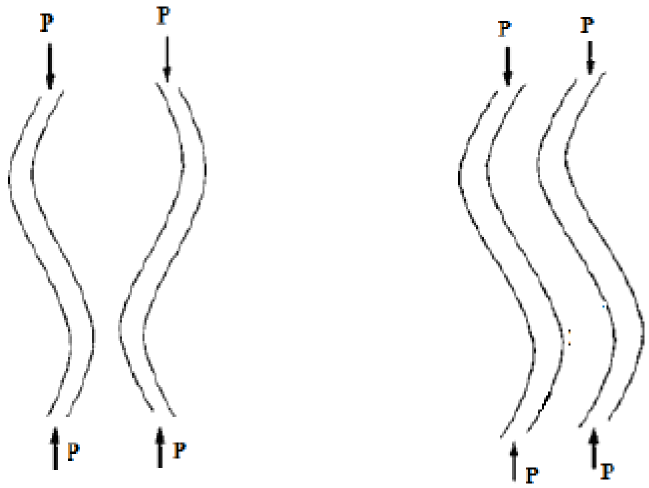
The Tsai-Wu failure criterion is chosen because it accounts for the interaction between different stresses components. In the Tsai-Wu failure criterion, the failure surface in the stress space is described by the following equation:

$$I_{Tsai-Wu} = \left(\frac{1}{S_{1T}} - \frac{1}{S_{1C}}\right)\sigma_1 + \left(\frac{1}{S_{2T}} - \frac{1}{S_{2C}}\right)\sigma_2 + \left(\frac{1}{S_{3T}} - \frac{1}{S_{3C}}\right)\sigma_3$$
$$+ \frac{\sigma_1^2}{S_{1T}\, S_{1C}} + \frac{\sigma_2^2}{S_{2T}\, S_{2C}} + \frac{\sigma_3^2}{S_{3T}\, S_{3C}} - \frac{\sigma_1\sigma_2}{2\sqrt{(S_{1T}\, S_{1C} S_{2T} S_{2C})}}$$
$$- \frac{\sigma_2\sigma_3}{2\sqrt{(S_{2T}\, S_{2C} S_{3T} S_{3C})}} - \frac{\sigma_1\sigma_3}{2\sqrt{(S_{1T}\, S_{1C} S_{3T} S_{3C})}} + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \left(\frac{\sigma_{23}}{S_{23}}\right)^2 + \left(\frac{\sigma_{13}}{S_{13}}\right)^2 \quad (2.12)$$

If $I_{Tsai-Wu} \geq 1,$ the structure is unsafe.

### 2.4.3 Buckling of Unidirectional Lamina

A micromechanical model was developed by Rosen (1965) for determining the compressive strength of a unidirectional lamina. Under the applied loads, elastic buckling occurs in two distinctive modes: the Out-of-phase and the in-phase modes. The out-of-phase mode assumes that both the fibres and the matrix exhibit anti-phase deformations, as shown in Figure 2.11(a). The in-phase mode indicates that the matrix deform together as shown in Figure 2.11(b).




(a) (b)

**Figure 2.11:** (a) Out-of-phase buckling mode (b) In-phase buckling mode

The critical in-phase buckling stress can be calculated from (Rosen, 1965):

$$\sigma_c = E_m/2(1 + v_m)V_m \quad (2.13)$$

The critical out-of-phase buckling stress can be calculated from (Rosen, 1965):

$$\sigma_c = 2V_f\sqrt{\frac{V_f E_m E_f}{3V_m}} \quad (2.14)$$

# Chapter 3 Wind Turbine Tower Design

This chapter mainly deals with the wind turbine design requirements and loads specified by the available standards. Similar to all other structures, a wind turbine tower must be designed for the strength as well as for serviceability. The serviceability requirements for a wind turbine include the maximum tower deflection and the range of the tower natural frequency which will be presented in section 3.1. For the strength requirement, the tower must be able to resist design loads detailed in sections 3.6 and 3.8.

## 3.1 Serviceability Requirements

### 3.1.1 Serviceability Limit for Lateral Deflection

According to DNV/RISO Guidelines for Design of Wind Turbine (Det Norske Veritas, 2002), a blade must not hit the tower when subjected to the extreme design load. This indicates that the serviceability limit for lateral deflection is defined as the distance between a rotor blade and the tower. In order to satisfy this serviceability limit, the maximum deflection at the tower top is set to 1.5 % of the tower height in this study.

### 3.1.2 Serviceability Limit on Natural Frequency

Since a wind turbine tower is subjected to both static and dynamic loadings, the dynamic behaviour of the tower is very important. This dynamic behaviour is dictated by the natural frequency of the tower and the excitation frequency of the rotor and the blades. The frequency, in Hz, of a particular turbine ( $f_p$ ) is obtained by dividing the turbine angular speed in rotations per minute (rpm) by sixty. The blade passing frequency ( $f_{bp}$ ) is determined by multiplying rotor frequency to the number of blades. On the basis of dynamics behavior, the wind turbine towers are divided in 3 classes in the wind turbine industry (Joshu and Wizeliu 2011).

***Stiff-stiff tower***

A stiff-stiff tower is a tower with the natural frequency $f_n$ of much higher than both the excitation frequencies of the rotor and of the blades i.e. $f_p$ and $f_{bp}$, respectively. This type of tower is very efficient in reducing the vibration but they are not cost effective.

***Soft-stiff tower***

A soft-stiff tower is a tower with the natural frequency $f_n$ of greater than rotor excitation frequency ($f_n > f_p$) but lower than the blade passing frequency ($f_n < f_{bp}$).

***Soft-soft tower***

A soft-soft tower is a tower which both the rotor and blade passing frequencies are greater than the natural frequency of the tower, $f_n$.

The soft-soft tower is the most economical among all three classes. However, it must be designed for resonant which will occur upon the starting up and the shutting down process since the frequencies of excitation of these processes will pass its natural frequency. The first natural frequency of the tower $f_n$ must not coincide with the rotor $f_p$ and blade-passing $f_{bp}$ frequencies to avoid resonance.

## 3.2 Design Loads

The CSA Guide to Canadian Wind Turbine Codes and Standards report (Canadian Standard Association, 2008) states that there are no specific regulations or codes in Canada for wind turbine towers. However, it is suggested the professional engineers to provide approved design drawings before any tower erection. The current National Standard of Canada for wind turbines, CSA-C61400-2 (CSA, 2008) provides the details guideline to design blade and shaft for small wind turbines, but not for wind turbine towers. This CSA-C61400-2 is actually adopted from International Electrotechnical Commission Standard 61400-2 (IEC, 2006). To design a wind turbine tower, DNV/RISO Guidelines for Design of Wind Turbine (Det Norske Veritas, 2002) is also a very useful resource. German Standard: Rules and Regulations, Part 1 – Wind Energy (Germanischer Lloyd, 1993) also provides simplified equations to calculate loadings which transfer from the wind turbine to the tower.

In the design of a wind turbine tower, it is very difficult to obtain an accurate loading due to the dynamic nature of the applied load (the time-varying wind and the spinning of the rotor). There are two types of loading that considered in the design of wind turbine tower: Wind turbine loading on the top of the tower; and wind and ice loads on the tower itself. The German Standard and the 61400-2 provides the guideline for the calculation of the wind turbine loading which will be briefed in section 3.4 and the Canadian Standard CAN/CSA S37-01 (CSA, 2001) gives the guideline for the estimation of the wind and ice loading on the tower which will be summarized in section 3.7.

### 3.3 Basics of Wind Turbine Loading

Similar to the wings of an airplane, wind turbine blades use the airfoil shape to create lift and drag forces. The lift forces create rotation for the wind turbine. Figure 3.1 shows how a lift force is created from the difference in the wind velocities between the upside and the downside of the rotor.

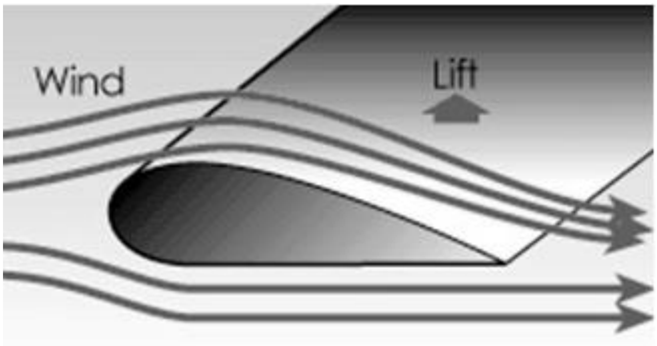



**Figure 3.1:** Airfoil blade section of a wind turbine

In the following loading definition, the reference coordinate system as defined by the IEC 61400-2 and the German Standard is used as shown in Figure 3.2. Note that the global coordinate system in the developed FEA model is different from the following coordinate system.

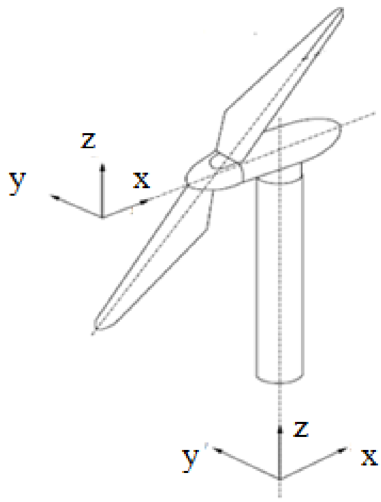
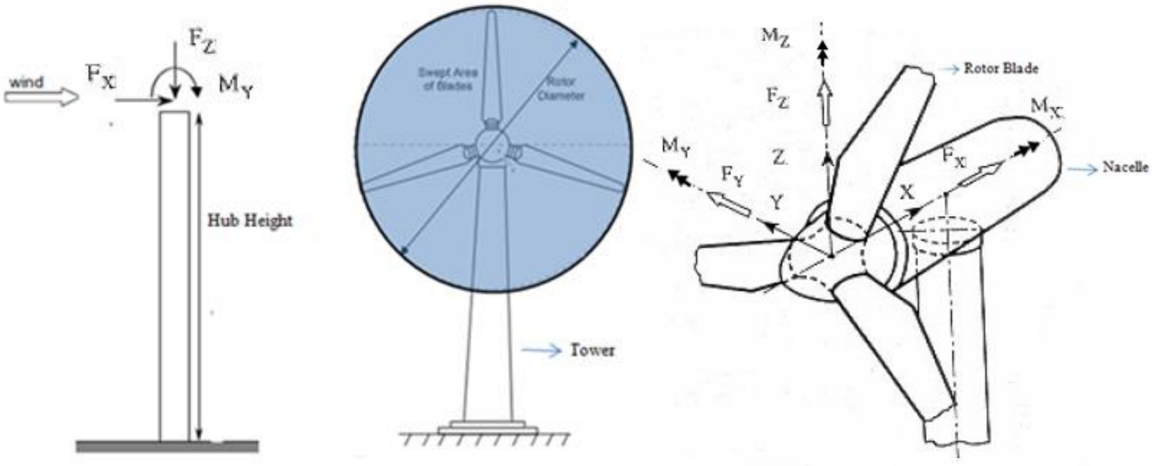



**Figure 3.2:** Wind turbine coordinate system

Based on the coordinate system in Figure 3.2, if it is assumed that the wind blows in the x direction which is perpendicular to the swept area of the blades; then the rotation of rotor crates the forces and moments  as shown in Figure 3.3 and will be summarized in the following.




(a) (b) (c)

**Figure 3.3:** (a) A simplified model of a tower subjected to rotor loadings at hub level (b) The swept area and (c) The rotor loadings and their directions

- A thrust force $F_x$ is created from the rotation of the blade and the wind force which is equal to pressure times the swept area of blade. The direction of $F_x$ is the same as wind direction.
- Due to change in the direction of wind and gust, $F_x$ force component creates a force $F_y$ in the direction perpendicular to wind direction. The amplitude of $F_y$ is calculated from the component of the thrust force, $F_x$.
- The self-weight of the turbine system, $F_z$ , which is sum of the weight of the rotor and the nacelle acts in the downward direction.
- A torque $M_x$ is created from the rotation of the rotor and its magnitude is proportional to the power production of the turbine.

- A bending moment $M_y$ is created from the eccentricity of the thrust, $F_x$. This eccentricity is created from the non-uniform pressure distribution on the swept area of the blade. The weight of the turbine system also creates a moment about the y axis.
- The $F_y$ force creates a torsional moment $M_z$ about the tower axis. The assumed eccentricity of the $F_y$ is equal to the distance between the centre of gravity of the rotor system and the tower centre line while the turbine is in operation.

## 3.4 Loads Transferred from the Wind Turbine

In this study, the wind turbine rotor loads are calculated following the German Standard and only the governing load cases are compared with the IEC 61400-2 load cases for verification.

### 3.4.1 The German Standard: Rules and Regulations, Part 1 –Wind Energy

According to the German Standard, the wind turbine towers should be designed to resist not only the following load cases but also their combinations when they exist:

- Dead loads (self-weight of the wind turbine system)
- Normal operating loads
- Extreme operating loads
- Annual wind (10 minutes)
- Annual gust (5 seconds)
- 50-year wind (10 minutes)
- 50-year gust (5 seconds)
- Generator short circuit (blackout)
- Rotor eccentricity

***Dead load due to rotor self-weight***

Dead load is due to the mechanical system stored at the top of the tower. There are three main weight components, which should be included in the calculations: the blades, the nacelle, and the rotor. These components are shown in Figure 3.3.The total gravitational load $F_z$ , is the result of combining the above weight components. There is also a mass eccentricity for the rotor that needs to be taken into account. This eccentricity is calculated by

$$e_m = 0.05R \tag{3.1}$$

$R$ : rotor radius

This eccentricity causes a moment $M_y$ at the top of the tower.

***Normal operating loads***

During normal operation, a mean pressure,$P_n$, which is dependent on the rated wind speed, $v_r$ , is used. This means pressure can be calculated from

$$P_n = \frac{C_{fb}\rho v_r^2}{2} \tag{3.2}$$

$$C_{fb} = \frac{8}{9}$$

$\rho$ : air density, kg/m$^3$

$v_r$: rated wind spend or design wind speed , m/s

The force acting in the wind direction $F_x$ on the top of the tower is

$$F_x = P_n A \tag{3.3}$$

$A$ : the rotor swept area, m$^2$

The eccentricity of this force $e_w$ developed during normal operation due to the turbulence, the influence of oblique wind flow, and the tower shadow is given by

$$e_w = \frac{wR^2}{2v_r^2} \quad (3.4)$$

$w$ : an extreme wind gradient over the rotor swept area which is the rate of increase of wind strength with unit increase in height above ground level.

This eccentricity produces an additional moment $M_y$.

During the operation of the wind turbine, the rotor rotates around its axis and causing a resisting moment about x axis. This moment is proportional to the electrical power output $P_{el}$ and to the inverse of the rotational speed of the rotor $n$ in rpm with the equation

$$M_x = 14\frac{P_{el}}{n} \quad (3.5)$$

If it is necessary to stop the blades while the wind turbine is operating, a hydraulic breaking system is used. The breaking of the wind turbine creates an overturning moment at the top of the tower. This moment is assumed to be in the same direction as and to be twice the value of $M_x$ derived in Equation 3.5.

***Extreme operating loads***

Loads due to the extreme operation are treated like the normal operating loads, but the wind speed is converted to the extreme condition speed (gust wind speed $v_b$) using the gust factor $k_b$ of 5/3. Therefore, the gust wind speed is,

$$v_b = k_b v_r \quad (3.6)$$

The gust wind speed needs to be compared to the cut-out speed of the wind turbine. This cut -out speed is specified in a rotor’s specification. The lesser value between the gust wind speed and the cut-out wind speed is used to determine the wind pressure acting on the swept area of the rotor. The wind pressure can be calculated form,

$$P_b = \frac{C_{fb} \rho v_b^2}{2} \tag{3.7}$$

The horizontal force $F_x$ acting on the top of the tower in this case can be calculated using Equation 3.3, with $P_b$ instead of $P_n$ . Forces from an oblique wind flow or the wind gradients must also be taken into account since the wind can change in the direction during operation. This force is characterized as a lateral wind impact and its magnitude can be calculated as

$$F_y = \pm \frac{P_n A}{\sqrt{2}} \tag{3.8}$$

This force acts on the rotor in the y direction and results in the torsional moment $M_z$ about the tower axis centre due to the distance between the tower centre and position of $F_y$ force.

Similarly to the normal operating condition, the moment caused by the electrical power generating can be calculated using Equation 3.5.

***Annual wind (10 minutes)***

The annual wind is the mean of wind speed averaged over 10 minutes with an exceeding probability of once a year. Annual wind speed is specified as 80 percent of the corresponding 50-year wind speed. Normally, wind data are collected at a reference height, $h^*$ (10 meters). In order to determine the wind pressure at hub height $h$, the 10-minutue mean wind speed has to be adjusted to hub height (shown in Figure 3.3) as follows

$$v_{hub} = v_{ref} \left( \frac{h}{h^*} \right)^{\alpha} \tag{3.9}$$

$v_{hub}$ : wind speed at hub height h

$v_{ref}$ : wind speed at reference height $h^*$

$h^*$ : reference height

$\alpha = 0.16$ for wind and 0.11 for gust

If the annual wind speed at hub height is more than the cut-out speed of the turbine, the stagnation pressure $P_s$ should be used. The stagnation pressure is given as

$$P_s = \frac{v_{hub}^2}{1600} \tag{3.10}$$

The horizontal force $F_x$ applied at the top of the tower can be determined using Equation 3.3 with $A$ being a surface area of the wind vane and $P_s$ replaces $P_n$. The wind vane is a mechanical device attached to the nacelle to show wind direction.

The gust effect must be taken into account since it may deviate by an angle of up to +15 and -15 degree from the wind direction. The force acting on the rotor in the y direction also creates a torsional moments $M_z$ about the tower axis.

***Annual gust (5 seconds)***

The annual gust is the maximum wind speed averaged over 5 seconds with an exceeding probability of once a year. The annual gust speed is specified as 80 percent of the corresponding 50-year gust speed. Similar to the annual wind (10 minutes) condition, the gust wind speed has to be adjusted to hub height according to the Equation 3.9. The wind pressure and the horizontal force $F_x$ acting at the top of the tower are calculated in the same manner as in the annual wind (10 minutes) condition. The lateral load $F_y$ caused by the oblique wind flow or wind gradients needs to be considered and is assumed to have the same magnitude as the horizontal force. This lateral force also creates a torsional moment $M_z$ about the tower axis.

***50-year wind (10 minutes)***

The 50-year wind is the mean of wind averaged over 10 minutes with an exceeding probability of once in 50 years. Similar to the annual wind (10 minutes) condition, the 50-

year wind has to be adjusted to hub height using the Equation 3.9. The loads for this case are determined in the same manner as those for the annual wind (10minutes) condition.

***50-year gust (5 seconds)***

The 50-year gust is the maximum wind speed averaged over 5 seconds with an exceeding probability of once in 50 years. Similar to the annual gust (5 seconds) condition, the 50-year gust has to be adjusted to hub height with the Equation 3.9. The loads for this case can be calculated as those for the annual gust (5 seconds) condition.

***Generator short circuit (blackout)***

In the event of a short circuit in the generator or the connection cables, peaks in torque may occur. If the generator short circuit moment is unknown, eight times the moment in Equation 3.5 can be assumed.

***Rotor blade eccentricity***

During the installation of the blades on the rotor/nacelle, the actual tolerance is to be taken into account. If this is not known, the following eccentricity applies:

$$e_r = 0.005R \tag{3.11}$$

The horizontal force acting at the top of the tower is then determined by

$$F_x = m e_r \omega^2 \tag{3.12}$$

$m$ : mass of the rotor blade,

$\omega$ : angular velocity of the rotor

### 3.4.2 IEC 61400-2

IEC 61400-2 provides a method to determine loadings for small wind turbines if certain conditions are met. The method is simple and thorough, covering most of the load cases that a small wind turbine would experience for its design life. In order to use these simplified equations, the wind turbine must meet the following criteria:

- Horizontal axis wind turbine
- Two or more blades
- Cantilevered Blade
- Have rigid hub (Hub should not rotate)

The 10kW wind turbine considered in this study meets all of the above specified requirements. Therefore the simplified load equation method can be used to calculate the loadings. The load cases are shown in Table 3.1. It is found that the load cases D and H are the most severe and are considered as the governing load cases for the wind turbine design here.

***Load case D: Maximum thrust***

A small wind turbine can be exposed to high thrust loads on the rotor. The thrust load acts parallel to the rotor shaft and has a maximum value given by.

$$F_{x\,\text{shaft}} = 3.125 C_T \rho v_{avg}^2 \pi R^2 \quad (3.13)$$

$v_{avg}$ : average wind velocity at hub height

$C_T$ : thrust coefficient = 0.5

**Table 3.1:** Design load cases specified in IEC 61400-2

| Design Situation | Load Cases | | Wind Inflow |
|---|---|---|---|
| Power Production | A | Normal Operation | |
| | B | Yawing | $v_{hub} = v_r$ |
| | C | Yaw Error | $v_{hub} = v_r$ |
| | D | Maximum Thrust | $v_{hub} = 2.5v_{avg}$ |
| Power Production plus occurrence of fault | E | Maximum Rotational Speed | |
| | F | Short at Load Connection | $v_{hub} = v_r$ |
| Shutdown | G | Shutdown (braking) | $v_{hub} = v_r$ |
| Parked | H | Parked Wind Loading | $v_{hub} = v_{e50}$ |
| Parked and fault condition | I | Parked Wind loading, maximum exposure | $v_{hub} = v_{ref}$ |
| Transport, assembly, maintenance and repair | J | To be stated by manufacturer | |

***Load case H: Parked wind loading***

In this load case, the wind turbine is parked condition. The thrust loads on the blade face is calculated according to the following formula when wind blows in the x direction.

$$F_{x\,\text{shaft}} = 0.5BC_d\rho v_{e50}^2 A_{\text{proj},B} \quad (3.14)$$

$B$ : number of blades

$C_d$ : drag coefficient = 1.5

$A_{\text{proj},B}$ : blade plan form area

$v_{e50}$ : reference wind velocity at hug height in 50 years recurrence period

When wind blows in the y direction, the thrust load has to be calculated based on the projected area of the nacelle/turbine components as:

$$F_{x\,\mathrm{component}} = 0.5 C_f \rho v_{e50}^2 A_{\mathrm{proj}} \tag{3.15}$$

$C_f$ : force coefficient = 1.5

$A_{\mathrm{proj}}$ : nacelle/turbine component area projected onto a plane perpendicular to the wind direction

## 3.5 Wind Turbine Technical Specification

The technical data of a 10 kW wind turbine in this study is listed in Table 3.2 and centre of gravity of the wind turbine is shown in Figure 3.4. The technical information is collected

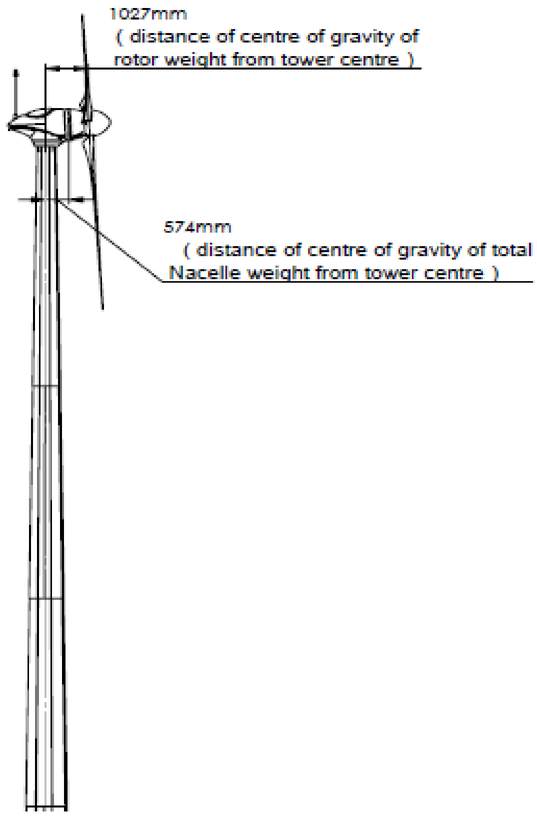



**Figure 3.4:** Centre of gravity of different components of 10 kW wind turbine

from turbine manufacturing company WINPhase Energy Inc, St. Philip's, Newfoundland.

**Table 3.2:** Technical data of a 10kW wind turbine

| Parameters | Value | Unit |
|---|---|---|
| Nominal Power | 10 | kW |
| No. of rotor blades | 3 | Nos |
| Rotor diameter | 9 | m |
| Rotor swept area | 63.61 | $m^2$ |
| Rotation speed | 150 | RPM |
| Hub height | 24.39 | m |
| Cut in wind Speed | 3.5 | m/s |
| Cut out wind Speed | 25 | m/s |
| Rated wind speed | 9 | m/s |
| Weight of 3 blades | 72 | kg |
| Total weight of the unit | 650 | kg |
| Wind van area /Nacelle cover area from side (assumed to be 7.5% of the swept area ) | 4.77 | $m^2$ |
| Centre of gravity of the turbine system from tower centre (calculated) | 0.6241 | m |
| Plan form area of each blade | 2.12 | $m^2$ |

### 3.6 Wind Turbine Rotor Loads Combinations and Safety Factors

The German Standard provides the load combinations (Table 3.3) for the load cases mentioned in section 3.4.1.In Table 3.3, “x” indicates that the corresponding load case is to be considered in the load combination.

**Table 3.3:** Wind turbine rotor loads combinations

| Load cases | Rotor load combinations | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| Dead Load (DL) | x | x | x | x | x | x |
| Normal Operating Load( NOL) | x | | | | | |
| Extreme Operating Load (EOL) | | x | | | | |
| Annual Wind(10 min) | | | x | | | |
| Annual Gust(5 Sec) | | | | x | | |
| 50 Year Wind (10 min) | | | | | x | |
| 50 Year Gust (5 Sec) | | | | | | x |
| Black Out | | | x | | x | |
| Rotor Eccentricity | x | x | | | | |

As shown in the Table 3.3, there are six possible load combinations. The first load combination is referred to as a normal operating condition. It includes dead loads, normal operating load, and loads due to the eccentricity caused during the rotor installation process. The second load combination is referred to as an extreme operating condition. Under this condition, the wind turbine works under a wind speed very close to the cut-out speed. The third load combination is referred to as an operating condition under an annual wind over a period of 10 minutes. In this case, the forces caused by a generator short circuit or blackout are included. The fourth load combination is referred to as an operating condition under an annual gust over a period of 5 seconds. The fifth load combination is referred to as an operation condition under a 50-year wind over a period of 10 minutes. Similarly to the third load combination, loads due to blackout are included. The last load combination is referred to as an operating condition under a 50-year gust over a period of 5 seconds. Similarly to the fourth load combination, other loads due to fault condition are not included.

In order to form the load combinations, the appropriate load factors specified in German standard given in Table 3.4 are to be applied to the various loads components according to the load case group.

**Table 3.4:** Load factors for rotor loads for ultimate strength analysis

| Load Cases | Safety Factor |
|---|---|
| Dead Load | 1.1 |
| Normal Operating Load | 1.2 |
| Extreme Operating Load | 1.2 |
| Annual Wind(10 min) | 1.5 |
| Annual Gust(5 Sec) | 1.5 |
| 50 Year Wind (10 min) | 1.0 |
| 50 Year Gust (5 Sec) | 1.0 |
| Black Out(BO) | 1.0 |
| Rotor Eccentricity(RE) | 1.35 |

## 3.7 Loads Acting on the Tower

The loadings acting on the tower consist of

- Dead loads ( Self weight of the tower)
- Live load due to ice
- Live load due to wind

### 3.7.1 Dead loads

The specified dead loads consist of the weight of the tower itself, internal fixtures weight and the loads from turbine which act at the top of the tower.

### 3.7.2 Live Load due to Ice and Radial Ice Thickness

In this study, live load due to ice is determined according to the Canadian Standard CAN/CSA S37-01 (CSA, 2001) for poles and towers. According to the CSA S37-01, the radial ice thickness around the tower must be considered to provide an extra projected area for the wind loading calculation as shown in Figure 3.5.

The CSA S37-01 also gives the minimum ice thickness map corresponding to the each class in Figure 3.6. According to the map, St Jones, Newfoundland is located in class IV and the minimum design ice thickness is 50 mm.

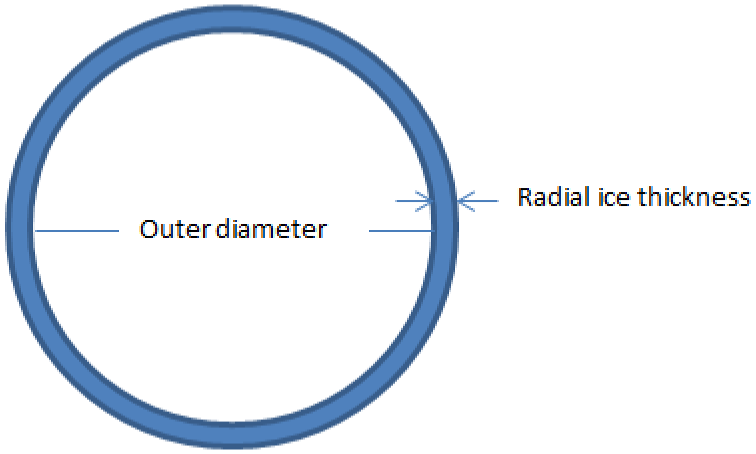



**Figure 3.5:** Radial ice thickness

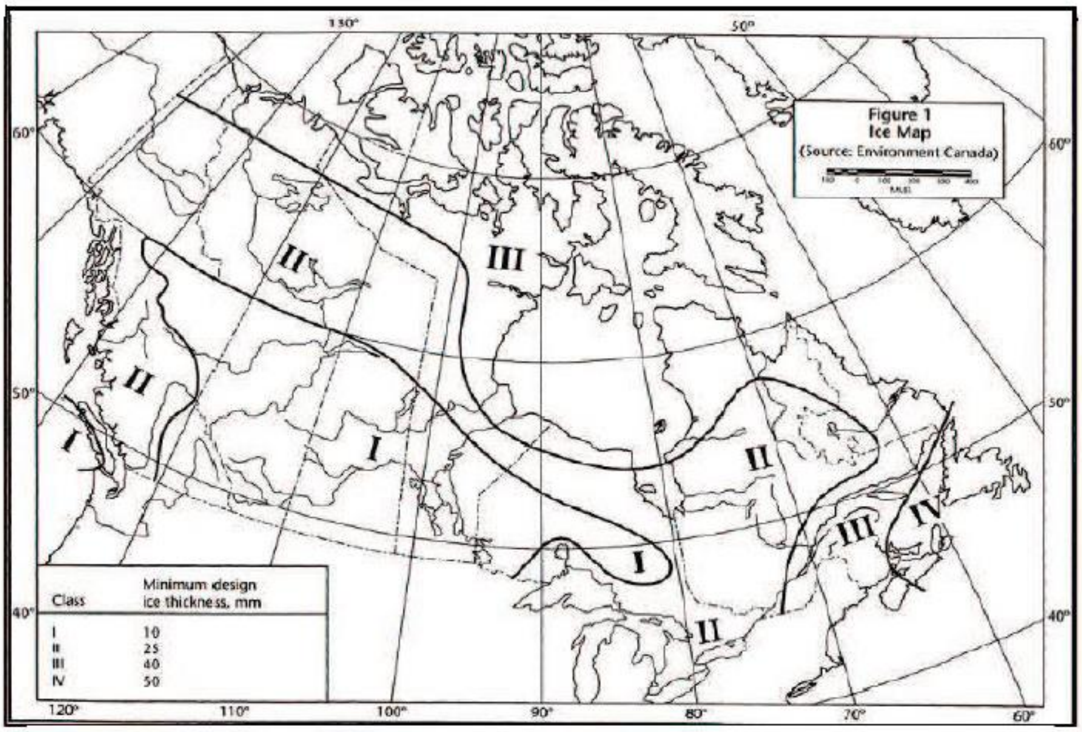



**Figure 3.6:** Ice map of Canada (CAN/CSA S37 -01)

### 3.7.3 Live load due to Wind

Based on the CSA-S37-01, a wind load $W$ is calculated using the net projected area of the tower $A_s$ for an un-iced tower and the net projected area of the tower including the radial ice thickness $A_i$ for an iced tower as given in Equation (3.16) and (3.17), respectively. The value of $C_d$ used in this study is 0.5 based on the Reynolds's number, $N > 7.2$ as described in Clause 4.9.2 of the CSA-S37-01.

$$W = PA_sC_d \text{ (Un-iced tower)} \tag{3.16}$$

$$W = PA_iC_d \text{ (Iced tower)} \tag{3.17}$$

$W$ : wind load (N)

$P$ : design wind pressure (Pa)

$C_d$: drag factor for smooth pole structure

$A_s$: net projected area ($m^2$)

$A_i$: net projected area including ice ($m^2$)

The design wind pressure $P$ acting on the composite tower is calculated in accordance with Clause 4.3.1 of the CSA-S37-01 as:

$$P = qC_eC_gC_a \tag{3.18}$$

$q$ : the reference wind velocity pressure, given in the National Building Code of Canada (Pa) (NBCC, 2010)

$C_e$ : the height factor defined as

$$C_e = \left(\frac{H_x}{10}\right)^{0.2} \tag{3.19}$$

$H_x$ : height above ground (m)

$C_g$ : gust factor = 2.5 as specified in Clause 4.6.1 in the CSA-S37-01

$C_a$ : Roof wind speed up factor = 1.0 according to Clause 4.7.1 in the CSA-S37-01

## 3.8 Load Factors and Load combination for Wind and Ice Loads

The following load combinations are considered according to clause 5.2 in the CSA-S37-01 for the dead, ice and wind loads on tower.

(a) $D + W$

(b) $D + W + I$

$D$ : dead load (tower self-weight)

$W$ : Wind load

$I$ : Ice load

Factored loads for ultimate limit state is mentioned in clause 5.3 of CSA-S37-01 as follows

$$P_f = \alpha_D D + \gamma(\psi \alpha_w W + \alpha_i I) \tag{3.19}$$

$\alpha_D$: dead load factor =1.25

$\psi$: combination factor =1.0 when wind and dead load act together

$\psi$: combination factor =0.5 when wind, ice and dead load act together

$\alpha_w$: wind load factor =1.5

$\alpha_i$: ice load factor =1.5

According to Equation 3.19, the factored load combination for $D$ and $W$ is,

$$P_f = 1.25D + 1.5W$$

According to Equation 3.19, the factored load combination for $D$ , $I$ and $W$ is,

$$P_f = 1.25D + 1.0(0.5 * 1.5 * W + 1.5I) = 1.25D + 0.75W + 1.5I$$

The factored load combination for the serviceability limit state, according to clause 5.4 of CSA-S37-01, is computed as follows

$$P_s = D + (\psi \tau W + I) \tag{3.20}$$

$\tau$: serviceability factor =1.0

$\psi$: combination factor =1.0 when wind and dead load act together

$\psi$: combination factor =0.5 when wind, ice and dead load act together

Based on Equation 3.20, the service load combination for $D$ and $W$ is,

$$P_s = D + W$$

Based on Equation 3.20, the service load combination for $D$ , $I$ and $W$ is,

$$P_s = D + 0.5W + I$$

# Chapter 4 10 kW Wind Turbine Composite Tower

## 4.1 Introduction

This chapter presents the design loads for a 10 kW tower, the development of finite element models for different cell configurations of the tower cross section, a proposed section based on deflection limit, tower self-weight and fabrication point of view, an optimization of the proposed section and the static and dynamic modal analyses of the proposed section.

## 4.2 Wind Turbine Design Loads

The wind turbine design loads are determined following the German standard and are verified with the governing of load cases of IEC 61400-2.

### 4.2.1 Wind Turbine Rotor Loads Summary according to German Standard: Rules and Regulations, Part 1 – Wind Energy

Using the technical data (section 3.5) and simplified equations mentioned in section 3.4.1, all the wind turbine rotor loads are derived and summarized in the following Table 4.1. The wind turbine tower considered is assumed to be located in St. Jones, Newfoundland, Canada. According to National Building Code Canada (2010), wind pressure in St. Jones is 0.78 kPa for fifty year return period and corresponding calculated wind speed is 34.62 m/s. It is also found that the maximum annual wind speed is 27.69 m/s. The details calculations of rotor loads are documented in the Appendix A1.

**Table 4.1:** Wind turbine rotor loads summary according to the German Standard

| Load Cases | | Unfactored Loads | | | | | |
|---|---|---|---|---|---|---|---|
| | | Fx (N) | Fy (N) | Fz (N) | Mx (N-m) | My (N-m) | Mz (N-m) |
| 1 | Dead Load (DL) | | | -6377 | | -1435 | |
| 2 | Normal Operating Load (NOL) | 2803 | | | 1867 | 2102 | |
| 3 | Extreme Operating Load (EOL) | 7786 | | | 1867 | 5839 | 5654 |
| 4 | Annual Wind (10 min) | 3042 | | | | | 491 |
| 5 | Annual Gust (5 Sec) | 5455 | | | | | 3404 |
| 6 | 50 Year Wind (10 min) | 4754 | | | | | 2967 |
| 7 | 50 Year Gust (5 Sec) | 8523 | | | | | 5319 |
| 8 | Black Out (BO) | | | | 7467 | | |
| 9 | Rotor Eccentricity (RE) | 400 | | | | | |

### 4.2.2 Wind Turbine Rotor loads determination according to IEC 61400-2

As mentioned in section 3.4.2, the governing load cases D and H of IEC 61400-2 are determined and compared with the same load cases of German Standard. The comparison is shown in Table 4.2. The detail load calculations of cases D and H are included in the Appendix A2. The difference for load case D is approximately 12% while for the case H is 2%.The load cases are compared for verification purposes, however the German standard will be followed for the structural analysis.

**Table 4.2:** Comparison of the load cases D and H of IEC 61400-2 and the German Standard

| Load Cases | Load Case Description | IEC 61400-2 | German Standard |
|---|---|---|---|
| D or 3 | Thrust load or Extreme operating load | 8793 N | 7786 N |
| H or 7 | Parked wind loading or 50 year Gust (5 sec) | 8680 N | 8523 N |

### 4.2.3 Wind Turbine Load Combinations

Service and factored wind load combinations calculated based on the German Standard are presented in Table 4.3 and Table 4.4, respectively.

**Table 4.3:** Rotor load combinations in service

| Load Combinations | | Service loads | | | | | |
|---|---|---|---|---|---|---|---|
| | | Fx (N) | Fy (N) | Fz (N) | Mx (N-m) | My (N-m) | Mz (N-m) |
| 1 | DL+NOL+RE | 3203 | 0 | -6377 | 1867 | 667 | 0 |
| 2 | DL+EOL+RE | 8186 | 0 | -6377 | 1867 | 4405 | 5654 |
| 3 | Annual Wind (10 min)+DL+BO | 3042 | 0 | -6377 | 7467 | -1435 | 491 |
| 4 | Annual Gust (5 Sec)+DL | 5455 | 0 | -6377 | 0 | -1435 | 3404 |
| 5 | 50 Year Wind (10 min)+DL+BO | 4754 | 0 | -6377 | 7467 | -1435 | 2967 |
| 6 | 50 Year Gust (5 Sec)+DL | 8523 | 0 | -6377 | 0 | -1435 | 5319 |

**Table 4.4:** Factored rotor load combinations

| Load Combinations | | Factored Loads | | | | | |
|---|---|---|---|---|---|---|---|
| | | Fx (N) | Fy (N) | Fz (N) | Mx (N-m) | My (N-m) | Mz (N-m) |
| 1 | DL+NOL+RE | 3903 | 0 | -7014 | 2240 | 944 | 0 |
| 2 | DL+EOL+RE | 9883 | 0 | -7014 | 2240 | 5429 | 6785 |
| 3 | Annual Wind (10 min)+DL+BO | 4564 | 0 | -7014 | 7467 | -1578 | 737 |
| 4 | Annual Gust (5 Sec)+DL | 8182 | 0 | -7014 | 0 | -1578 | 5106 |
| 5 | 50 Year Wind (10 min)+DL+BO | 4754 | 0 | -7014 | 7467 | -1578 | 2967 |
| 6 | 50 Year Gust (5 Sec)+DL | 8523 | 0 | -7014 | 0 | -1578 | 5319 |

### 4.3 Design Loading on the Tower

As mentioned, there are two types of loading that need to be considered in the design and analysis of a wind turbine tower, i.e. the loading transfer from a turbine on the top of the tower and the loading on the tower itself. The loading from a turbine depends on the turbine and the location of the tower. In this study, a 10 kW turbine is used and the location is fixed in St John's, Newfoundland. The loadings and their combinations on the top of the tower are presented in section 4.2.

The loading on the tower itself is dependent on the dimensions and the configuration of the tower section as well as the location of the tower. This type of loading consists of wind and ice loads and the tower self-weight. The wind and ice loads are determined in accordance to the CAN/CSA S37-01 as discussed in sections 3.7and 3.8 . Note that the towers investigated in this study are eight, ten, and twelve-cell circular section with section diameter and difference shell thickness. Samples of the wind and ice loads will be presented in the

Appendices A3 and A4. The self-weight of the towers is determined from ANSYS models. The commands in the construction of the models will be presented in section 4.5 and the detailed codes for self-weight determination are in the Appendix A5.

## 4.4 Design Load Combinations

According to the technical specification (Table 3.2), the cut in and cut off wind speed of wind turbine are 3.5 m/s and 25 m/s respectively, which means the wind turbine is operational between wind speed of 3.5 m/s and 25 m/s, if wind speed exceeds 25 m/s at hub level, the turbine goes to parking condition. The rotor load combinations (section 4.2.3) 1 and 2 are related operating condition and 3 to 6 are related to parking condition of turbine. It is important to mention that the dead load for the turbine system is considered in rotor load combinations (section 4.2.3) and increased projected area for radial ice is considered in those combinations when ice load is in effect. The design load combinations of the design rotor load and the wind and ice loads considered are as follows-

***Wind turbine is in operation***

1) Rotor load combination 1 + Tower self-weight+ Wind load for 25 m/s wind speed
2) Rotor load combination 1 + Tower self-weight+ Wind load for 25 m/s wind speed+ Ice load
3) Rotor load combination 2 + Tower self-weight+ Wind load for 25 m/s wind speed
4) Rotor load combination 2 + Tower self-weight+ Wind load for 25 m/s wind speed+ Ice load

***Wind turbine is in parking condition***

5) Rotor load combinations 3 + Tower self-weight+ Wind load for maximum annual wind speed of 27.69 m/s
6) Rotor load combinations 3 + Tower self-weight+ Wind load for maximum annual wind speed of 27.69 m/s+ Ice load
7) Rotor load combinations 4 + Tower self-weight+ Wind load for maximum annual wind speed of 27.69 m/s
8) Rotor load combinations 4 + Tower self-weight+ Wind load for maximum annual wind speed of 27.69 m/s+ Ice load
9) Rotor load combinations 5 + Tower self-weight+ Wind load speed of 34.62 m/s (50 year recurrence wind speed)
10) Rotor load combinations 5 + Tower self-weight+ Wind load speed of 34.62 m/s (50 year recurrence wind speed) + Ice load
11) Rotor load combinations 6 + Tower self-weight+ Wind load speed of 34.62 m/s (50 year recurrence wind speed)
12) Rotor load combinations 6 + Tower self-weight+ Wind load speed of 34.62 m/s (50 year recurrence wind speed) + Ice load

The above twelve design load combinations are considered in the structural analysis.

## 4.5 The Construction of FEA Model

In the current study, the ANSYS software program is used. In the model, the global Y-axis lies along the towers length starting from the base of the tower. The following subsections outline the commands and the variables in the construction of the FEA models.

### 4.5.1 Tower Geometry

The following variables are used to define the basic geometry of the tower:

RB = radius in mm at the bottom of the tower

RT = radius in mm at the top of the tower

IR = radius in mm in the inner side of the tower

H = tower height = 24390 mm

The coordinates of the Tower geometry are defined by key points. For example:

K, 1, 0, 0, 0 (Key point, #1, X-coordinate, Y-coordinate, Z-coordinate)

K, 2, 0, 0, H (Key point, #2, X-coordinate, Y-coordinate, Z-coordinate)

Line commands are used to connect to two key points. For example:

L, 3, 4 (Line, key point#4, key point#3)

Cylindrical surfaces are created using AROTAT command. This command also has an option to segment the cylindrical area into multiple pieces which is used to create multi-cell segments. For example:

AROTAT, 2,,,,,, 1,2,360,8 (A cylindrical surface will be created by rotating line number 2 with 8 segments)

The surface areas for the stiffeners are created using AREA (A) command. For example:

A,3,4,6,5 (A surface area is created by connecting the key points 3,4,6 and 5)

### 4.5.2 Element Selection

An eight-node quadrilateral layered shell element SHELL99 is used to model the composite tower. SHELL 99 can be used to model up to 250 layers of laminates, as shown in Figure 4.1.

The element has six degrees of freedom at each node: Translations in the nodal x-, y-, and z-directions; and Rotations about the nodal x-, y-, and z-axes. This element is selected because of its capacity to account for large deflection and large deformation; its ability to have 250 layers of different thickness; and its node offset option. The material properties of an element are defined in terms of the principal axes of the element. The element coordinate system is as follows: the x-axis is parallel to the fibre direction; the y-axis is perpendicular to the fibre direction; and the z-axis is in the thickness direction of the element.

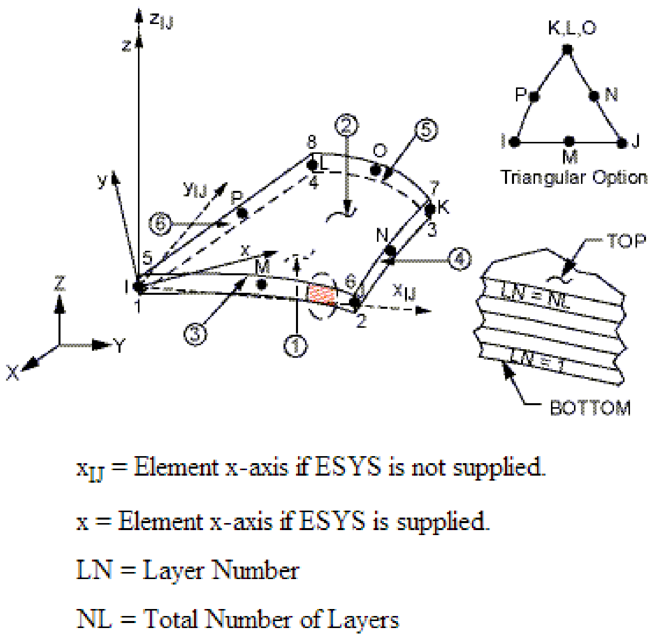



**Figure 4.1:** SHELL 99 linear layered structural shells (ANSYS, 2006)

### 4.5.3 Stacking Sequence and Thickness

In this study, the thickness (t) of each layer is 1.25 mm and the stacking sequence is $(90, 0_N, 90)$ with respect to mandrel's longitudinal axis, where N+2 is the total number of layers. For example, if the thickness of the wall is 7.5 mm, the stacking sequence would be $(90, 0_6, 90)$

with respect to the longitudinal axis of the mandrel. The corresponding ANSYS commands are,

R, 1, 6, 0

RMORE,

RMORE, 1, 0, t, 1, 90, t

RMORE, 1, 90, t, 1, 90, t

RMORE, 1, 90, t, 1, 0, t

Here, in the first line, 1 refers to the first set of real constants and 6 refers to 6 numbers of layers. In the second line, RMORE refers to additional subset of real constants. In the third lines, 0 refers to the angle between the fibre direction and the x-axis of the elemental coordinate system, t refers to the layer thickness and 90 refers to the fibre direction perpendicular to the elemental x-axis.

### 4.5.4 Material Property Defining and Meshing

The MP command is used to define material properties of the GFRP material. The size of each element is decided mainly by two commands: LESIZE and ESIZE. The LESIZE command defines the size of the element towards global Y-axis and the ESIZE command defines the size of the element in the global XZ-plane. Once the size of the element is decided for each area, the AMESH command is used to mesh the area.

### 4.5.5 Tower Boundary Condition

The tower base is designed to be fixed. The NSEL command is used to select the nodes at the base to input the boundary conditions. The D command is used to restrain all the six degrees of freedom of each node at the base of the tower as:

D,ALL,UZ,0,0,,,UX,UY,ROTX,ROTY,ROTZ (D defines constraints, Node#, restrain translation UZ, UX, and UY and rotation ROTX,ROTY,ROTZ)

### 4.5.6 Load Application on the Tower

The wind loads are calculated at every 5-m interval and are uniformly distributed to all of the nodes in that 5-m segment. The sample of ANSYS command for the wind load application along the tower segment is as follows:

A1 = -6160.78 (Total wind load in Newton for 0 to 5m height range)

ASEL, S, AREA,, 5 (Selecting the area no 5 which is in the direction of the wind)

ASEL, A, AREA,, 6 ( Selecting of an additional area no 6 which is in the direction of the wind)

NSLA, S, 0 (Selecting of all the nodes which are in the selected areas)

NSEL, R, LOC, Y, 0, 5000 (Reselecting the nodes only within the height range between 0 and 5 m in the global Y-axis)

*GET, NCOUNT, NODE, 0, COUNT (Counting the number of nodes within the 0 to 5 m height range)

F, ALL, FZ, A1/NCOUNT (Applying the wind load A1 equally to all the nodes within the 0 to 5 m height range)

The lateral thrust force from rotor loading is applied on the key points of the top of the tower. The moments are converted to coupling forces and then applied on the key points of the top of the tower. The rotor self-weight is applied to the all the nodes at the top of tower.

### 4.6 Preliminary Investigation of the 10 kW Tower Section

To arrive with a design section, preliminary investigation is carried out for 8-, 10-, and 12-cell sections. Based on the deflection limit discussed in section 3.1.1 and self-weight of the tower, a section will be selected. This section will be refined to obtain a design section. The following sub sections present the analysis results.

#### 4.6.1 Eight-Cell Sections

A finite element model for 8-cell tower is developed in such a way that there are options to change some basic parameters such as bottom outer diameter, top outer diameter, inner diameter, wall thickness and loading. In Figure 4.2(a), a typical eight-cell tower section is shown and an isometric view of an eight-cell tower section is shown in Figure 4.2(b). The details results of the ANSYS for all the trials of the 8-cell sections and loading are included in the Appendix B1 and the ANSYS code for trial # 5 is given in the Appendix B2. The summary of the results of the 8-cell trial sections are shown in Table 4.5.

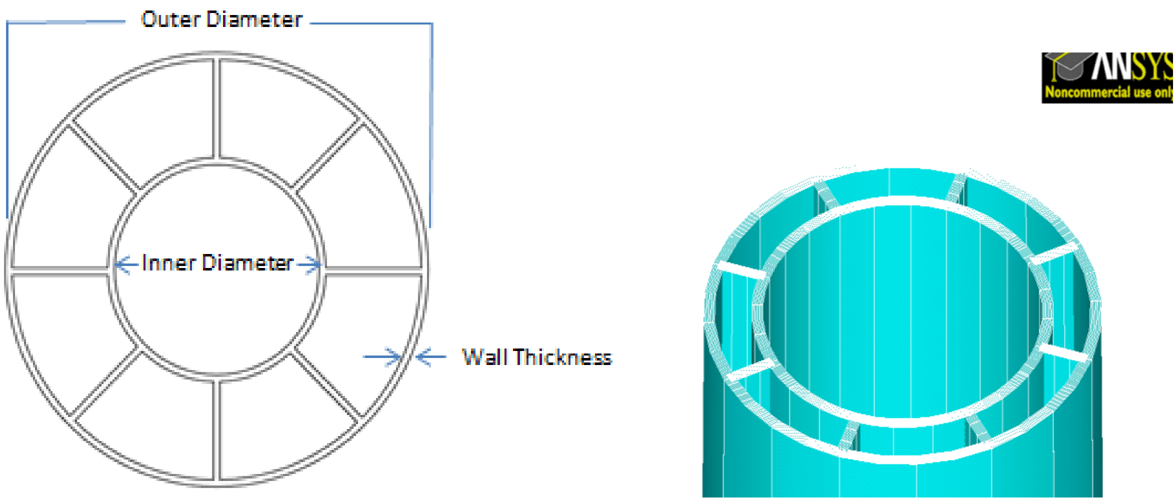



**Figure 4.2:** (a) Typical 8-cell tower section (b) Isometric view of 8-cell FEA model at the top of tower

**Table 4.5:** Trial results summary for the eight-cell sections

| Tower Dimensions | | | | | | Results for 8-cell sections | |
|---|---|---|---|---|---|---|---|
| Trial No | Outer diameter at bottom c/c (mm) | Outer diameter at top c/c (mm) | Inside diameter c/c (mm) | Outer and inner shell thickness (mm) | Stiffener thickness (mm) | Weight (kg) | Max Deflection (mm) |
| 1 | 1000 | 600 | 300 | 7.5 | 7.5 | 2001 | 1190 |
| 2 | 1500 | 600 | 300 | 7.5 | 7.5 | 2656 | 476 |
| 3 | 1500 | 800 | 600 | 7.5 | 7.5 | 2824 | 420 |
| 4 | 1500 | 800 | 600 | 11.25 | 11.25 | 4235 | 254 |
| 5 | 1300 | 800 | 600 | 11.25 | 11.25 | 3842 | 353 |
| 6 | 1300 | 800 | 600 | 10 | 10 | 3415 | 404 |
| 7 | 1300 | 800 | 600 | 8.75 | 8.75 | 2988 | 472 |
| 8 | 1300 | 800 | 600 | 7.5 | 7.5 | 2561 | 567 |

### 4.6.2 Ten-Cell Sections

Similar to the 8-cell sections, different parameter are investigated in the 10-cell sections. Figure 4.3(a) and Figure 4.3 (b) show the typical 10 –cell cross section and an isometric view rom ANSYS, respectively. The summary of the results for the 10-cell sections are shown in Table 4.6.The detailed analysis results and loading are in the Appendix B3 while the ANSYS sample code for trial #4 is in the Appendix B4.

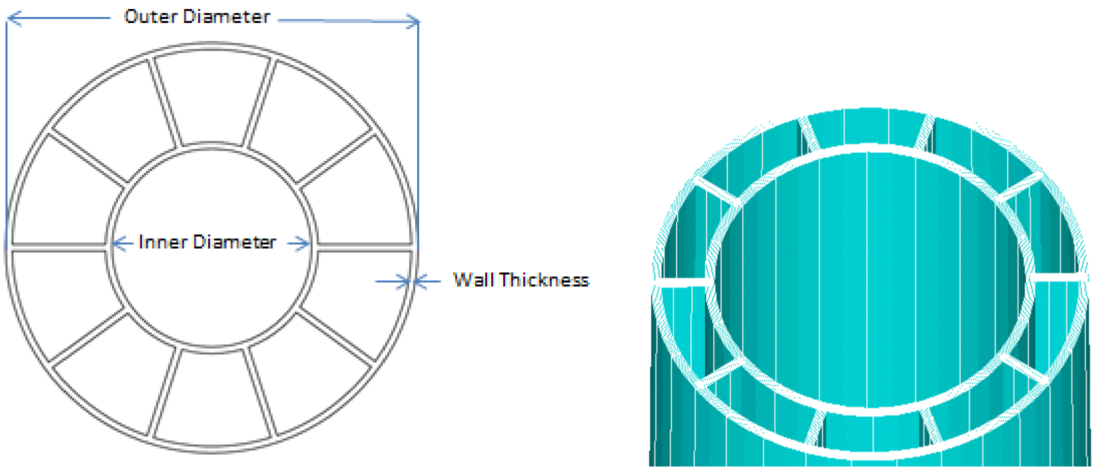



**Figure 4.3:** (a) Typical 10-cell tower section (b) Isometric view of 10-cell FEA model at the top of the tower

**Table 4.6:** Trial results summary for the ten-cell sections

| Tower Dimensions | | | | | | Results for 10-cell Sections | |
|---|---|---|---|---|---|---|---|
| Trial No | Outer diameter at bottom c/c (mm) | Outer diameter at top c/c (mm) | Inside diameter c/c (mm) | Outer and inner shell thickness (mm) | Stiffener thickness (mm) | Weight (kg) | Max Deflection (mm) |
| 1 | 1300 | 800 | 600 | 7.5 | 7.5 | 2726 | 488 |
| 2 | 1300 | 800 | 600 | 11.25 | 11.25 | 4089 | 290 |
| 3 | 1300 | 800 | 600 | 10 | 10 | 3635 | 335 |
| 4 | 1300 | 800 | 600 | 8.75 | 8.75 | 3180 | 397 |

### 4.6.3 Twelve-Cell Sections

Similar to the 8- and 10-cell sections, different parameter are investigated in the 12-cell sections also. Figure 4.4(a) and Figure 4.4(b) show the typical 12-cell section and the isometric view of a 12-cell FEA model at the top of the tower, respectively. The analysis of

12-cell sections and loading are included in the Appendix B5 and a sample ANSYS code for trial # 4 is included in the Appendix B6. The summary of the analysis of 12-cell is shown in Table 4.7.

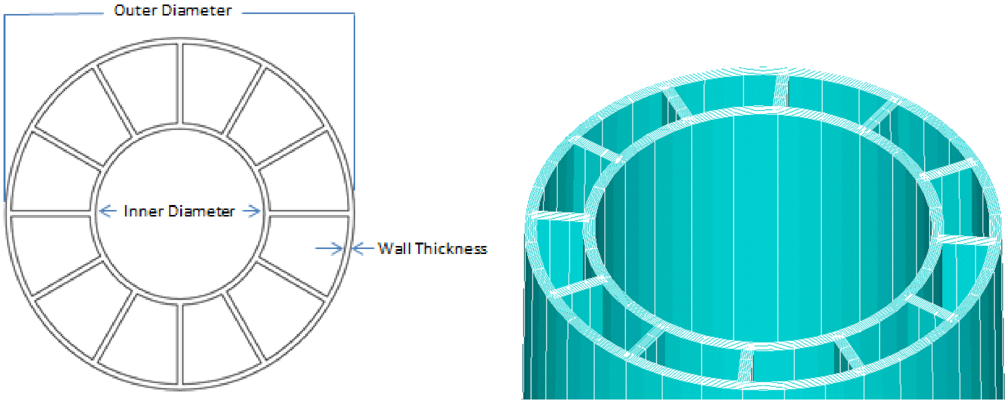



**Figure 4.4:** (a) Typical 12-cell tower section (b) Isometric view of a 12-cell FEA model section at the top of the tower

**Table 4.7:** Trial results summary for the twelve-cell sections

| Tower Dimensions | | | | | | Results for 12-cell sections | |
|---|---|---|---|---|---|---|---|
| Trial No | Outer diameter at Bottom c/c (mm) | Outer diameter at c/c (mm) | Inside diameter c/c (mm) | Outer and inner shell thickness (mm) | Stiffener thickness (mm) | Weight (kg) | Max Deflection (mm) |
| 1 | 1300 | 800 | 600 | 7.5 | 7.5 | 2891 | 462 |
| 2 | 1300 | 800 | 600 | 8.75 | 8.75 | 3373 | 376 |
| 3 | 1300 | 800 | 600 | 10 | 10 | 3855 | 317 |
| 4 | 1300 | 800 | 600 | 11.25 | 11.25 | 4337 | 275 |

### 4.7 Design Section

From Table 4.5, Table 4.6 and Table 4.7, the trial results of 8-, 10-, and 12-cells sections are plotted in Figure 4.5. From Figure 4.5, it can be seen that the increase in the weight of the tower results in the decease of the tip deflection for all numbers of cell configurations. It is also noticed that the deflection does not significantly depend on the numbers of cell but on the weight of the tower. Therefore, an 8-cell section will be chosen as a preliminary design section because it requires less lever of labor in the fabrication in comparison to the 10- and 12- cell sections.

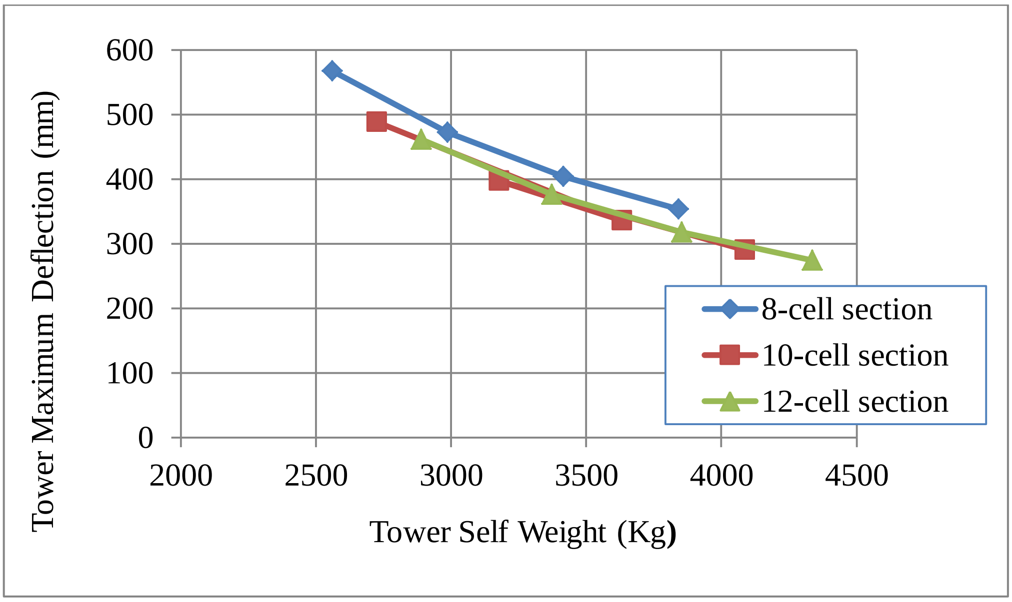



**Figure 4.5:** Tower self-weight and deflection

The 8-cell section that meets the deflection limit which is 1.5% of the tower height has the following geometric data which the trial section # 5 of the 8-cell section:

- Tower's outer diameter at bottom: 1300 mm c/c
- Tower's outer diameter at top: 800 mm c/c
- Tower's Inner diameter: 600 mm c/c

- Wall thickness: 11.25 mm

According to the tower fabrication company Dimension Composite Inc, Quebec, the following are the fabrication criteria

- Fibre volume ratio cannot be more than 45% for the hand lay-up method of composite fabrication.
- Cell unit cannot be closed for the hand lay-up method and must be closed for the filament winding process.

Considering the above fabrication criteria, a proposed design section is customized to have an average wall thickness of 11.25 mm and have similar moment of inertia as that of the 8-cell section trial # 5. The outer top c/c diameter, the outer bottom c/c diameter and the inside c/c diameter are same as those of the 8-cell trial no 5 section. The conceptual fabrication drawings based on the above information is shown in Figure 4.6, where the stiffener and the circumferential cell unit are fabricated from the hand lay-up method and the inside core cell unit is fabricated from the filament winding process. Note that the section is proven to have a constant moment of inertia regardless of the orientation of the global X- and Z-axes.

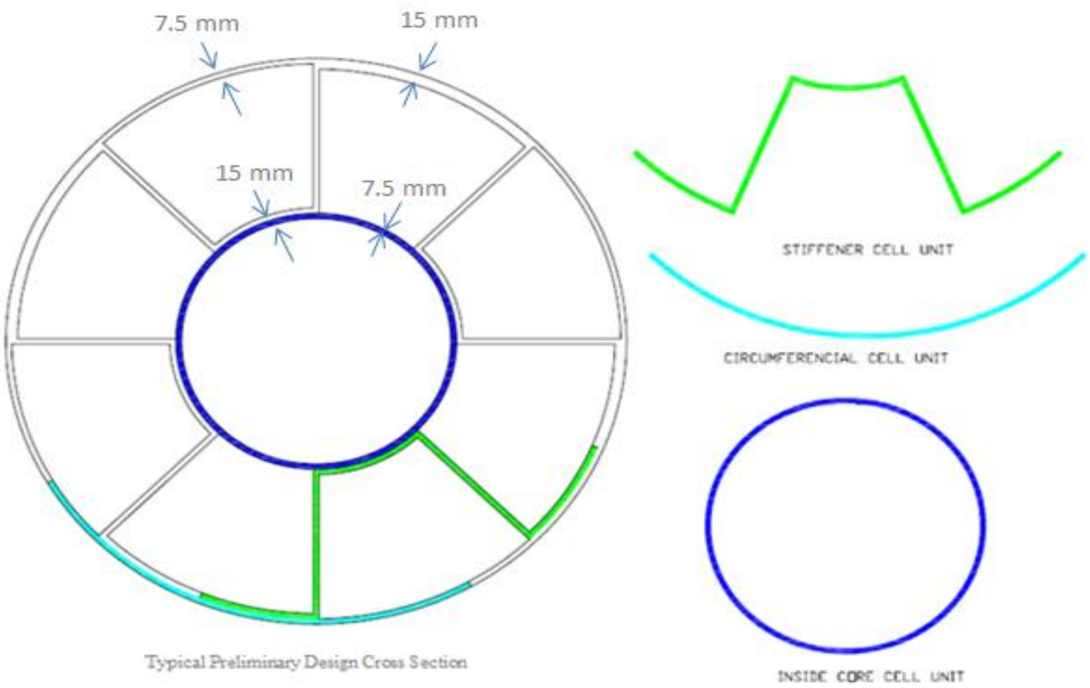



**Figure 4.6:** Conceptual fabrication drawing of the proposed design section

The proposed design section in Figure 4.6 is further optimized and is detailed in the following subsections.

### 4.7.1 FEA Model of the Proposed Design Section and the Verification of the Model

A FEA model is constructed based on the conceptual drawing in Figure 4.6 and is shown in Figure 4.7.In the verification of the developed FEA model, a lateral point load of 5000 N is applied at the top of the tower and the tip deflection is compared with the theoretical solution.

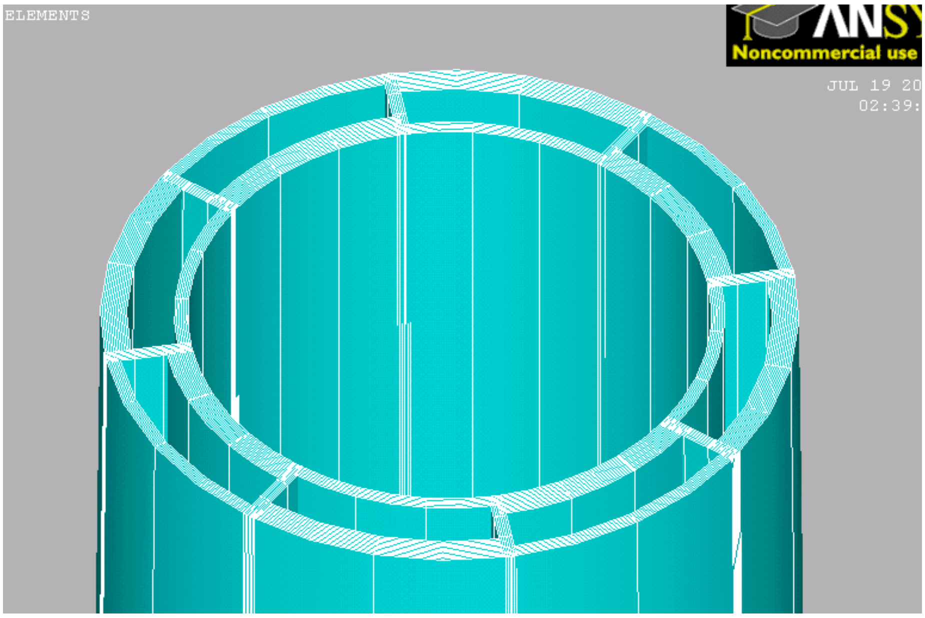



**Figure 4.7:** Isometric view of the proposed design section (at the top section of the tower)

***Theoretical Solution***

The expression of the tower's moment of inertia along its length is obtained from the trend line connecting the calculated moments of inertia at different locations using AUTOCAD based on the geometry of that location. The plot of the moment of the inertia is shown in Figure 4.9. The direct integration method is chosen to analyse a cantilevered tapered tower subjected to a transverse point load at the tip of the tower shown in Figure 4.8.

From the direct integration method, the deflection at any point of the tower is given by

$$\Delta = \int \int (Px/EI)\, dxdx$$

Here $I = 7.1864x^2 + 214637\text{x} + 3 * 10^9$ , $E = 34125\, MPa$. Using Maple software, the above integration is solved (the Appendix B7) and the maximum deflection at the top of the tower is calculated to be 80 mm.

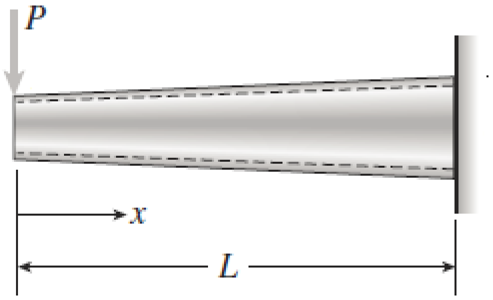



**Figure 4.8:** Analytical model of the tower

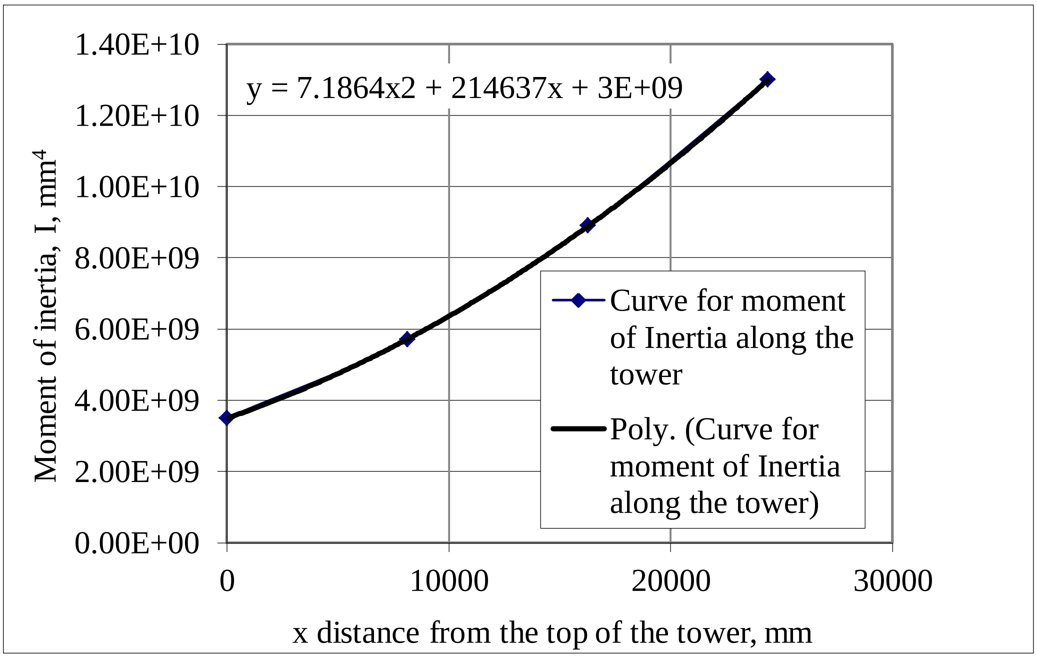



**Figure 4.9:** Area moment of inertia curve along the tower

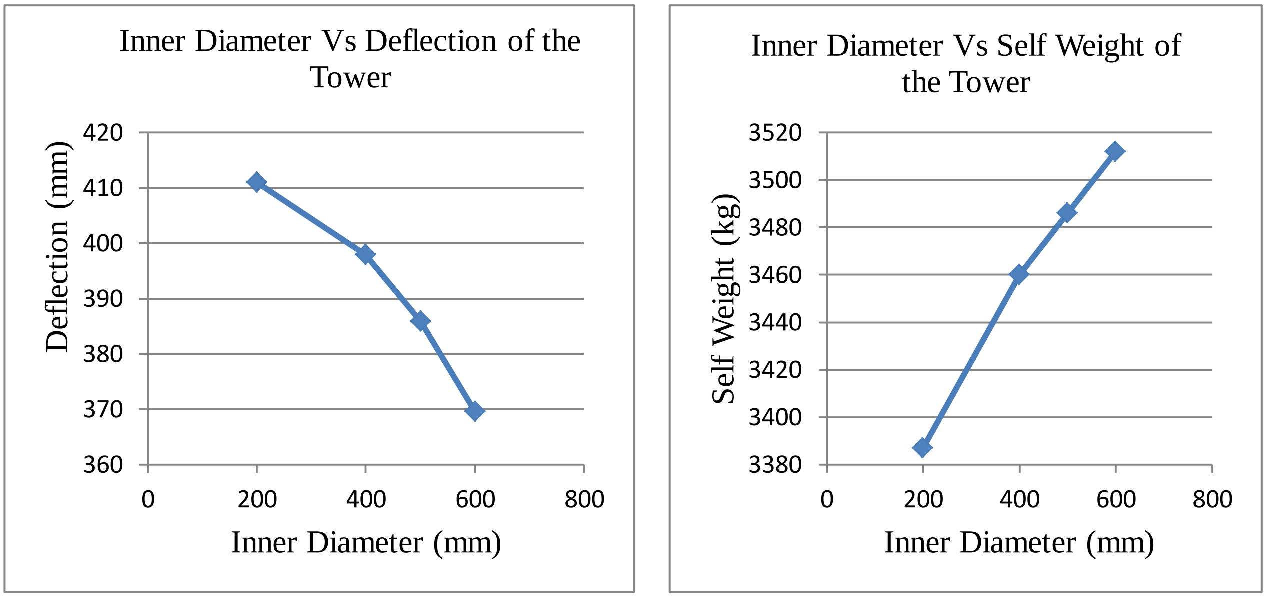
***The FEA result***

In order to compare the analysis result with the direct integration method, the material property of the GFRP is assumed to be isotropic. The same Modulas of Elasticity, $E$ =34125 MPa is used. The static nonlinear analysis gives the maximum deflection of 77 mm which is 3.8% difference.

### 4.7.2 Parametrical Studies of the Proposed Design Section

The following parametrical studies are investigated for the possibility to optimize the proposed section:

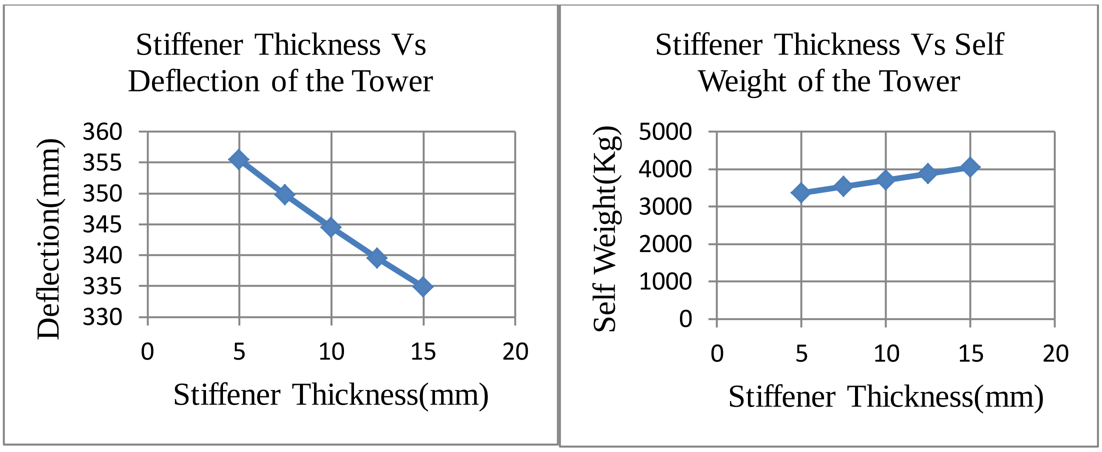
- To study the effects of the inner diameter, all other parameters are kept constant. The results of the analysis are shown in Figure 4.10.




(a) (b)

**Figure 4.10:** (a) The inner diameter and the deflection and (b) the inner diameter and self-weight of the tower

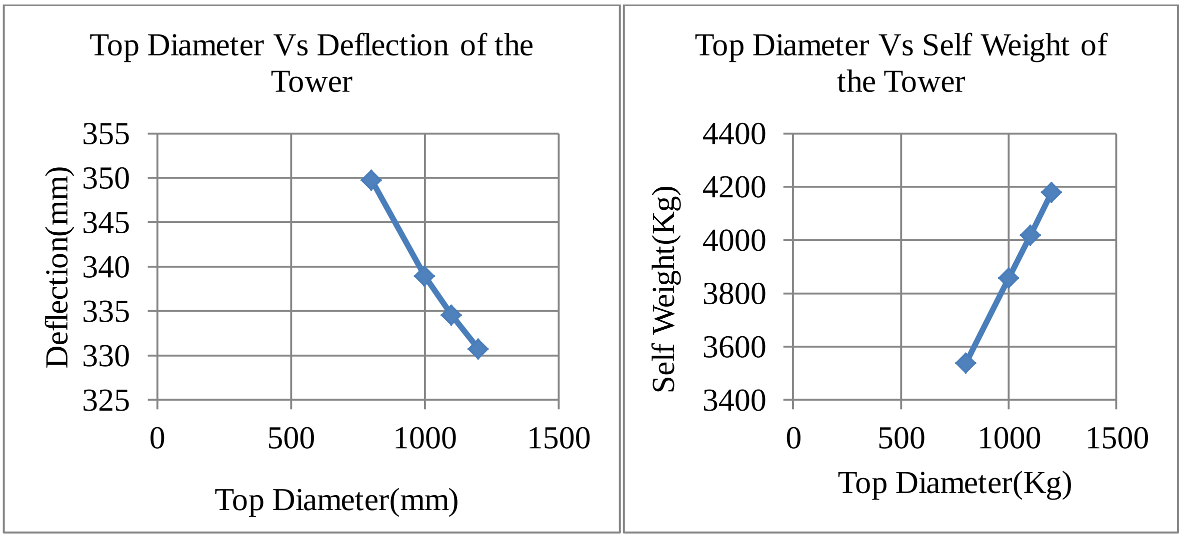
- To study the effects of the stiffener thickness, all other parameters are kept constant. The results of the analysis are shown in Figure 4.11.




(a) (b)

**Figure 4.11:** (a) The stiffener thickness and the deflection (b) The stiffener thickness and the self-weight of the tower

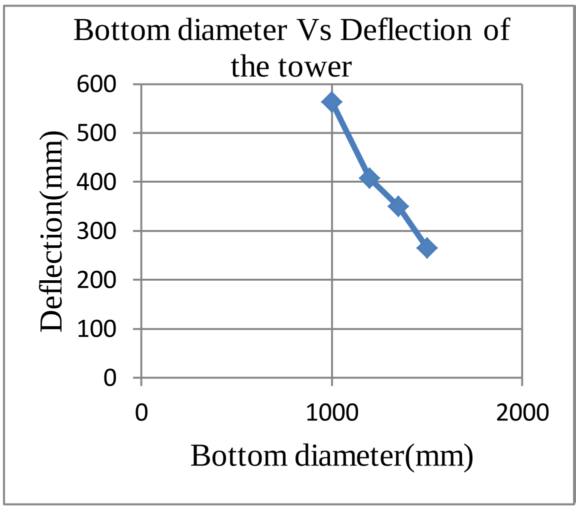
- To study the effects of the top diameter, all other parameters are kept constant. The results of the analysis are shown in Figure 4.12.



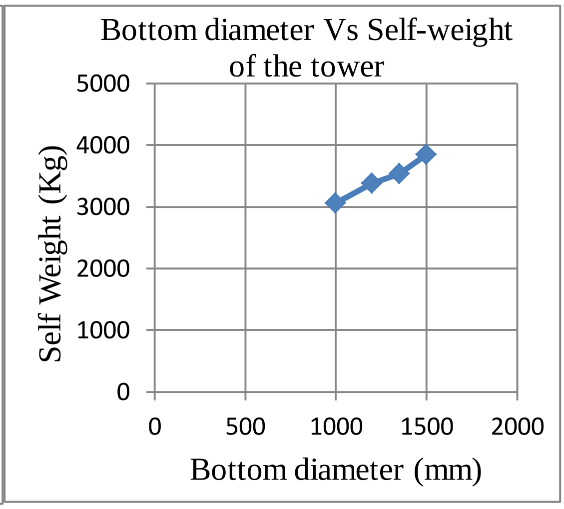

(a) (b)

**Figure 4.12:** (a) The top diameter and the deflection (b) The top diameter and the self-weight of the tower

- To study the effects of the bottom diameter, all other parameters are kept constant and the results are shown in Figure 4.13.




(a)




(b)

**Figure 4.13:** (a) The bottom diameter and the deflection of the tower (b) The bottom diameter and the self-weight of the tower

The discussion of the parametrical studies is detailed in section 5.1.

### 4.7.3 Tower Deflection for the Proposed Design Section

To determine the deflection of the wind turbine tower for the proposed design section as outlined in section 4.7, a static nonlinear analysis is performed for the design governing load combination #11 in section 4.4, where the wind turbine loading in service condition specified in Table 4.3 and the service wind loading in Table 4.8.The wind loads are applied to parallel to the global Z-axis of the FEA model. An FRP structure can experiences large deformations, and therefore, can change in its geometric configuration that causes the structure to respond in a nonlinear fashion. Thus, the geometric nonlinearity must be taken into account in the analysis. The large deflections result in changes to the element orientation, and, consequently, changes in the element stiffness matrix.

**Table 4.8:** Service wind loading in the FEA of the proposed section

| Height Range, m | Projected Area ($m^2$) | Exposure factor, (Ce) | Gust Factor (Cg) | Pressure, (P), KPa | Wind Force (F), N |
|---|---|---|---|---|---|
| 0-5 | 6.32 | 1.00 | 2.50 | 1.95 | 6161 |
| 5-10 | 5.81 | 1.00 | 2.50 | 1.95 | 5661 |
| 10-15 | 5.29 | 1.08 | 2.50 | 2.11 | 5597 |
| 15-20 | 4.78 | 1.15 | 2.50 | 2.24 | 5355 |
| 20-24.39 | 4.30 | 1.20 | 2.50 | 2.33 | 5011 |

The deflected shape of the tower is shown in Figure 4.14 and the deflection is found to be 370 mm. The corresponding ANSYS codes are included in the Appendix C1.

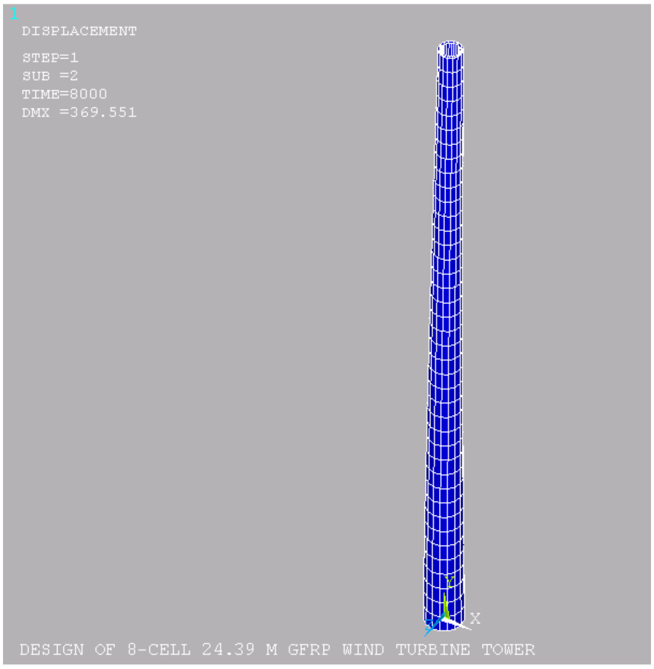



**Figure 4.14:** Deflected shape of the wind turbine tower for the preliminary design section

### 4.7.4 Tsai-Wu Failure Criterion

The Tsai-Wu failure criterion is checked for the proposed design section under the factored design governing load combination # 11 in section 4.4, where the factored wind loading specified in Table 4.9 and the wind turbine rotor loading specified in Table 4.4.

**Table 4.9:** Factored wind load in the FEA of the proposed section

| Height Range, m | Projected Area ($m^2$) | Exposure factor, (Ce) | Gust Factor (Cg) | Pressure, (P), Kpa | Wind Force (F), N | Factored Wind load without Ice, N |
|---|---|---|---|---|---|---|
| 0-5 | 6.32 | 1.00 | 2.50 | 1.95 | 6161 | 9241 |
| 5-10 | 5.81 | 1.00 | 2.50 | 1.95 | 5661 | 8492 |
| 10-15 | 5.29 | 1.08 | 2.50 | 2.11 | 5597 | 8396 |
| 15-20 | 4.78 | 1.15 | 2.50 | 2.24 | 5355 | 8032 |
| 20-24.39 | 4.30 | 1.20 | 2.50 | 2.33 | 5011 | 7516 |

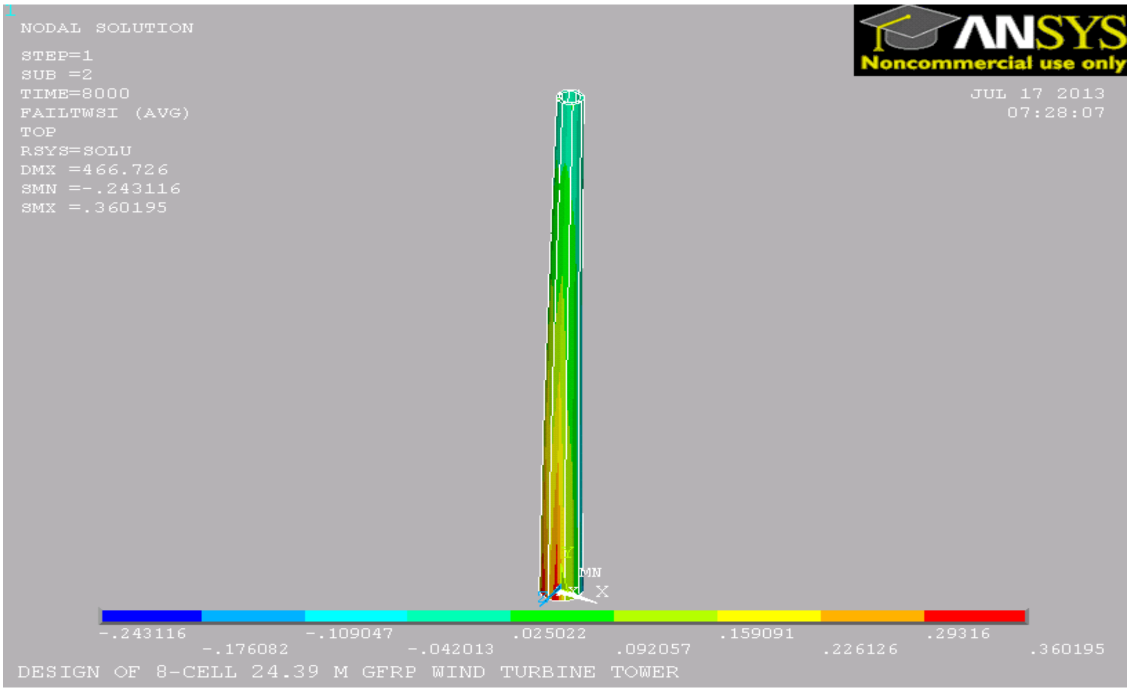



**Figure 4.15:** Distribution of Tsai-Wu indexes along the tower

The distributions of Tsai-Wu failure indexes along the tower are shown in Figure 4.15 .The corresponding ANSYS codes are included in the Appendix C2. It is found that the maximum value of Tsai-Wu failure index is 0.36.

### 4.7.5 Maximum Stress Criterion

The Maximum stress criterion is checked for the proposed design section under the factored design governing load combination # 11 in section 4.4,where the wind turbine rotor loading specified in Table 4.4 and the factored wind loading specified in Table 4.9.The distributions of the maximum stress indexes along the tower are shown in Figure 4.16. The corresponding ANSYS codes are included in the Appendix C2. It is found that the maximum value of the maximum stress index is 0.43.

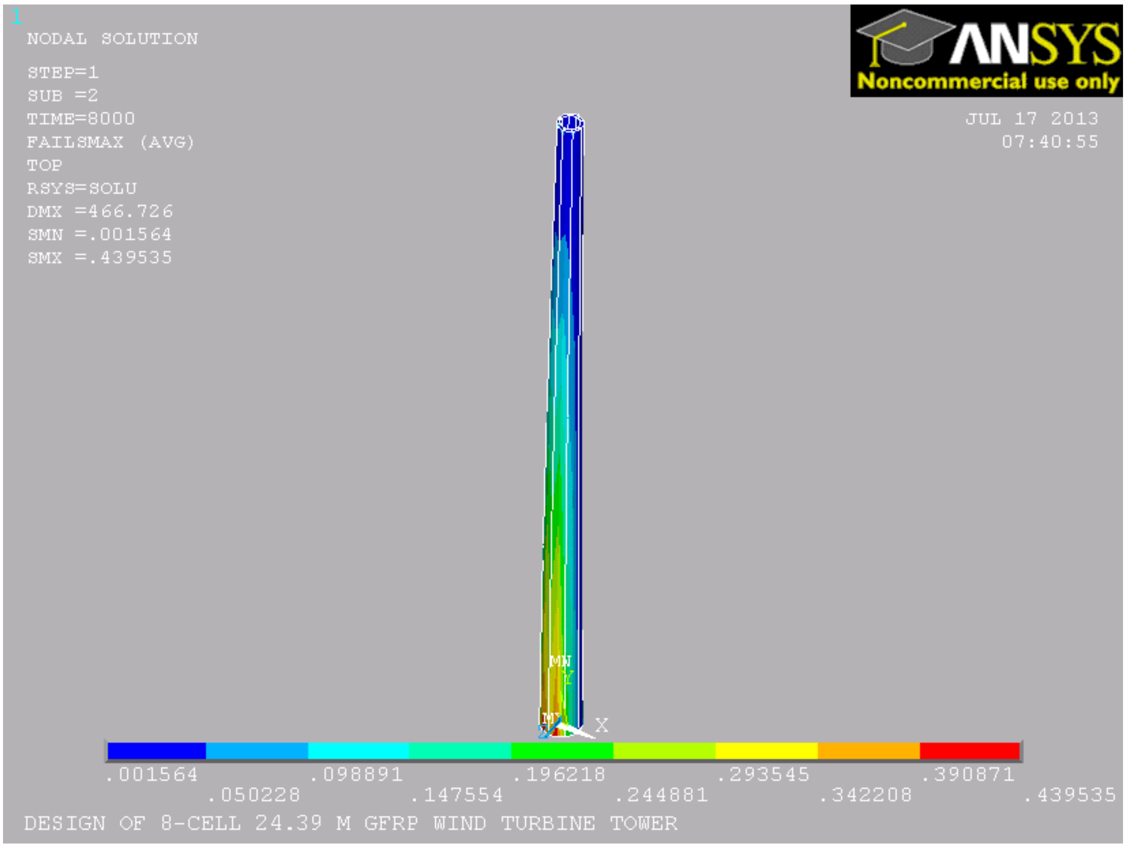



**Figure 4.16:** Distribution of the maximum stress indexes along the tower

### 4.7.6 Free Vibration Analysis of the Proposed Design Tower

The FEA is also used to perform free vibration analysis of the proposed tower to determine the mode shapes and their associated natural frequencies of the tower. The first ten natural frequencies of the tower are listed in Table 4.10 and the first five mode shapes are shown in Figure 4.17 to Figure 4.21. The corresponding ANSYS codes are included in the Appendix C3.

**Table 4.10:** The first ten natural frequencies of the tower

| Modes | Natural frequencies of tower (Hz) |
|---|---|
| 1 | 0.966 |
| 2 | 0.967 |
| 3 | 5.38 |
| 4 | 5.48 |
| 5 | 10.46 |
| 6 | 14.41 |
| 7 | 15.41 |
| 8 | 23.90 |
| 9 | 24.71 |
| 10 | 27.91 |

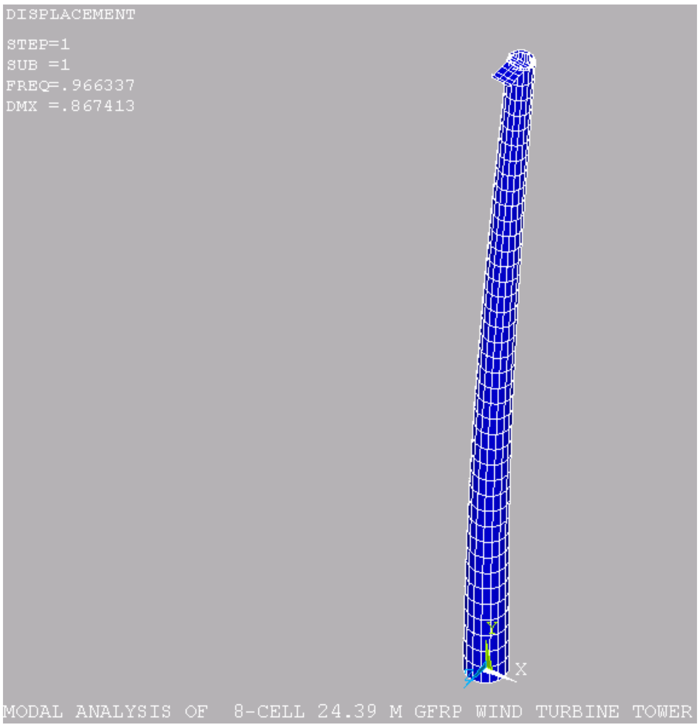



**Figure 4.17:** Tower 1st mode shape at 0.966 Hz

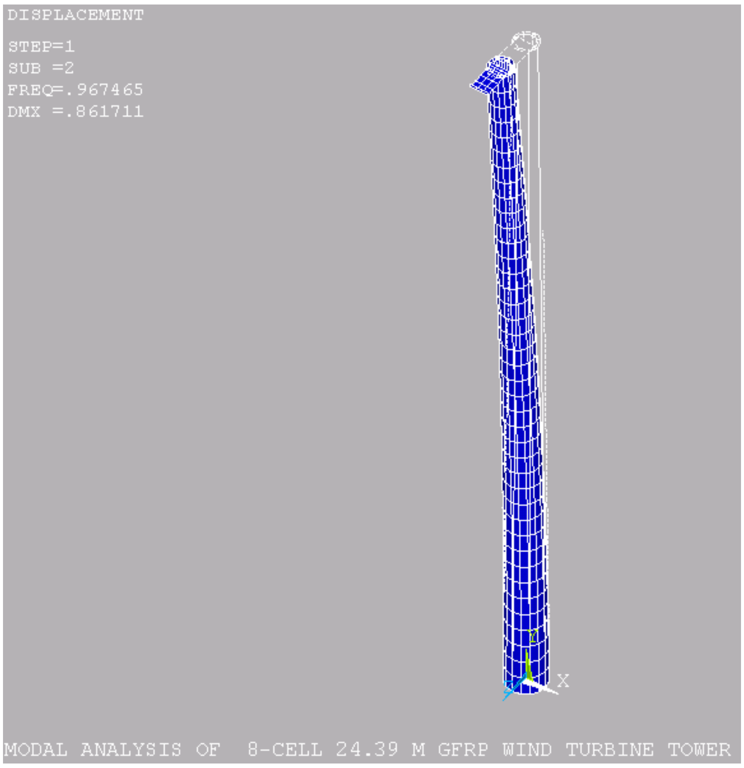



**Figure 4.18:** Tower 2nd mode shape at 0.967 Hz

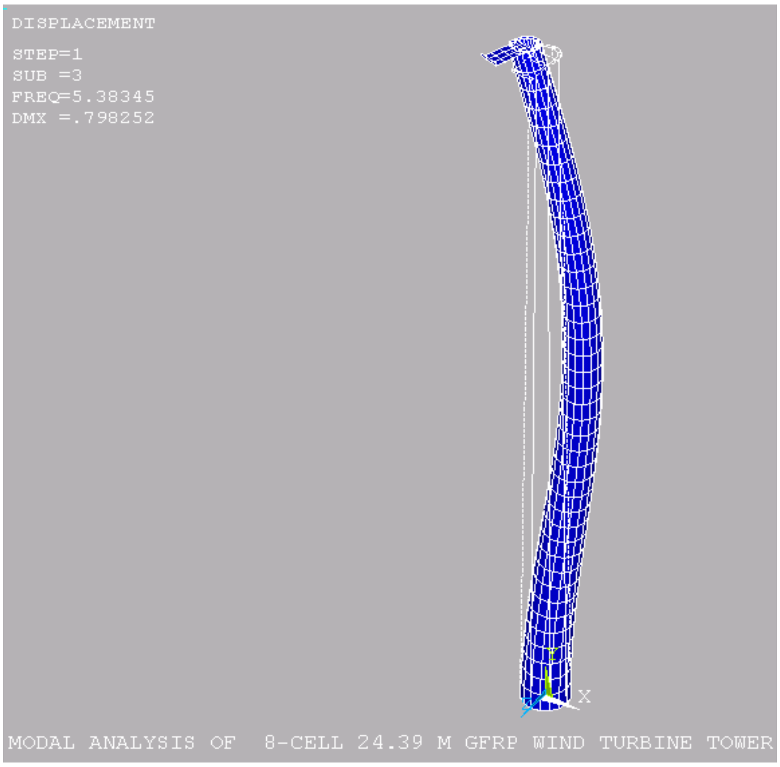



**Figure 4.19:** Tower 3rd mode shape at 5.38 Hz

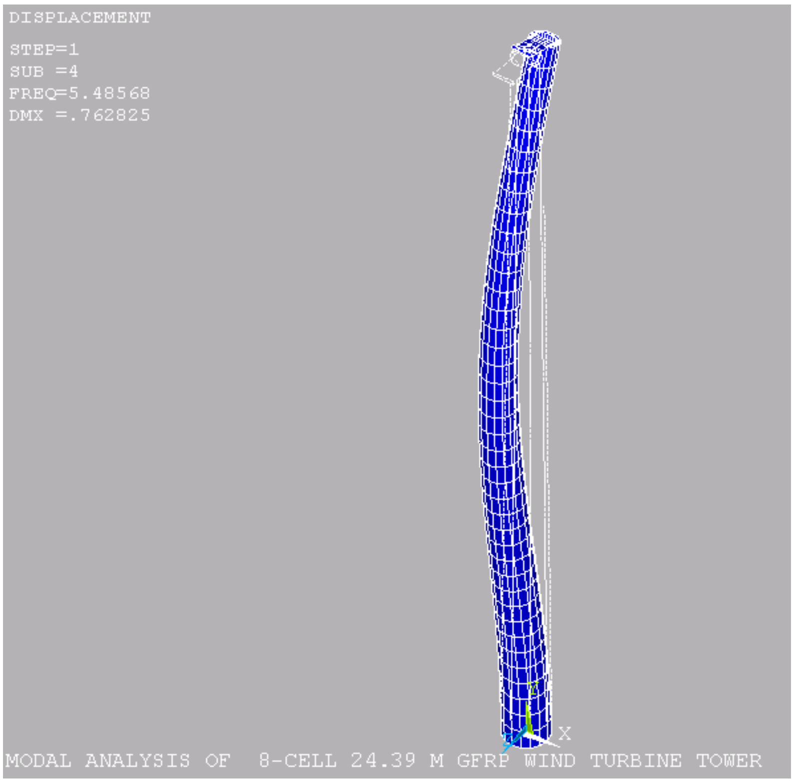



**Figure 4.20:** Tower 4th mode shape at 5.48 Hz

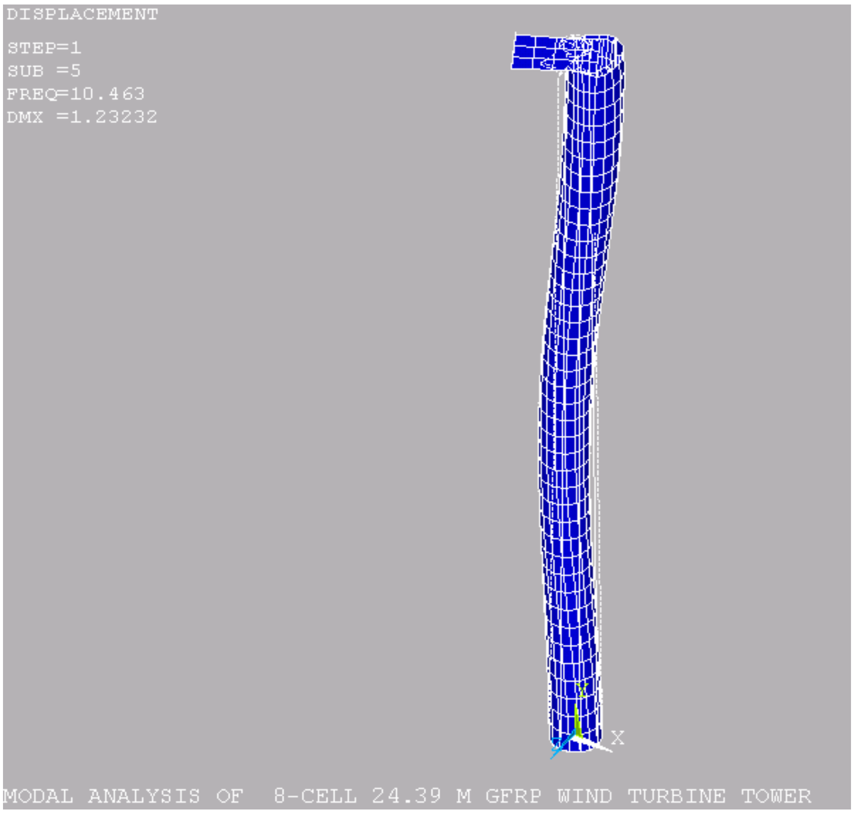



**Figure 4.21:** Tower $5^{th}$ mode shape at 10.46 Hz

### 4.7.7 Buckling Analysis of the Proposed Design Section

The Eigen buckling analysis is performed to predict the theoretical overall buckling strength of the proposed design tower under compressive loads. In the analysis, an axial load is uniformly applied at the tower top. This axial load is increased until buckling is observed. Figure 4.22 shows the wind turbine tower under an axial load and Figure 4.23 shows the buckling shape of the tower under compression. The Eigen buckling load is found to be 937050 N. The ANSYS codes for the Eigen buckling analysis are included in the Appendix C4.

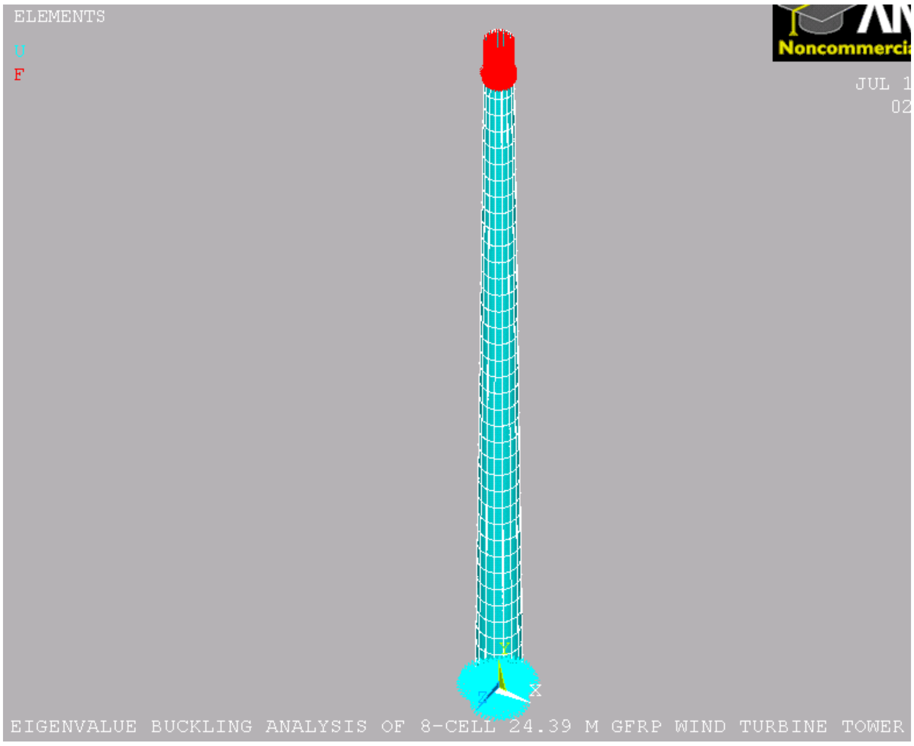



**Figure 4.22:** The proposed wind turbine tower under an axial load

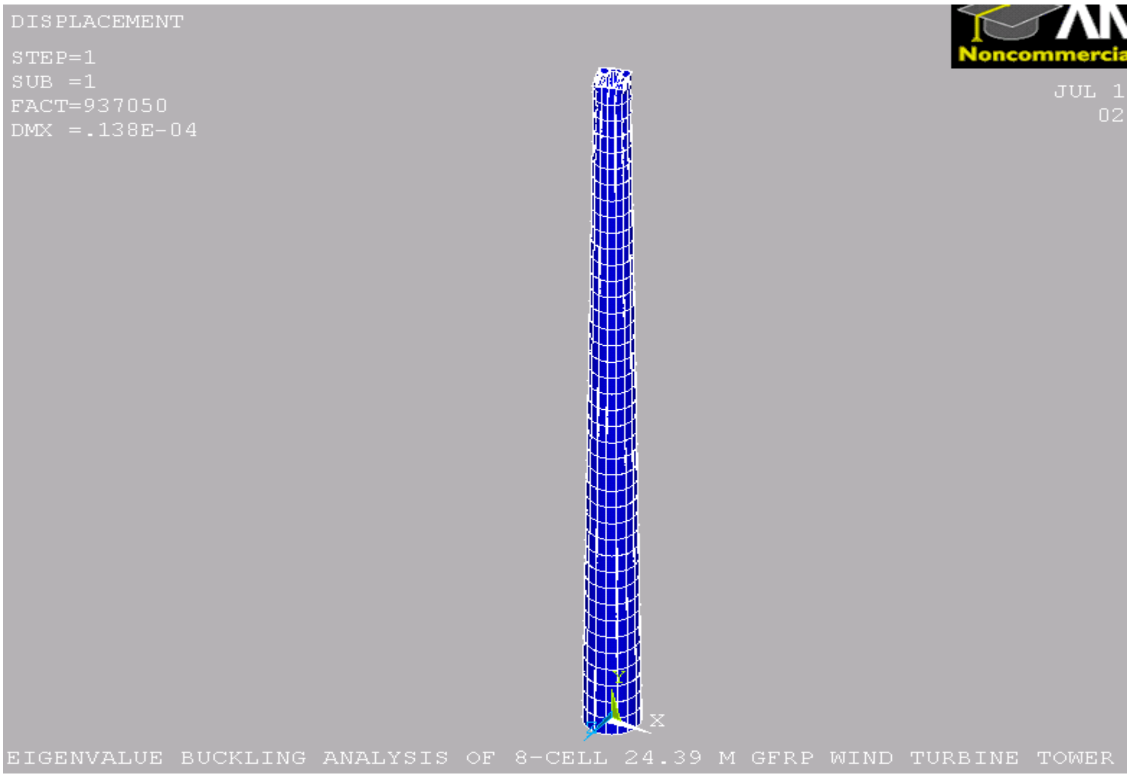



**Figure 4.23:** Buckling mode shape of the proposed wind turbine tower

### 4.7.8 Failure Lateral Load Prediction of the Proposed Tower

The FEA is used to determine the maximum lateral loads that will cause failure of the proposed tower. Note that although the wind and the rotor loads are typically not proportionate, the same increment of the wind and the rotor loads are investigated here. In the analysis, a loop is established in the ANSYS input file to enable the wind and the rotor loads to be increased by small intervals until the maximum principal stresses in the tower exceed the failure index specified by any of the two failure criteria. It is found that the tower can resist 25568 N lateral factored thrust load at the top of the tower and the factored wind loads as in Table 4.11.

**Table 4.11:** The maximum factored wind loads that can be resisted by the proposed design tower

| Height Range (m) | Wind loads (N) |
|---|---|
| 0-5 | 18482 |
| 5-10 | 16983 |
| 10-15 | 16792 |
| 15-20 | 16064 |
| 20-24.39 | 15032 |

## 4.8 Comparison between a Steel and the Proposed Design Tower

A FEA model of a 24.3m steel tower is developed to compare with the proposed GFRP tower. The cross-section of the steel tower is circular in shape with a bottom and top outer diameter of 620 mm and 580 mm, respectively and a constant thickness of 11.25 mm, as shown in Figure 4.24. The diameter and the thickness of the steel tower are chosen so that the deflection of the tower is the same as the proposed section. The procedure for the calculation of the wind turbine, the wind and the ice loads are the same as that used in sections 4.2 and 4.3, respectively. The ANSYS codes for the steel tower are included in the Appendix C5.

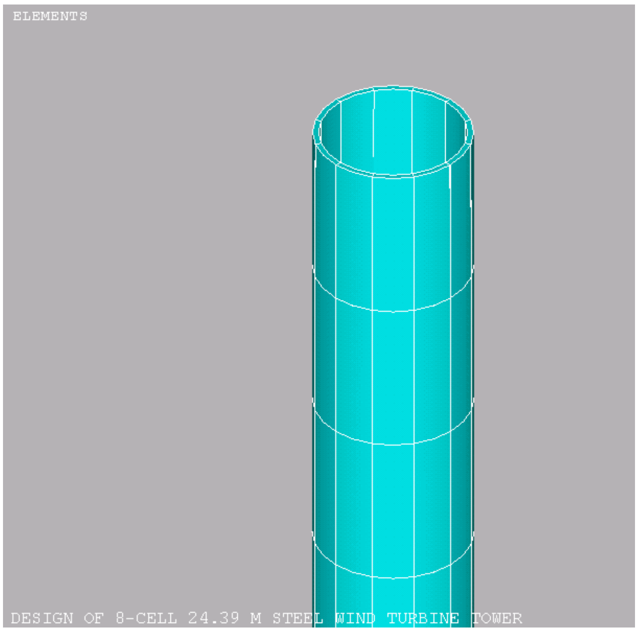



**Figure 4.24:** Steel wind turbine tower (FEA model)

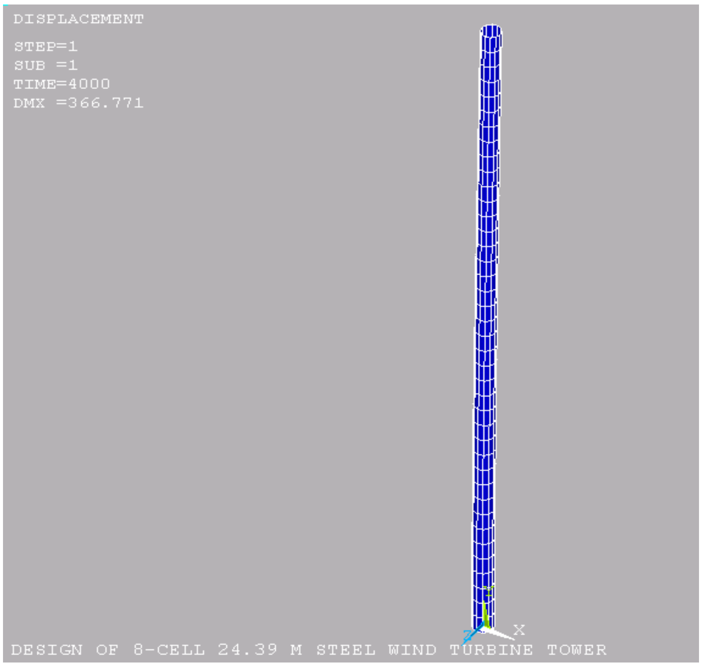



**Figure 4.25:** Deflected shape of 24.3m steel wind turbine tower

The weight of steel tower is 4064 Kg and the stresses in the tower are less than the factored resistance of 315 MPa ($0.9F_y$). The deflected shape of the steel tower under the service load condition is shown in the Figure 4.25.

In determining the cost of the GFRP towers, Alshurafa (2012) used the average cost per 1kg of epoxy (resin and hardener) is \$6 and the average cost of glass fibre is \$2 per kg for the laboratory experiment at University of Manitoba. The fibre weight fraction of the FRP tower with fibre volume fraction of 45% and a density of 0.002 gm/mm$^3$ is calculated using the following equation:

$$V_f = W_f \frac{density\ of\ composite}{density\ of\ fibre}$$

It is found that the weight fraction of fibre is 0.56. The cost of the structural steel sheet is assumed to be \$3.5 per kg (Foshan Rongkunyang Steel Co Ltd, 2013). The cost comparison between the steel and the designed towers is shown in Table 4.12.

**Table 4.12:** The comparison between the steel and the proposed GFRP tower

| Tower | Maximum deflection (mm) | Weight of the tower (kg) | Cost ($) |
|---|---|---|---|
| Steel tower | 367 | 4064 | 14,225.00 |
| Proposed GFRP tower | 370 | 3512 | 13205.00 |

Note that only the material cost is considered in the Table 4.12. The fabrication, transport and erection cost will be much lesser for the GFRP tower in comparison to the steel tower.

# Chapter 5 Discussion, Conclusion and Recommendation for Future Study

## 5.1 Discussion

Based on the results of the numerical studies, the following conclusions are drawn:

### 5.1.1 Parametrical Studies of the Proposed Design Section

- From Figure 4.10(a), it can be seen that when the inner diameter of the section is increased from 200 mm to 600 mm (200% increase in the diameter), the deflection of the tower decreases by 10% and the weight increases by only 4% (Figure 4.10(b)). Therefore, the 600 mm inner diameter is more effective and preliminary chosen for a proposed section.
- From Figure 4.11(a), it is found that the increase in the stiffener thickness from 5 mm to 15 mm (200% increase) results in 6% less deflection with 21% increase in weight (Figure 4.11(b)). Hence the increase in the stiffener thickness is not a good option to reduce the deflection of the tower.
- From Figure 4.12(b), it can be seen that if the top diameter is increased from 800 mm to 1200 mm or 50% increase, the self-weight increases by 18% and the deflection decreases by 6% (Figure 4.12(a)). Hence the increase in the top diameter of the tower does not significantly reduce the deflection of the tower. Note that the inner diameter is chosen to be 600 mm; the top outer diameter must be greater than 600 mm. Here 800 mm is chosen for the top outer diameter for the proposed section.
- From Figure 4.13(a), it is found that if the bottom outer diameter of the section is increased from 1000 mm to 1500 mm which is 50% increase, the deflection is

reduced by 54% while the weight of the tower increases by 25% (Figure 4.13(b)). Therefore it can be concluded that the effects of the bottom outer diameter of the tower are more pronounced than other parameters. Here 1350 mm is chosen for the proposed section because it produces the deflection that meets the serviceability requirement.

### 5.1.2 Deflection of the Proposed Design Section

The maximum deflection of the proposed wind turbine tower is found to be 370 mm as shown in Figure 4.14 which meets the serviceability requirement of the design of the wind turbine tower specified in section 3.1.1 and also within the range of 1.5% of the tower height.

### 5.1.3 Tsai-Wu Failure Index of the Proposed Design Section

Figure 4.15 shows the profile of the Tsai-Wu failure criterion along the tower and the maximum failure index is 0.36. This value is less than unity as specified in section 2.4.2 which indicates that the tower is safe to resist the designed factored loads. Note that the composite tower can resist a greater load; the serviceability limit for lateral deflection is the controlling factor in the design here.

### 5.1.4 Maximum Stress Index of the Proposed Design Section

Figure 4.16 shows the distribution of the Maximum Stress criterion along the tower and the maximum failure index is 0.43 which is less than unity as specified in section 2.4.1 Therefore, the structure is safe for the design factored loads.

### 5.1.5 Free Vibration Analysis of the Proposed Tower

From the free vibration analysis, it is found that the first natural frequency $f_n$ of the tower is 0.96 Hz (Table 4.10), which is considerably less that the wind turbine rotor frequency $f_p$ of 2.5 Hz and blade passing frequency $f_{bp}$ of 7.5 Hz. Hence, the design tower will not undergo the resonance during the operation as specified in section 3.1.2. Note that the design tower is categorized as the soft-soft tower because the rotor frequency and the blade passing frequency are higher than the tower's fundamental frequency. This indicates that the tower is economical as discussed in section 3.1.2.

### 5.1.6 Eigen Buckling Analysis of the Proposed Design Section

From the Eigen Buckling analysis, it is found that the tower can resist the maximum of 937 KN compressive loads as seen in Figure 4.23. Hence the tower is safe for a much larger turbine.

### 5.1.7 Failure Load Prediction of the Proposed Tower

From Table 4.11, it is found that that the tower can resist 3 times the lateral loads compared to the design service lateral wind turbine rotor and wind loads. This can be interpreted as the safety of factor of 3.

### 5.1.8 Comparison between a Steel and the Proposed GFRP Tower

From Table 4.12, it can be observed that for the same value of maximum deflection, the proposed GFRP tower is 14% lighter and 7% less cost than the tapered steel tower of a uniform thickness of 11.25 mm.

## 5.2 Conclusion

Based on the objectives of the study, the following conclusions are made:

- The material properties of unidirectional composite layers are determined and are presented in Table 2.2;
- Loads for the 10kW wind turbine are determined and are presented in Table 4.1;
- Wind and ice loads are determined for various sections. Samples of calculation are presented in the Appendix A3 and the Appendix A4;
- Based on the analyses of the 8-, 10-, and 12-cells tower, an 8-cell is chosen for the proposed section. The following parameters are arrived for a proposed section:
  - The bottom outer diameter is 1350 mm;
  - The top outer diameter is 800 mm;
  - The inner diameter is constant of 600 mm;
  - The wall thickness is uniform of 11.25 mm.
- The analyses of the proposed tower result in the following:
  - The lateral deflection under the service load is 370 mm;
  - The maximum value of the Tsai-Wu failure index of the tower is 0.36;
  - The maximum value of the Maximum stress failure index of the tower is 0.43;
  - The Eigen Buckling load of the tower is 937 KN;
  - The maximum failure load is 3 times the service load;
  - The fundamental frequency of the tower is 0.96 Hz;
  - The weight of the tower is 3512 kg;
  - The tower is considered a soft-soft tower.

- The tower is 14% lighter and 7% less cost than the steel tower considering the material only; and
- From the study, it is found that the serviceability limit for the lateral deflection is the controlling factor in the design of the GFRP wind turbine towers.
- The necessary fabrication drawings of the proposed design tower are shown in Figure 5.1 to Figure 5.6 .

### 5.3 Recommendation for the Future Study

The research work for the development of eight-cell 24.3m GFRP wind turbine tower at the University of Manitoba is the first of its kind since the developed design will go for fabrication and full scale prototype experiments. However, more research is still required in order to make this product economically attractive and to broaden the understanding of the behavior of multi-cell GFRP towers. Further research is recommended in the following areas:

- Evaluation of performance and strength of joints between GFRP segments
- Evaluation of the fatigue performance of the members and connections.
- Full scale prototype testing to observe the response of the GFRP tower under time varying dynamic loading
- Evaluation of the long term bonding performance of segmented GFRP section under adverse environmental condition.

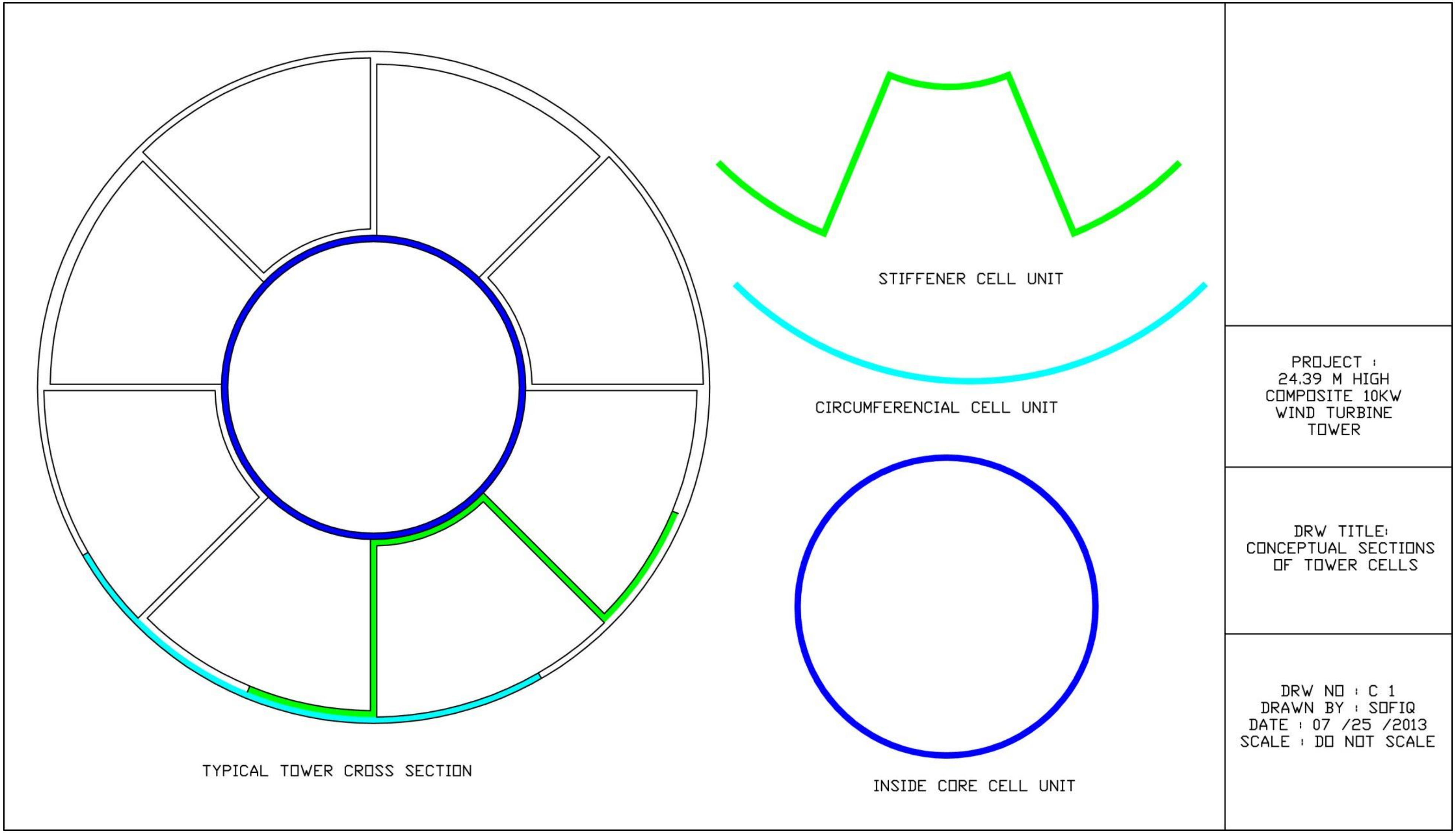



**Figure 5.1:** Conceptual fabrication drawing

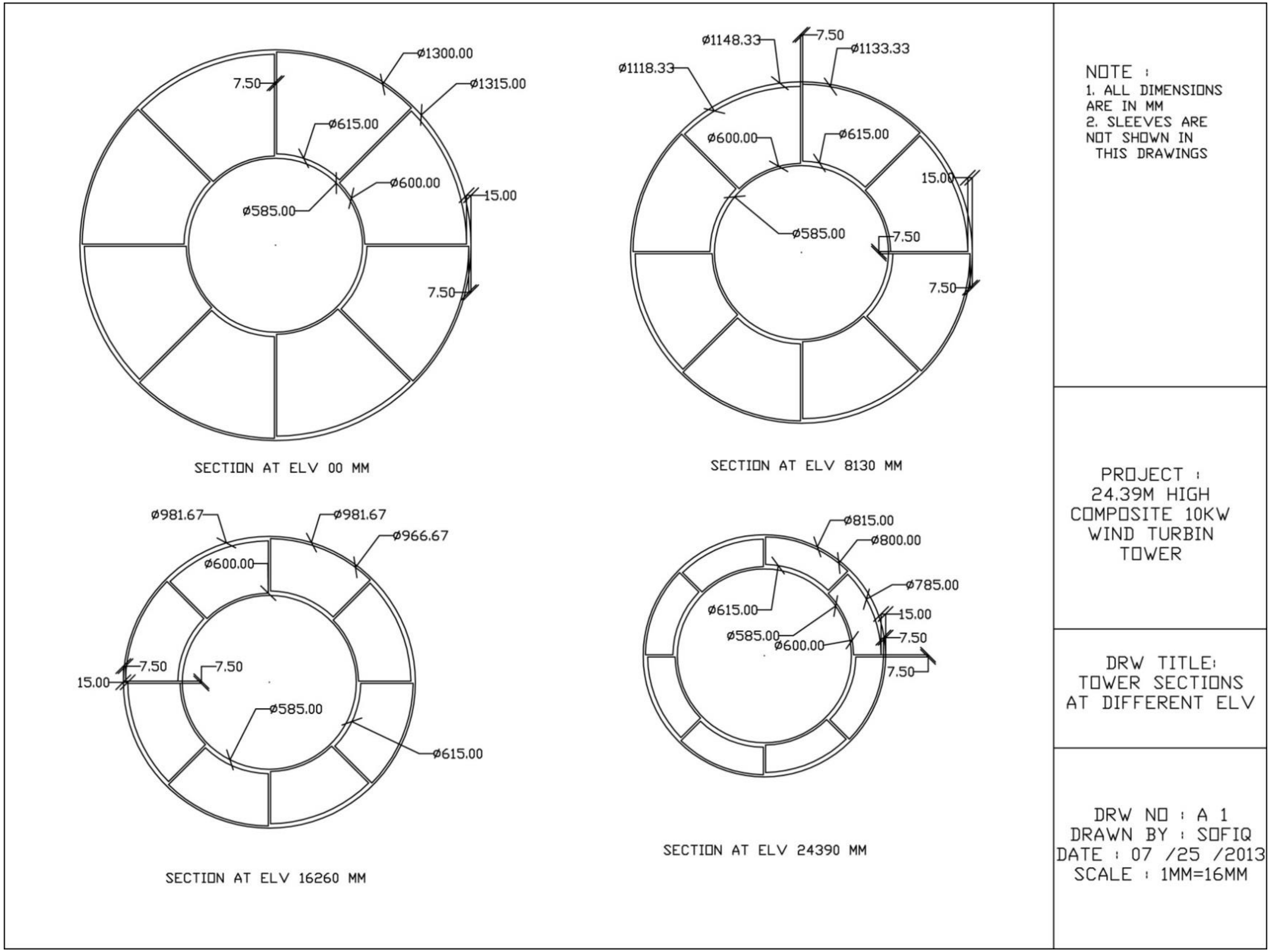



**Figure 5.2:** Sections at different elevations

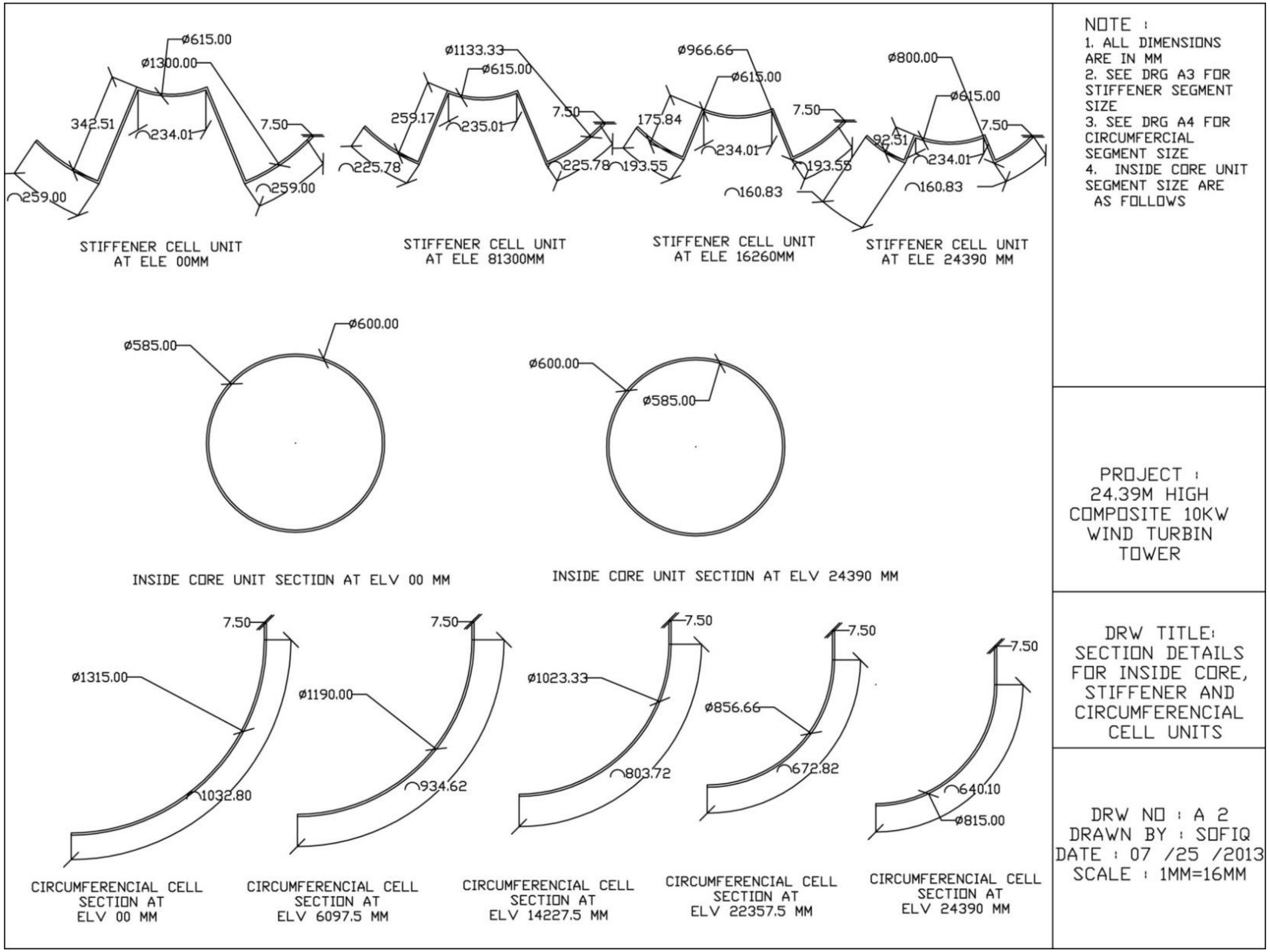



**Figure 5.3:** Cell unit details

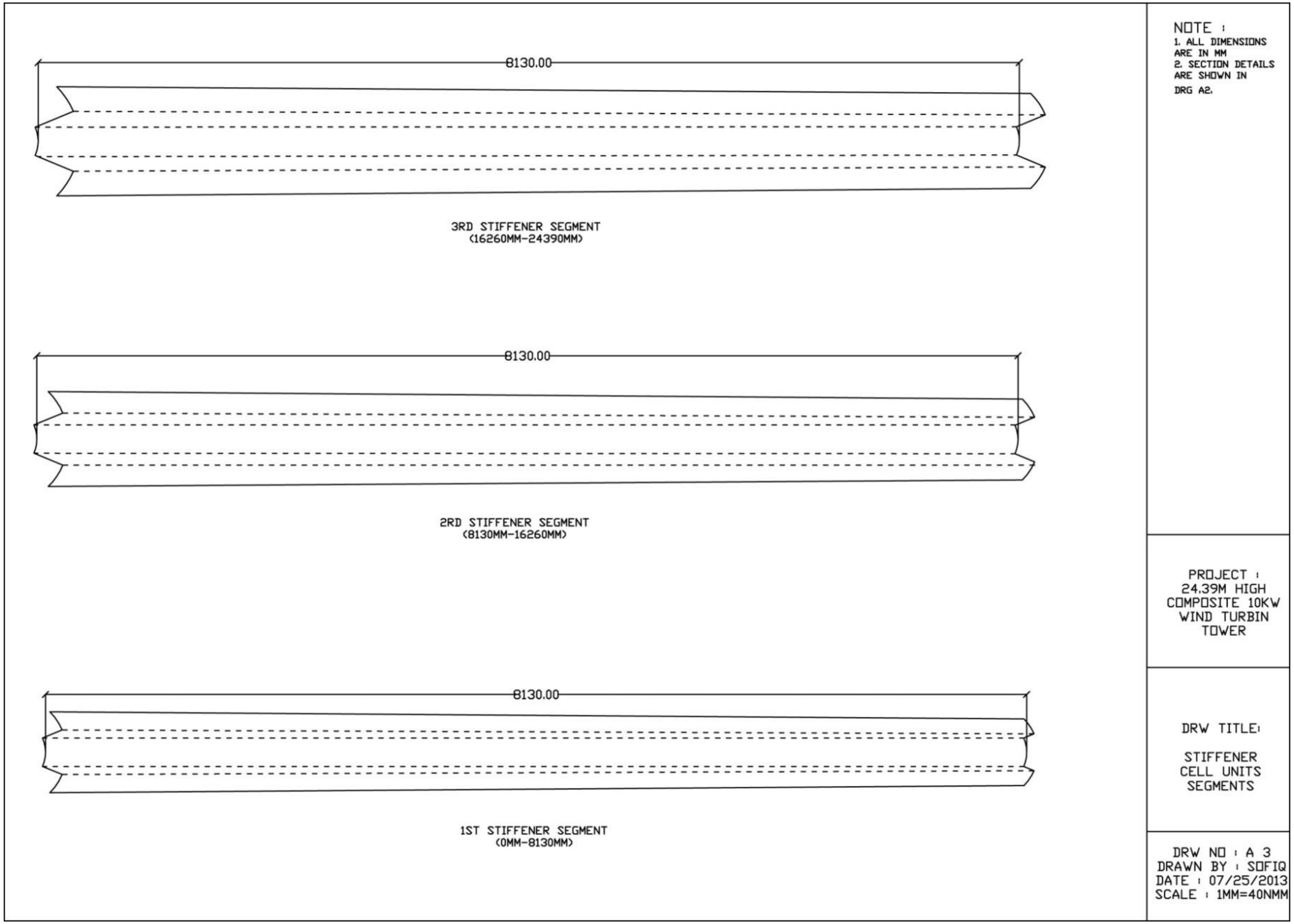



**Figure 5.4:** Stiffener cell unit segments

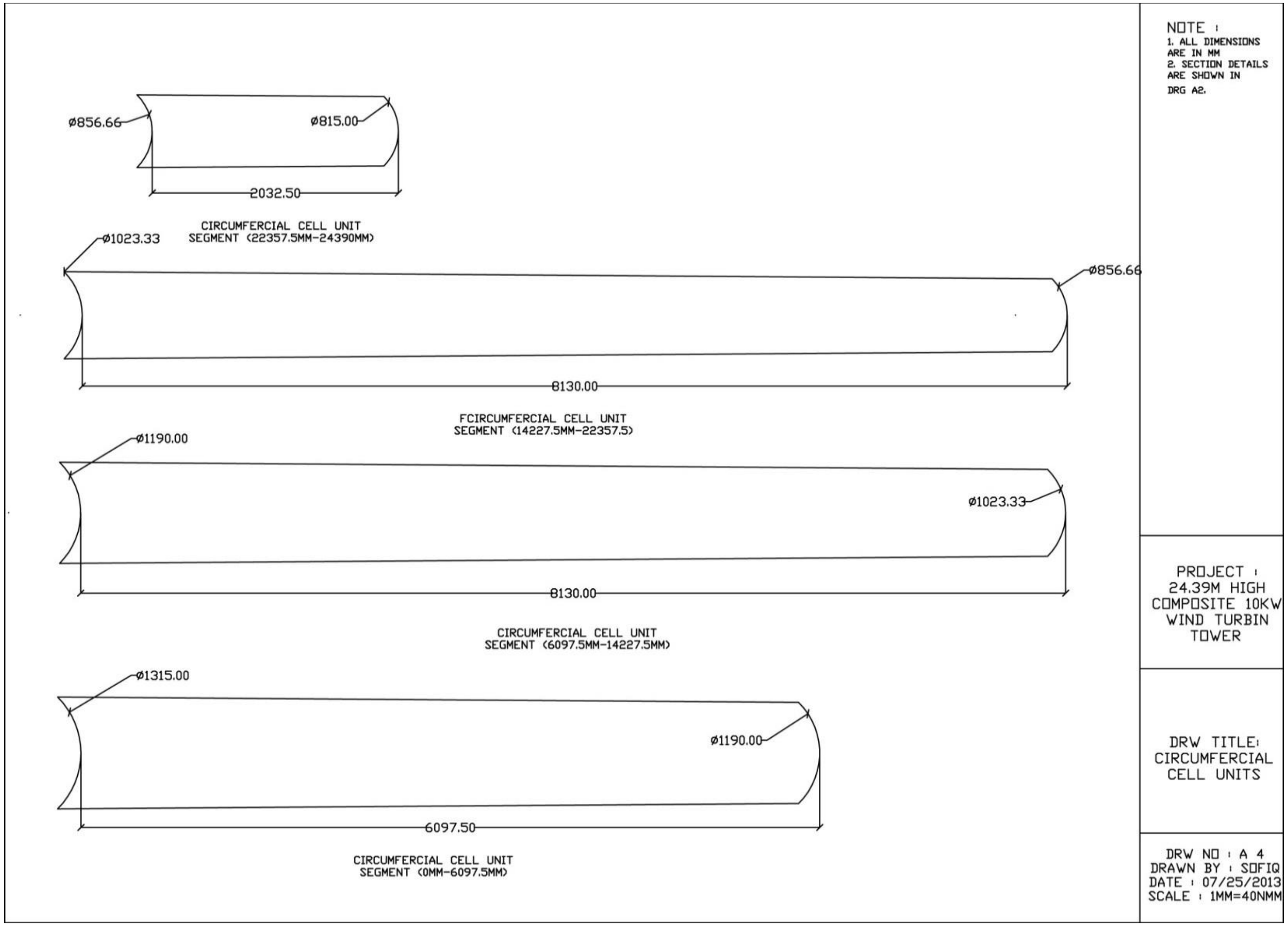



**Figure 5.5:** Circumferential cell unit segments

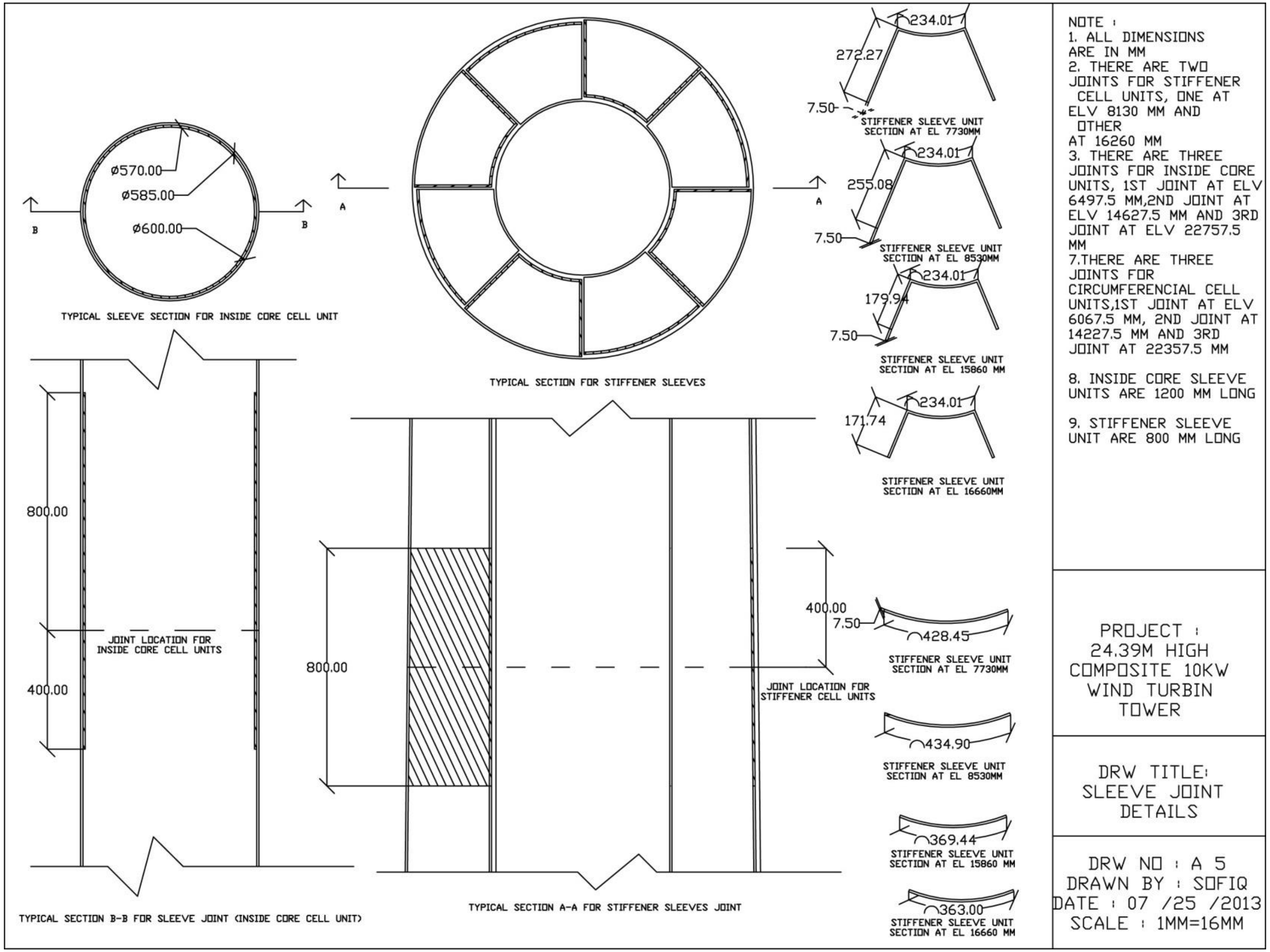



**Figure 5.6:** Sleeve joint details

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# Appendix A1

The detail calculations of wind turbine rotor loads according to Germanischer Lloyd : Rules and Regulations, Part 1 – Wind Energy (1993)

**10kW - Wind Turbine Parameters**

**Reference:** http://www.winphase.com/index.php?CM=goods&CI=1722

| | | |
|---|---|---|
| Nominal Power = | 10.00 | kW |
| No. of rotor blades = | 3.00 | Nos |
| Rotor dia ( D ) = | 9.00 | m |
| Rotor swept area ( A ) = | 63.61 | $m^2$ |
| Rotation speed (n) = | 150.00 | RPM |
| Hub height (h) = | 24.39 | m |
| Cut in wind Speed = | 3.50 | m/s |
| Cut out wind Speed = | 25.00 | m/s |
| Nominal (rated) wind speed (Operational Speed), $v_r$ = | 9.00 | m/s |
| Weight of 3 blades = | 72.00 | kg |
| total weight of the unit = | 650.00 | kg |
| Maximum cover area from any side/Van area (assumed 7.5% of swept area) = | 4.77 | $m^2$ |
| Centre of gravity of the turbine system from tower centre (Calculated)= | 0.62 | m |
| Plan form Area of each Blade( approximate) | 2.12 | $m^2$ |
| Centre of gravity of Rotor weight= | 1.03 | m |

**(a) Dead Loads**

| | | |
|---|---|---|
| Total axial load, $F_Z$ = | 6376.50 | N |
| Eccentricity, $e_m = 0.05R$ = | 0.23 | m |
| Moment due to eccentricity, $M_Y = F_Z * e_m$ = | 1434.71 | N-m |

$e_m$ is the assumed centre of gravity of the system defined by equation 3.1

**(b) Normal Operating Loads**

**1) Force acting on the tower head**

| | | |
|---|---|---|
| Mean pressure, $P_n = C_{fb}*\rho*v_r^2/2$ = | 44.06 | $N/m^2$ |
| Force acting on the top of the tower, $F_X = P_n * A$ = | 2802.91 | N |

**2) Turbulence, influence of oblique wind flow**

| | | |
|---|---|---|
| Reference height (h*) = | 10.00 | m |
| The reference wind speed at the height of 10 m = 39.2 $\sqrt{q}$ = | 34.62 | m/s |
| Wind speed at hub height, $v(h) = v(h/h^*)^{0.16}$ = | 39.93 | m/s |
| gradient, w=(41.37-34.62)/(24.39-10) = | 0.37 | |
| Eccentricity, $e_w = wR^2/2v^2$ = | 0.05 | m |

| | | |
|---|---|---|
| Minimum eccentricity for Fx according DNV/RISO,e=R/6= | 0.75 | m |
| Moment, $M_Y = F_X$*e = | 2102.18 | N-m |

**3) Moment for maximum electrical output**

| | | |
|---|---|---|
| Rotor resisting moment, $M_X = 14*P_{el}/n$ = | 933.33 | N-m |
| Overturning moment due to braking of the turbine = 2* $M_X$= | 1866.67 | N-m |

**(c) Extreme Operating loads**

| | | |
|---|---|---|
| gust factor, $K_b$ = | 1.67 | |
| Gust wind speed, $V_b = k_b * v_r$ = | 15.00 | m/s |
| Gust speed is less than 25 m/s. For designing consider Vb = | 15.00 | m/s |
| Wind pressure, $P_b = C_{fb}*\rho*v_b^2/2$ = | 122.40 | $N/m^2$ |
| Force acting on the top of the tower, $F_X = P_b * A$ = | 7785.86 | N |
| Rotor resisting moment, $M_X = 14*P_{el}/n$ = | 933.33 | N-m |
| Overturning moment due to braking of the turbine = 2* $M_X$ = | 1866.67 | N-m |

**Loads from Oblique wind flow or wind gradient**

| | | |
|---|---|---|
| Moment My due to Lateral force Fx with an eccentricity R/6= | 5839.40 | N-m |
| Lateral wind impact, $F_X=(1/\sqrt{2})*P_n*A$ = | 5505.44 | N |
| Lateral wind impact, $F_Y=(1/\sqrt{2})*P_n*A$ = | 5505.44 | N |
| Moment, Mz = Fy* cg of rotor weight= | 5654.08 | N-m |

**Extreme load cases**

| | | |
|---|---|---|
| 50 year wind speed at the reference height (h*) = 39.2 $\sqrt{q}$ = | 34.62 | m/s |
| 50 year gust at the reference height , $V_e$ = 1.4 * 34.6205 = | 48.47 | m/s |
| Annual wind speed ( v ) = 0.8 times 50 years wind speed = | 27.70 | m/s |
| Annual gust = 0.8 times 50 year gust = | 38.77 | m/s |

**(d ) Load due to annual wind speed (10 min)**

| | | |
|---|---|---|
| reference height, h* = | 10.00 | m |

| | | |
|---|---|---|
| Annual wind speed at hub height, $v(h) = v(h/h^*)^{0.16}$ = | 31.94 | m/s |
| annual wind spped at hub height is more than cut-out speed | | |
| Stagnation pressure, $P_s = v^2/1600$ = | 0.64 | $kN/m^2$ |
| Horizontal force, F = Ps*Av = | 3042.43 | N |
| **Consider wind direction at 15 degree** | | |
| $F_X$ = Force * cos 15 = | 2938.77 | N |
| $F_Y$= force * sin 15 = | 787.44 | N |
| Moment, $M_Z = F_Y$*CG | 491.44 | N-m |

**(e) Load due to annual gust (5 sec)**

| | | |
|---|---|---|
| Annual gust at hub height, $v(h) = v(h/h^*)^{0.11}$ = | 42.77 | m/s |
| Stagnation pressure, $P_s = v^2/1600$ = | 1.14 | $kN/m^2$ |
| Horizontal force, $F_X$= Ps*Av = | 5454.51 | N |
| $F_Y$ = | 5454.51 | N |
| Moment, $M_{ZN} = F_Y$*CG | 3404.16 | N-m |

**(f) Load due to 50 year wind (10 min)**

| | | |
|---|---|---|
| 50 year wind speed at hub height, $v(h) = v(h/h^*)^{0.16}$ = | 39.93 | m/s |
| Stagnation pressure, $P_s = v^2/1600$ = | 1.00 | $kN/m^2$ |
| Horizontal force, F = Ps*Av = | 4753.80 | N |
| **Consider wind direction at 15 degree** | | |
| $F_X$ = Force * cos 15 = | 4591.82 | N |
| $F_Y$= force * sin 15 = | 1230.37 | N |
| Moment, $M_Z = F_Y$*CG | 2966.85 | N-m |

**(g) Load due to 50 year gust (5 sec)**

| | | |
|---|---|---|
| 50 year wind speed at hub height, $v(h) = v(h/h^*)^{0.11}$ = | 53.46 | m/s |
| Stagnation pressure, $P_s = v^2/1600$ = | 1.79 | $kN/m^2$ |
| Horizontal force, $F_X$ = Ps*Av = | 8522.68 | N |

| | | |
|---|---|---|
| $F_Y$ = | 8522.68 | N |
| Moment, $M_Z = F_Y$*CG | 5319.00 | N-m |

**(h) Generator short circuit (Black out)**

| | | |
|---|---|---|
| Rotor resisting moment, $M_X$ = 14*$P_{el}$/n = | 933.33 | N-m |
| Peak torque due to blackout = $M_X$ = 8*res. moment = | 7466.67 | N-m |

**(i) Load due to rotor blade eccentricity**

| | | |
|---|---|---|
| Eccentricity, $e_r$ = 0.005R = | 0.02 | m |
| Angular velocity of the rotor, $\omega$ = | 15.71 | rad/sec |
| Horizontal force, Fx = m*$e_r$*$\omega^2$ = | 399.72 | N |

# Appendix A2

The detail calculations of rotor loads according to IEC-614200-2

Rotor load Calculation according to IEC-61400-2

**Load Case D :**

$\rho = air\ density = 1.225 Kg / m^3$

$Vavg = average\ wind\ density\ at\ hub\ height = 8.5 m/s$

$R = Rotor\ radius = 4.5 m$

$C_T$ is the thrust coefficient, equal to 0.5

$\text{Fx.shaft} = 3.125 C_T \rho v_{avg}^2 \Pi R^2$ = 8793.23 N

**Load Case H :**

$B = number\ of\ Blades = 3$

$C_d = drag\ coeeficient, 1.5$

$\rho = air\ density = 1.2225 Kg / m^3$

$A_{proj,B} = blade\ plan\ form\ area = 2.12 m^2$

$R = Radius\ of\ Rotor = 4.5 m$

$V_{e50} = reference\ wind\ velocity\ at\ hub\ height\ in\ 50 years\ occuence\ period$

$= 34.94 * (24.39 / 10) \wedge 0.11 = 38.54 m/s (Formula\ From\ IEC 61400)$

$Fx - Shaft = BC_d 0.5 \rho V_{e50}^2 A_{proj,B}$ = 8679.16 N

$C_f = force\ coefficient, 1.5$

$\rho = air\ density = 1.225 kg / m^3$

$A_{proj}$ = Nacelle / Turbine component area projected on to a plane perpendicular to the wind direction=4.77m$^2$

$V_{e50} = reference\ wind\ velocity\ at\ hub\ height\ in\ 50 years\ occuence\ period = 38.19 m/s$

$Fx - component = C_f 0.5 \rho V_{e50}^2 A_{proj}$ = 6391.68 N

## Appendix A3

Sample Wind load Calculations for the wind speed of 50 year recurrence period

**Wind load calculation for 50 years recurrance period as per CSA S-37**

| | | | |
|---|---|---|---|
| Height of the Tower = | 24390 | mm | |
| Outside diameter of the bower at bottom = | 1315 | mm | Including thickness |
| Outside Diameter of the tower at Top = | 815 | mm | Including thickness |
| Ice thickness = | 50 | mm | CSA S37 - 01 |
| Total wind ward force, F = Cd*P*A | | | CSA S37 Clause 4.8.2 |
| Pressure ,P = qh*Ce*Cg* Ca | | | CSA S37 Clause 4.3.1 |
| qh= | qCe | q= Referece velocity Pressure | |
| Ce= | (H/10)^0.2 | CL 4.5.1 | |
| Ca= | 1 | CL 4.7.1 | |
| Wind Pressure at reference height, q = | 0.78 | Kpa | From NBCC 2010 |

This Tower is designed for the 50 year return period mean hourly wind pressure

| | | | |
|---|---|---|---|
| Drag Coefficient, Cd= | 0.5 | CL 4.9.2 | N = 32.51757 >7.2 |
| Gust Factor, Cg = | 2.5 | CSA S37 (4.6.1) for the Pole Structure | |
| an important parameter | 39755.7 | | |
| Diameter at tower's base = | 1315 | mm | |
| Diameter at 5m height = | 1212.5 | mm | |
| Diameter at 10m height = | 1110 | mm | |
| Diameter at 15m height = | 1007.5 | mm | |
| Diameter at 20m height = | 904.996 | mm | |
| Diameter at 24.39m height = | 815 | mm | |

WIND FORCES AT 5M INTERVAL ALONG TOWER HEIGHT

| Height Range, m | Projected Area ($m^2$) | Additional Projected Area for Ice ($m^2$) | Exposure factor, (Ce) | Gust Factor (Cg) | Pressure, (P),Kpa | Wind Force (F), N | Factoed Wind load without Ice, N | Wind Force considering additional radial Ice area,N | Factored Wind Force considering additional radial Ice area,N |
|---|---|---|---|---|---|---|---|---|---|
| 0-5 | 6.32 | 6.82 | 1.00 | 2.50 | 1.95 | 6160.78 | 9241.17 | 4986.21 | 7479.31 |
| 5-10 | 5.81 | 6.31 | 1.00 | 2.50 | 1.95 | 5661.09 | 8491.63 | 4611.44 | 6917.16 |
| 10-15 | 5.29 | 5.79 | 1.08 | 2.50 | 2.11 | 5597.39 | 8396.08 | 4594.55 | 6891.82 |
| 15-20 | 4.78 | 5.28 | 1.15 | 2.50 | 2.24 | 5354.89 | 8032.33 | 4436.16 | 6654.24 |
| 20-24.39 | 4.30 | 4.80 | 1.20 | 2.50 | 2.33 | 5010.88 | 7516.33 | 4195.16 | 6292.74 |

Note : When wind load and Ice load are in action together, additional load factor 0.5 is used for wind loading for both in service and ultimate limit state according to CSA-S37-01,Clause 5.3

# Appendix A4

Sample ice load calculations

ICE LOAD CALCULATION

| | | |
|---|---|---|
| Outside Bottom Diameter of the tower, Do = | 1.315 | m |
| Outside Top Diameter of the tower, Di = | 0.915 | m |
| Radial Ice thickness= | 0.05 | m |
| Height of the tower, H= | 24.39 | m |
| Ice Density = | 900 | kg/cum |
| Total surface area of Turbine system including blade(assumed)= | 12 | sqm |
| Ice Mass due to radial ice around the tower = | 4014.948 | KG |
| Ice Weight due to radial ice around the tower = | 39386.64 | N |
| Ice mass due to Turbine system top of the tower= | 540 | KG |
| Ice weight due to Turbine system top of the tower= | 5297.4 | N |
| Factored Ice Weight due to radial ice around the tower = | 59079.95 | N |
| Factored Ice weight due to Turbine system top of the tower= | 7946.1 | N |
| Tower Mass (ANSYS OUTPUT) = | 3.512 | Ton |
| Tower Self Weight = | 34417.6 | N |
| Factored Tower's Self Weight = | 41301.12 | N |

# Appendix A5

ANSYS commands for structure's self-weight determination.

```
/solu

outpr,basic,all

irlf,-1

/output,mass_output,txt

psolve,elform

psolve,elprep

/output

Finish
```

The file will be saved as mass_output.txt file in ANSY installed directory.

# Appendix B1

Analysis of 8 cell sections

**<u>8-cell section trial # 1</u>**: For trial # 1, the following geometric parameters are selected.

Bottom diameter: 1000 mm c/c

Top diameter: 600 mm c/c

Inner diameter: 300 mm c/c

Wall thickness: 7.5 mm

Rotor loads: Referred in Table 4.3: Rotor load combination in service for deflection determination of the tower

Wind loads: The governing wind loads for 50 year recurrence period according CSA-S37-01 corresponding to the trial section are mentioned in Table B1

**Table B1:** Wind loads for 8-cell section trail # 1

| Height Range, m | Projected Area ($m^2$) | Exposure Factor, (Ce) | Gust Factor (Cg) | Pressure,(P), Kpa | Wind Force (F),N |
|---|---|---|---|---|---|
| 0-5 | 4.83 | 1.00 | 2.50 | 1.95 | 4712 |
| 5-10 | 4.42 | 1.00 | 2.50 | 1.95 | 4312 |
| 10-15 | 4.01 | 1.08 | 2.50 | 2.11 | 4243 |
| 15-20 | 3.60 | 1.15 | 2.50 | 2.24 | 4035 |
| 20-24.39 | 3.22 | 1.20 | 2.50 | 2.33 | 3749 |

For 8-cell section trail # 1, it has been found that the deflection is 1190 mm (Figure B1) and weight of the structure is 2001 Kg.

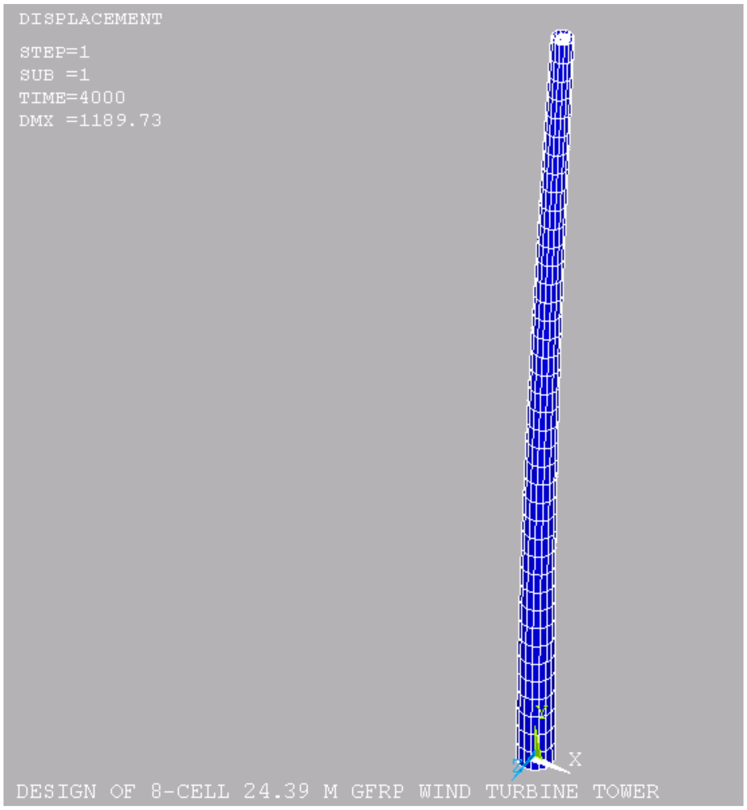


**Figure B1:** Deflection for 8 -cell section trail # 1

**8-cell section trial # 2**: For trial # 2, the following geometric parameters are selected

Bottom diameter: 1500 mm c/c

Top diameter: 600 mm c/c

Inner diameter: 300 mm c/c

Wall thickness: 7. 5mm

Rotor loads: Referred in Table 4.3: Rotor load combination in service for deflection determination of the tower

Wind loads: The governing wind loads for 50 year recurrence period according CSA-S37-01 corresponding to the trial section # 2 are mentioned in Table B2

**Table B2:** Wind loads for 8-cell section trial # 2

| Height Range, m | Projected Area ($m^2$) | Exposure factor, (Ce) | Gust Factor (Cg) | Pressure,(P), Kpa | Wind Force (F), N |
|---|---|---|---|---|---|
| 0-5 | 7.08 | 1.00 | 2.50 | 1.95 | 6899 |
| 5-10 | 6.15 | 1.00 | 2.50 | 1.95 | 6000 |
| 10-15 | 5.23 | 1.08 | 2.50 | 2.11 | 5531 |
| 15-20 | 4.31 | 1.15 | 2.50 | 2.24 | 4826 |
| 20-24.39 | 3.44 | 1.20 | 2.50 | 2.33 | 4012 |

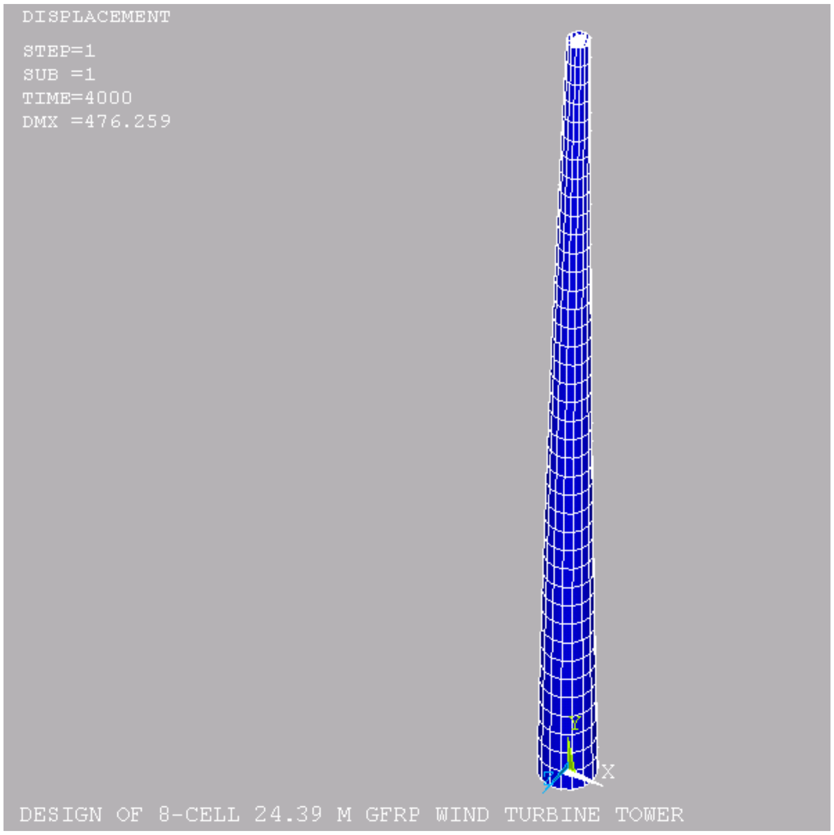


**Figure B2:** Deflection for 8 -cell section trial # 2

For 8-cell section trial # 2, from finite element analysis it has been found that the deflection is 476 mm (Figure B2) and weight of the structure is 2656 Kg.

**8-cell section trial # 3:** For trial # 3, the following geometric parameters have been selected.

Bottom diameter: 1500 mm c/c

Top diameter: 800 mm c/c

Inner diameter: 600 mm c/c

Wall thickness: 7.5 mm

Rotor loads: Referred in Table 4.3: Rotor load combination in service for deflection determination of the tower

Wind loads: The governing wind loads for 50 year recurrence period according CSA-S37-01 corresponding to the trial section # 3 are mentioned in Table B3

**Table B3:** Wind loads for 8-cell section trail # 3

| Height Range, m | Projected Area ($m^2$) | Exposure factor, (Ce) | Gust Factor (Cg) | Pressure,(P), Kpa | Wind Force (F), N |
|---|---|---|---|---|---|
| 0-5 | 7.18 | 1.00 | 2.50 | 1.95 | 6999 |
| 5-10 | 6.46 | 1.00 | 2.50 | 1.95 | 6300 |
| 10-15 | 5.74 | 1.08 | 2.50 | 2.11 | 6073 |
| 15-20 | 5.03 | 1.15 | 2.50 | 2.24 | 5629 |
| 20-24.39 | 4.35 | 1.20 | 2.50 | 2.33 | 5072 |

For 8-cell section trail # 3, from finite element analysis it is found that the deflection is 420 mm (Figure B3) and weight of the structure is 2656 Kg.

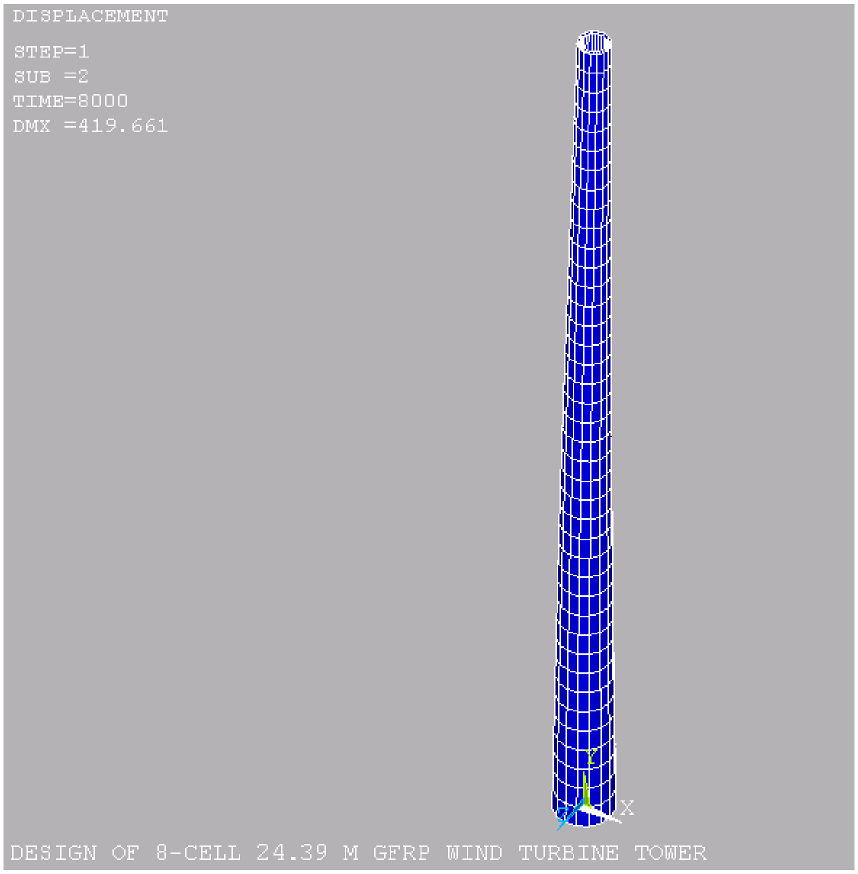


**Figure B3:** Deflection for 8 -cell section trial no 3

**<u>8-cell section trial # 4</u>:** For trial # 4, the following geometric parameters are selected.

Bottom diameter: 1500 mm c/c

Top diameter: 800 mm c/c

Inner diameter: 600 mm c/c

Wall thickness:  11.25 mm

Rotor loads: Referred in Table 4.3: Rotor load combination in service for deflection determination of the tower

Wind loads: The governing wind loads for 50 year recurrence period according CSA-S37-01 corresponding to the trial section # 4 are mentioned in Table B4

**Table B4:** Wind loads for 8-cell section trial # 4

| Height Range,m | Projected Area ($m^2$) | Exposure Factor, (Ce) | Gust Factor (Cg) | Pressure,(P), Kpa | Wind Force (F) N |
|---|---|---|---|---|---|
| 0-5 | 7.18 | 1.00 | 2.50 | 1.95 | 6999 |
| 5-10 | 6.46 | 1.00 | 2.50 | 1.95 | 6300 |
| 10-15 | 5.74 | 1.08 | 2.50 | 2.11 | 6073 |
| 15-20 | 5.03 | 1.15 | 2.50 | 2.24 | 5629 |
| 20-24.39 | 4.35 | 1.20 | 2.50 | 2.33 | 5072 |

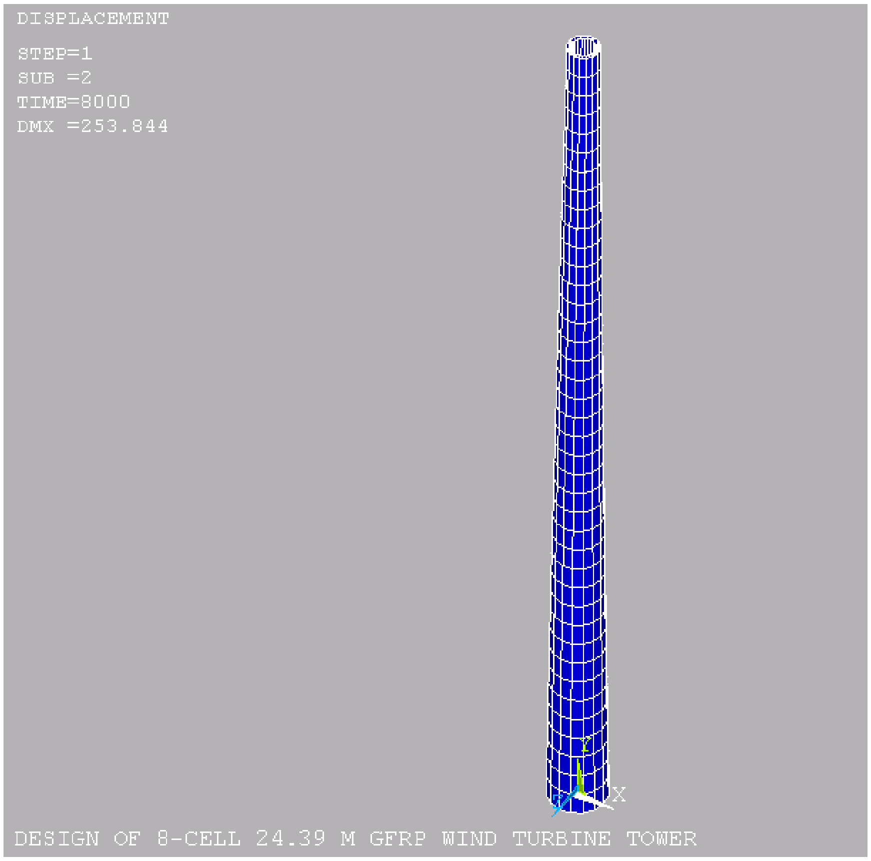


**Figure B4:** Deflection for 8-cell section trial no 4

For 8-cell section trial # 4, from finite element analysis it is found that the deflection is 254 (Figure B4) and weight of the structure is 2824 Kg.

**8-cell section trial # 5:** For trial # 5, the following geometric parameters are selected.

Bottom diameter: 1300 mm c/c

Top diameter: 800 mm c/c

Inner diameter: 600 mm c/c

Wall thickness: 11.25 mm

Rotor loads: Referred in Table 4.3: Rotor load combination in service for deflection determination of the tower

Wind loads: The governing wind loads for 50 year recurrence period according CSA-S37-01 corresponding to the trial section no 5 have been mentioned in Table B5.

**Table B5:** Wind loads for 8-cell section trial # 5

| Height Range, m | Projected Area ($m^2$) | Exposure factor, (Ce) | Gust Factor (Cg) | Pressure,(P), Kpa | Wind Force (F), N |
|---|---|---|---|---|---|
| 0-5 | 6.30 | 1.00 | 2.50 | 1.95 | 6143 |
| 5-10 | 5.79 | 1.00 | 2.50 | 1.95 | 5643 |
| 10-15 | 5.27 | 1.08 | 2.50 | 2.11 | 5578 |
| 15-20 | 4.76 | 1.15 | 2.50 | 2.24 | 5334 |
| 20-24.39 | 4.28 | 1.20 | 2.50 | 2.33 | 4989 |

For 8-cell section trial # 5, from finite element analysis it is found that the deflection is 353 mm (Figure B5) and weight of the structure is 3842 Kg.

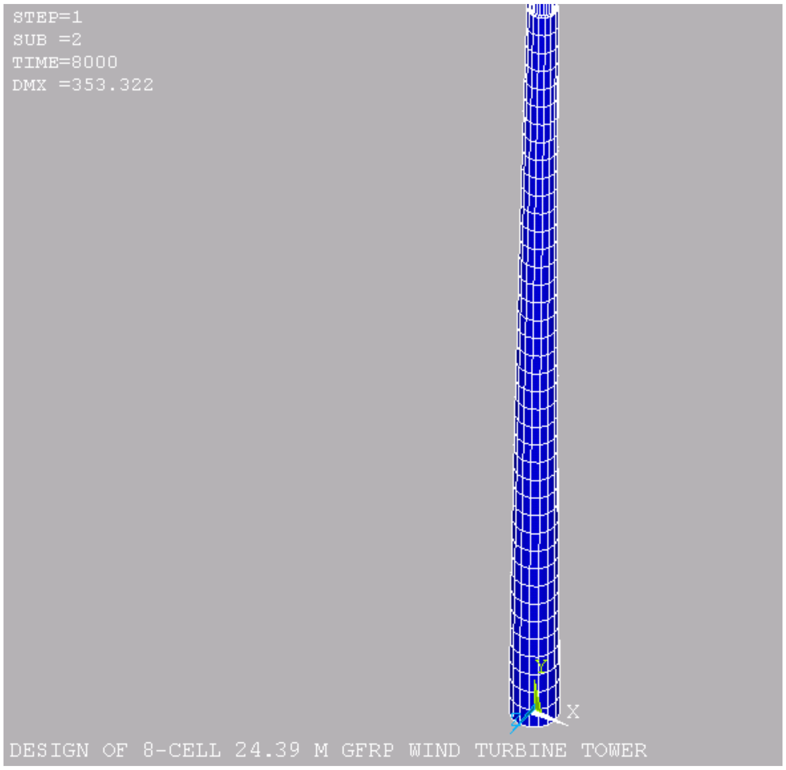


**Figure B5:** Deflection for 8-cell section trial # 5

Sample ANSYS codes related to 8-cell section (trial no 5) are included in the Appendix B2.

**8-cell section trial # 6:** For trial # 6, the following geometric parameters are selected.

Bottom diameter: 1300 mm c/c

Top diameter: 800 mm c/c

Inner diameter: 600 mm c/c

Wall thickness: 10 mm

Rotor loads: Referred in Table 4.3: Rotor load combination in service for deflection determination of the tower

Wind loads: The governing wind loads for 50 year recurrence period according CSA-S37-01 corresponding to the trial section # 6 are mentioned in Table B6

**Table B6:** Wind loads for 8-cell section trial # 6

| Height Range m | Projected Area ($m^2$) | Exposure factor, (Ce) | Gust Factor (Cg) | Pressure,(P), Kpa | Wind Force (F), N |
|---|---|---|---|---|---|
| 0-5 | 6.29 | 1.00 | 2.50 | 1.95 | 6136 |
| 5-10 | 5.78 | 1.00 | 2.50 | 1.95 | 5637 |
| 10-15 | 5.27 | 1.08 | 2.50 | 2.11 | 5571 |
| 15-20 | 4.76 | 1.15 | 2.50 | 2.24 | 5327 |
| 20-24.39 | 4.27 | 1.20 | 2.50 | 2.33 | 4982 |

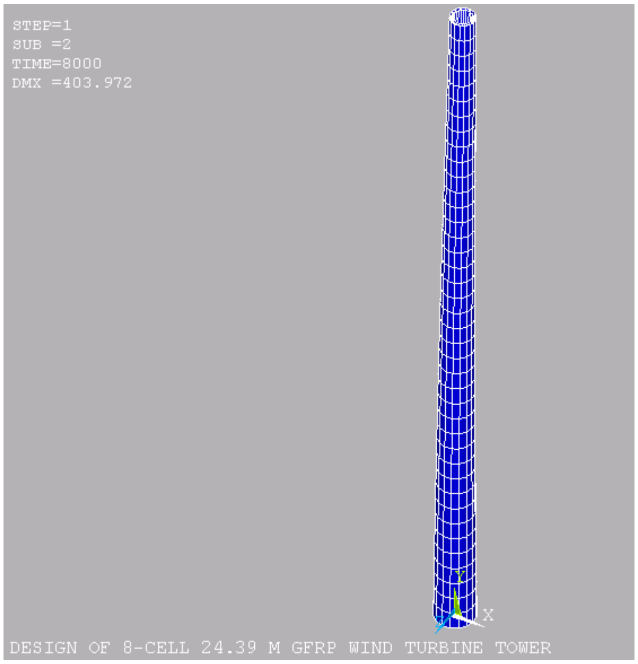


**Figure B6:** Deflection for 8-cell section trial # 6

For 8-cell section trial # 6, from finite element analysis it has been found that the deflection is 404 mm (Figure B6) and weight of the structure is 3415 Kg.

**8-cell section trial # 7:** For trial # 7, the following geometric parameters have been selected.

Bottom diameter: 1300 mm c/c

Top diameter: 800 mm c/c

Inner diameter: 600 mm c/c

Wall thickness: 8.75 mm

Rotor loads: Referred in Table 4.3: Rotor load combination in service for deflection determination of the tower

Wind loads: The governing wind loads for 50 year recurrence period according CSA-S37-01 corresponding to the trial section # 7 are mentioned in Table B7

**Table B7:** Wind loads for 8-cell section trial # 7

| Height Range,m | Projected Area ($m^2$) | Exposure factor, (Ce) | Gust Factor (Cg) | Pressure,(P) Kpa | Wind Force (F), N |
|---|---|---|---|---|---|
| 0-5 | 6.29 | 1.00 | 2.50 | 1.95 | 6130 |
| 5-10 | 5.77 | 1.00 | 2.50 | 1.95 | 5631 |
| 10-15 | 5.26 | 1.08 | 2.50 | 2.11 | 5564 |
| 15-20 | 4.75 | 1.15 | 2.50 | 2.24 | 5320 |
| 20-24.39 | 4.27 | 1.20 | 2.50 | 2.33 | 4974 |

For 8-cell section trial # 7, from finite element analysis it is found that the deflection is 472 mm (Figure B7) and weight of the structure is 2988 Kg.

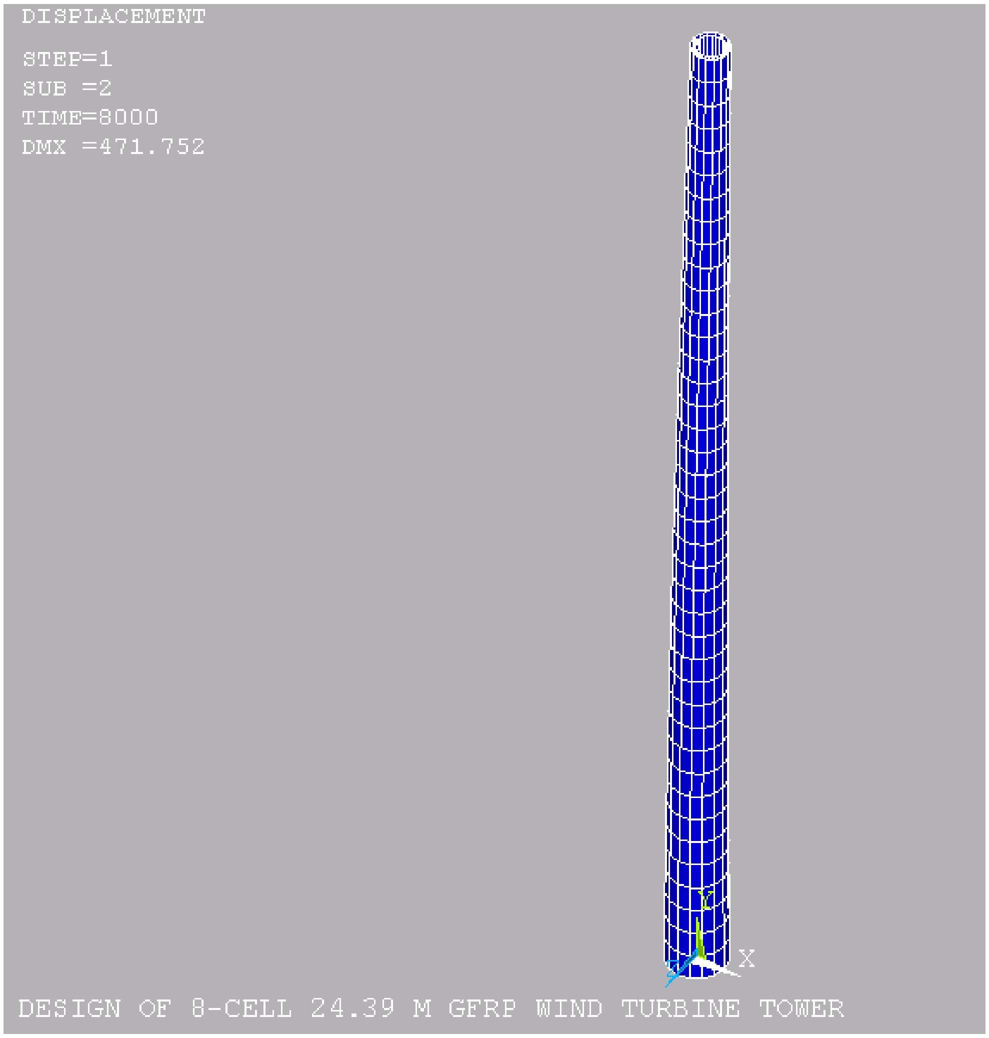


**Figure B7:** Deflection for 8-cell section trial # 7

**8-cell section trial # 8:** For trial # 8, the following geometric parameters are selected.

Bottom diameter: 1300 mm c/c

Top diameter: 800 mm c/c

Inner diameter: 600 mm c/c

Wall thickness:  7.5 mm

Rotor loads: Referred in Table 4.3: Rotor load combination in service for deflection determination of the tower

Wind loads: The governing wind loads for 50 year recurrence period according CSA-S37-01 corresponding to the trial section # 8 are mentioned in Table B8

**Table B8:** Wind loads for 8-cell section trial # 8

| Height Range,m | Projected Area ($m^2$) | Exposure factor, (Ce) | Gust Factor (Cg) | Pressure,(P),Kpa | Wind Force (F), N |
|---|---|---|---|---|---|
| 0-5 | 6.28 | 1.00 | 2.50 | 1.95 | 6124 |
| 5-10 | 5.77 | 1.00 | 2.50 | 1.95 | 5625 |
| 10-15 | 5.26 | 1.08 | 2.50 | 2.11 | 5558 |
| 15-20 | 4.74 | 1.15 | 2.50 | 2.24 | 5313 |
| 20-24.39 | 4.26 | 1.20 | 2.50 | 2.33 | 4967 |

For 8-cell section trial # 8, from finite element analysis it is found that the deflection is 567 mm (Figure B8) and weight of the structure is 2561 Kg.

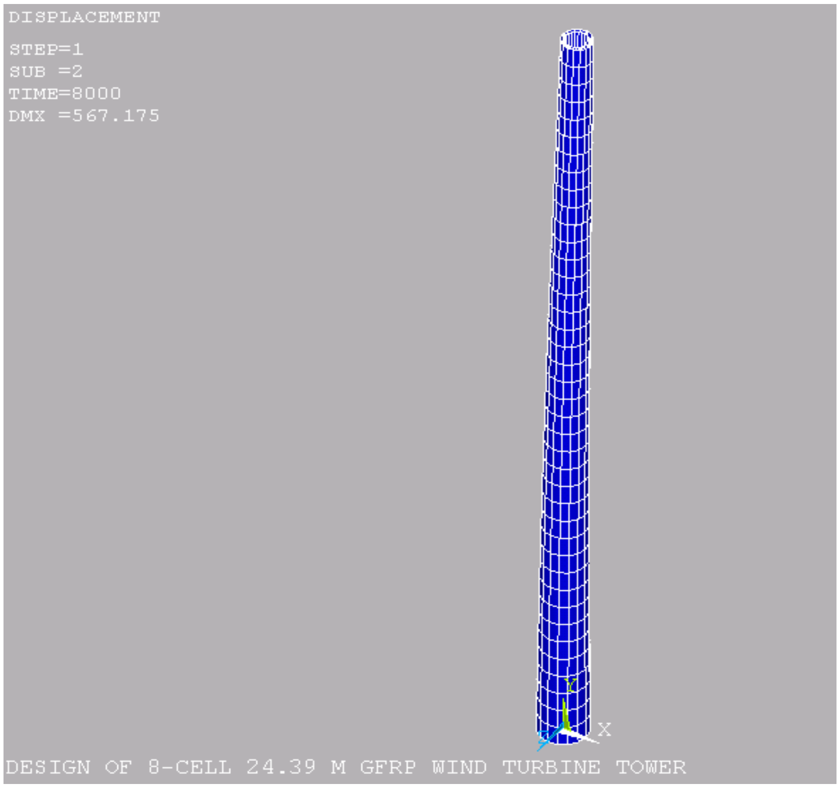


**Figure B8:** Deflection for 8-cell section trial # 8

# Appendix B2

ANSYS codes for 8-cell trial # 5

```
FINISH
/CLEAR
/TITLE, DESIGN OF 8-CELL 24.39 M GFRP WIND TURBINE TOWER
/PREP7
/PBC,F,,1
/PBC,U,,1
/NERR,5,50000000
/PNUM,KP,1
/PNUM,LINE,1
/PNUM,AREA,1
/VIEW,1,3500,6000,5000

!ROTOR LOADS
FYY=-6376.50!Fz N ROTOR DEAD LOAD
FZZ=-8522.68  !Fx N
MXX=1434.71e3 !My N.MM
MYY=5319e3!Mz N.MM
MZZ=0!Mx N.MM

!WIND LOAD
A1=-6142.50
A2=-5642.81
A3=-5577.56
A4=-5333.89
A5=-4989.0

RB=650
RT=400
IR=300
H=24390

!GEOMETRY
K,1,0,0,0
K,2,0,H,0
K,3,IR,0,0
K,4,IR,H,0
K,5,RB,0,0
K,6,RT,H,0

L,3,4
L,5,6
AROTAT,2,,,,,,1,2,360,8
AROTAT,1,,,,,,1,2,360,8
```

```
A,3,4,6,5
A,21,22,8,7
A,23,24,10,9
A,25,26,12,11
A,27,28,14,13
A,29,30,16,15
A,31,32,18,17
A,33,34,20,19

!ELEMENT TYPE
ET,1,SHELL99,,0,0,0,1,3

!REAL CONSTANT
t=1.25

R,1,9,0
RMORE,
RMORE,1,0,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,0,t

R,2,9,0
RMORE,
RMORE,1,0,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,0,t
RMORE,1,90,t,1,90,t
RMORE,1,0,t

!MATERIAL PROPERTIES
MP,EX,1,34125 !N/MM^2 (MPA)
MP,EY,1,6852 !N/MM^2 (MPA)
MP,EZ,1,6852
MP,GXY,1,3330 !N/MM^2 (MPA)
MP,GYZ,1,3330
MP,GXZ,1,3330
MP,PRXY,1,0.2865
MP,PRYZ,1,0.2865
MP,PRXZ,1,0.2865
MP,DENS,1,2.005E-9 !ton/MM^3

!MATERIAL PROPERTIES
```

```
MP,EX,2,34125 !N/MM^2 (MPA)
MP,EY,2,6852 !N/MM^2 (MPA)
MP,EZ,2,6852
MP,GXY,2,3330 !N/MM^2 (MPA)
MP,GYZ,2,3330
MP,GXZ,2,3330
MP,PRXY,2,0.2865
MP,PRYZ,2,0.2865
MP,PRXZ,2,0.2865
MP,DENS,2,2.005E-9 !ton/MM^3

!MASHING CONTROL
LSEL,S,LOC,Y,H/2
LESIZE,ALL,,,40,1
LSEL,ALL

ESIZE,0,2
ASEL,S,AREA,,1,8,1 !INNER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,9,16,1 !OUTER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,17,24,1 !STIFFENER
AATT,1,2,1
AMESH,ALL
ASEL,ALL
SAVE

!ANALYSIS
/SOLU
/TITLE, DESIGN OF 8-CELL 24.39 M GFRP WIND TURBINE TOWER
ANTYPE,STATIC
NLGEOM,ON
AUTOTS,ON
SSTIF,ON
NSUBST,2,500,2,ON
NROPT,AUTO
```

```
NEQIT,20
CNVTOL,F,,0.001,,1
CNVTOL,M,,0.001,,1
CNVTOL,U,,0.04,,0
TIME,8000
!BOUNDARY CONDITIONS
NSEL,S,LOC,Y,0
D,ALL,UZ,0,0,,,UX,UY,ROTX,ROTY,ROTZ
NSEL,ALL
!=====================================================
!Applying Gravity
!=====================================================
ACEL,,9800
!=====================================================
!Applying wind load parallel to Z Direction between 0-5m
!=====================================================
ASEL,S,AREA,,5
ASEL,A,AREA,,6
ASEL,A,AREA,,7
ASEL,A,AREA,,8
NSLA,S,0
NSEL,R,LOC,Y,0,5000
*GET,NCOUNT,NODE,0,COUNT
F,ALL,FZ,A1/NCOUNT
!=====================================================
!Applying wind load parallel to Z Direction between 5-10m
!=====================================================
ASEL,S,AREA,,5
ASEL,A,AREA,,6
ASEL,A,AREA,,7
ASEL,A,AREA,,8
NSLA,S,0
NSEL,R,LOC,Y,5001,10000
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A2/Ncnt
!=====================================================
!Applying wind load parallel to Z Direction between 10-15m
!=====================================================
ASEL,S,AREA,,5
ASEL,A,AREA,,6
ASEL,A,AREA,,7
ASEL,A,AREA,,8
NSLA,S,0
NSEL,R,LOC,Y,10001,15000
```

```
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A3/Ncnt
!===================================================
!Applying wind load parallel to Z Direction between 15-20m
!===================================================
ASEL,S,AREA,,5
ASEL,A,AREA,,6
ASEL,A,AREA,,7
ASEL,A,AREA,,8
NSLA,S,0
NSEL,R,LOC,Y,15001,20000
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A4/Ncnt
!===================================================
!Applying wind load parallel to Z Direction between 20-H m
!===================================================
ASEL,S,AREA,,5
ASEL,A,AREA,,6
ASEL,A,AREA,,7
ASEL,A,AREA,,8
NSLA,S,0
NSEL,R,LOC,Y,20001,H
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A5/Ncnt

!Applying Rotor Load at the top of Tower
!===================================================
NSEL,S,LOC,Y,H
*GET,Ncnt,NODE,0,COUNT
FYAV=FYY/Ncnt
F,ALL,FY,FYAV
NSEL,ALL
!
!MX IN TERM OF COUPLE MOMENT
FMX=MXX/(RT*2)

!MY IN TERM OF COUPLE MOMENT
FMY=MYY/(RT*4)

!MZ IN TERM OF COUPLE MOMENT
FMZ=MZZ/(RT*2)

KSEL,S,,,10
FK,ALL,FX,FMY
```

```
FK,ALL,FY,-FMX
FK,ALL,FZ,FZZ/4
KSEL,ALL

KSEL,S,,,18
FK,ALL,FX,-FMY
FK,ALL,FY,FMX
FK,ALL,FZ,FZZ/4
KSEL,ALL
KSEL,S,,,6
FK,ALL,FZ,FMY
FK,ALL,FY,-FMZ
KSEL,ALL
KSEL,S,,,14
FK,ALL,FZ,-FMY
FK,ALL,FY,FMZ
KSEL,ALL
KSEL,S,,,32
FK,ALL,FZ,FZZ/4
KSEL,ALL
KSEL,S,,,24
FK,ALL,FZ,FZZ/4
KSEL,ALL
LSWRITE,1
LSSOLVE,1
SAVE
FINISH
```

# Appendix B3

Analysis of 10-cell sections

**<u>10-cell section trial # 1</u>:** For trial # 1, the following geometric parameters have been selected.

Bottom diameter: 1300 mm c/c

Top diameter: 800 mm c/c

Inner diameter: 600 mm c/c

Wall thickness: 7.5 mm

Rotor loads: Referred in Table 4.3: Rotor load combination in service for deflection determination of the tower

Wind loads: The governing wind loads for 50 year recurrence period according CSA-S37-01 corresponding to the trial section # 1 are mentioned in Table B9

**Table B9:** Wind loads for 10-cell section trial # 1

| Height Range, m | Projected Area ($m^2$) | Exposure factor, (Ce) | Gust Factor (Cg) | Pressure,(P) ,Kpa | Wind Force (F), N |
|---|---|---|---|---|---|
| 0-5 | 6.28 | 1.00 | 2.50 | 1.95 | 6124 |
| 5-10 | 5.77 | 1.00 | 2.50 | 1.95 | 5625 |
| 10-15 | 5.26 | 1.08 | 2.50 | 2.11 | 5558 |
| 15-20 | 4.74 | 1.15 | 2.50 | 2.24 | 5313 |
| 20-24.39 | 4.26 | 1.20 | 2.50 | 2.33 | 4967 |

For 10-cell section trial # 1, from finite element analysis it is found that the deflection is 488 mm (Figure B9) and weight of the structure is 2726 Kg.

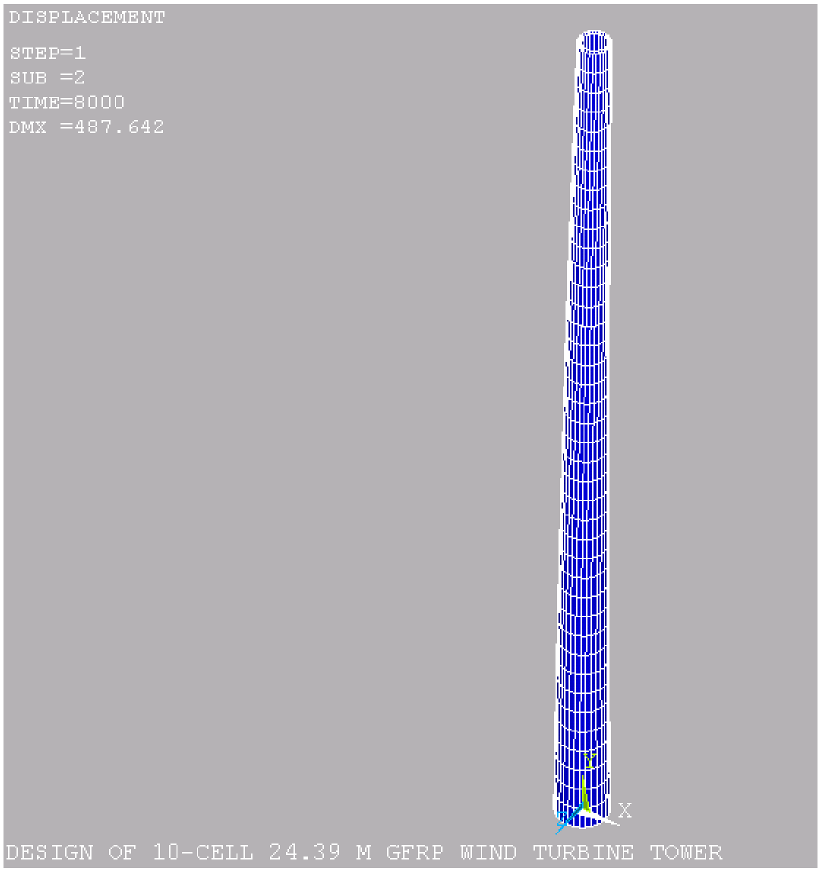


**Figure B9:** Deflection for 10-cell section trial # 1

**<u>10-cell section trial # 2</u>:** For trial # 2, the following geometric parameters have been selected.

Bottom diameter: 1300 mm c/c

Top diameter: 800 mm c/c

Inner diameter: 600 mm c/c

Wall thickness: 11.25 mm

Rotor loads: Referred in Table 4.3: Rotor load combination in service for deflection determination of the tower

Wind loads: The governing wind loads for 50 year recurrence period according CSA-S37-01 corresponding to the trial # 2 are mentioned in Table B10

**Table B10:** Wind loads for 10-cell section trial # 2

| Height Range, m | Projected Area ($m^2$) | Exposure factor, (Ce) | Gust Factor (Cg) | Pressure,(P) ,Kpa | Wind Force (F), N |
|---|---|---|---|---|---|
| 0-5 | 6.30 | 1.00 | 2.50 | 1.95 | 6143 |
| 5-10 | 5.79 | 1.00 | 2.50 | 1.95 | 5643 |
| 10-15 | 5.27 | 1.08 | 2.50 | 2.11 | 5576 |
| 15-20 | 4.76 | 1.15 | 2.50 | 2.24 | 5334 |
| 20-24.39 | 4.28 | 1.20 | 2.50 | 2.33 | 4989 |

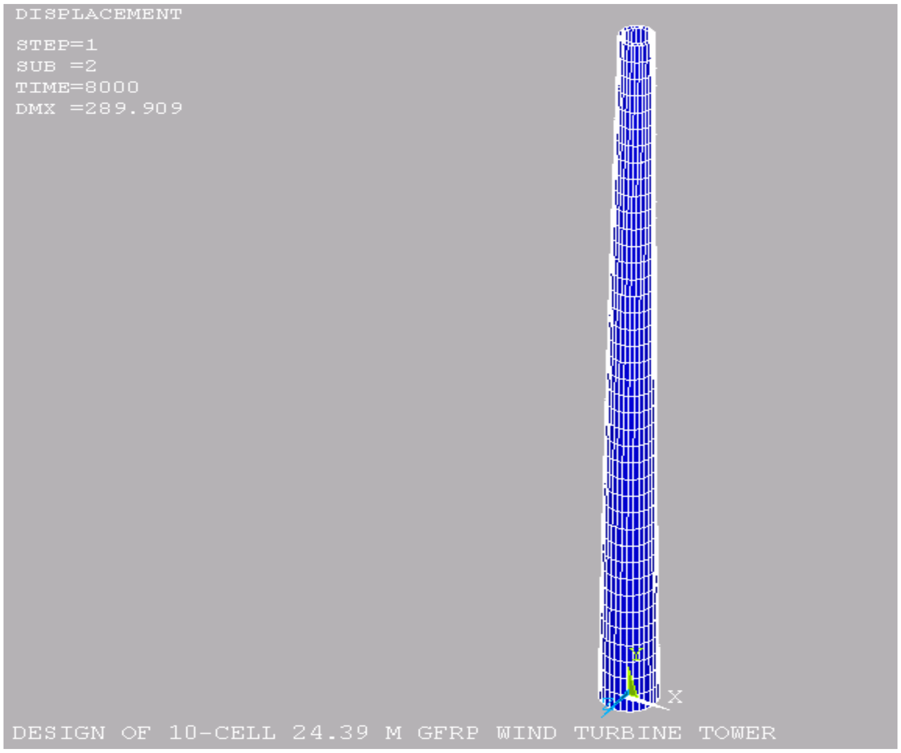


**Figure B10:** Deflection for 10-cell section trial # 2

For 10-cell section trial # 2, from finite element analysis it is found that the deflection is 290 mm (Figure B10) and weight of the structure is 4089 Kg.

**10-cell section trial # 3:** For trial # 3, the following geometric parameters have been selected.

Bottom diameter: 1300 mm c/c

Top diameter: 800 mm c/c

Inner diameter: 600 mm c/c

Wall thickness: 10 mm

Rotor loads: referred in Table 4.3: Rotor load combination in service for deflection determination of the tower

Wind loads: The governing wind loads for 50 year recurrence period according CSA-S37-01 corresponding to the trial # 3 are mentioned in Table B11

**Table B11:** Wind loads for 10-cell section trial # 3

| Height Range, m | Projected Area ($m^2$) | Exposure factor, (Ce) | Gust Factor (Cg) | Pressure,(P) ,Kpa | Wind Force(F), N |
|---|---|---|---|---|---|
| 0-5 | 6.29 | 1.00 | 2.50 | 1.95 | 6136 |
| 5-10 | 5.78 | 1.00 | 2.50 | 1.95 | 5637 |
| 10-15 | 5.27 | 1.08 | 2.50 | 2.11 | 5571 |
| 15-20 | 4.76 | 1.15 | 2.50 | 2.24 | 5327 |
| 20-24.39 | 4.27 | 1.20 | 2.50 | 2.33 | 4982 |

For 10-cell section trial # 3, from finite element analysis it has been found that the deflection is 335 mm (Figure B11) and weight of the structure is 3635 Kg.

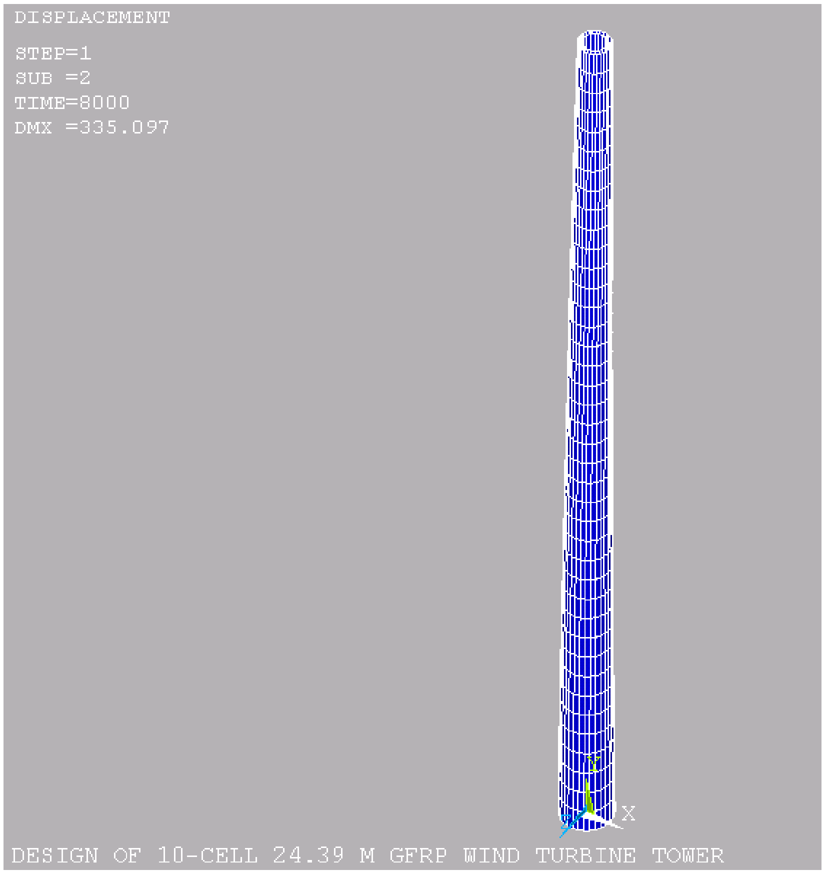


**Figure B11:** Deflection for 10 -cell section trial # 3

**<u>10-cell section trail # 4:</u>** For trial # 4, the following geometric parameters have been selected.

Bottom diameter: 1300 mm c/c

Top diameter: 800 mm c/c

Inner diameter: 600 mm c/c

Wall thickness: 8.75 mm

Rotor loads: referred in Table 4.3: Rotor load combination in service for deflection determination of the tower

Wind loads: The governing wind loads for 50 year recurrence period according CSA-S37-01 corresponding to the trial # 4 are mentioned in Table B12

**Table B12:** Wind loads for 10-cell section trial # 4

| Height Range, m | Projected Area ($m^2$) | Exposure factor, (Ce) | Gust Factor (Cg) | Pressure,(P) Kpa | Wind Force(F), N |
|---|---|---|---|---|---|
| 0-5 | 6.29 | 1.00 | 2.50 | 1.95 | 6130 |
| 5-10 | 5.77 | 1.00 | 2.50 | 1.95 | 5631 |
| 10-15 | 5.26 | 1.08 | 2.50 | 2.11 | 5564 |
| 15-20 | 4.75 | 1.15 | 2.50 | 2.24 | 5320 |
| 20-24.39 | 4.27 | 1.20 | 2.50 | 2.33 | 4974 |

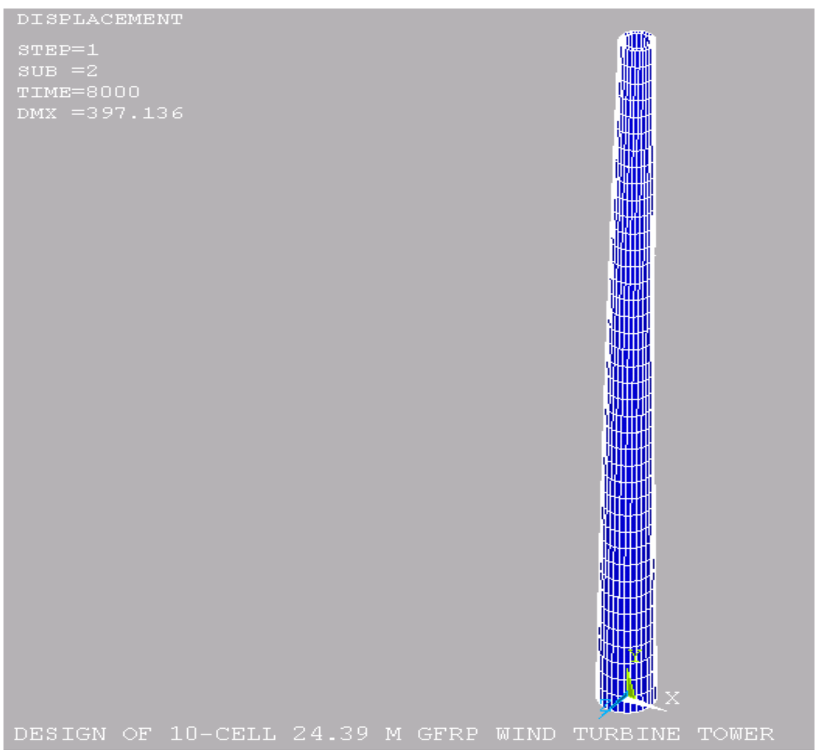


**Figure B12:** Deflection for 10 -cell section trial # 4

For 10-cell section trial # 4, from finite element analysis it is found that the deflection is 397 mm (Figure B12) and weight of the structure is 3635 Kg. A sample ANSYS codes related to 10-cell (trial # 4) are included in the Appendix B4.

# Appendix B4

A sample ANSYS codes for 10-cell (trial # 4).

```
FINISH
/CLEAR
/TITLE, DESIGN OF 10-CELL 24.39 M GFRP WIND TURBINE TOWER
/PREP7
/PBC,F,,1
/PBC,U,,1
/NERR,5,50000000
/PNUM,KP,1
/PNUM,LINE,1
/PNUM,AREA,1
/VIEW,1,3500,6000,5000

!ROTOR LOADS
FYY=-6376.50!Fz N ROTOR DEAD LOAD
FZZ=-8522.68  !Fx N
MXX=1434.71e3 !My N.MM
MYY=5319e3!Mz N.MM
MZZ=0!Mx N.MM

!WIND LOAD
A1=     -6130.31
A2=     -5630.62
A3=     -5564.34
A4=     -5319.89
A5=     -4974.47

RB=650
RT=400
IR=300
H=24390
!
!GEOMETRY
K,1,0,0,0
K,2,0,H,0
K,3,IR,0,0
K,4,IR,H,0
K,5,RB,0,0
K,6,RT,H,0

L,3,4
L,5,6
AROTAT,2,,,,,,1,2,360,10
AROTAT,1,,,,,,1,2,360,10
```

```
A,3,5,6,4
A,25,7,8,26
A,27,9,10,28
A,29,11,12,30
A,31,13,14,32
A,33,15,16,34
A,35,17,18,36
A,37,19,20,38
A,39,21,22,40
A,41,23,24,42
!
!ELEMENT TYPE
ET,1,SHELL99,,0,0,0,1,3

!REAL CONSTANT
t=1.25

R,1,7,0
RMORE,
RMORE,1,0,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,0,t

R,2,7,0
RMORE,
RMORE,1,0,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,0,t

!MATERIAL PROPERTIES
MP,EX,1,34125 !N/MM^2 (MPA)
MP,EY,1,6852 !N/MM^2 (MPA)
MP,EZ,1,6852
MP,GXY,1,3330 !N/MM^2 (MPA)
MP,GYZ,1,3330
MP,GXZ,1,3330
MP,PRXY,1,0.2865
MP,PRYZ,1,0.2865
MP,PRXZ,1,0.2865
MP,DENS,1,2.005E-9 !ton/MM^3

!MATERIAL PROPERTIES
```

```
MP,EX,2,34125 !N/MM^2 (MPA)
MP,EY,2,6852 !N/MM^2 (MPA)
MP,EZ,2,6852
MP,GXY,2,3330 !N/MM^2 (MPA)
MP,GYZ,2,3330
MP,GXZ,2,3330
MP,PRXY,2,0.2865
MP,PRYZ,2,0.2865
MP,PRXZ,2,0.2865
MP,DENS,2,2.005E-9 !ton/MM^3

!MASHING CONTROL
LSEL,S,LOC,Y,H/2
LESIZE,ALL,,,40,1
LSEL,ALL
!
ESIZE,0,2
ASEL,S,AREA,,11,20,1 !INNER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,1,10,1 !OUTER
AATT,1,1,1
AMESH,ALL
ASEL,ALL
!
ESIZE,0,3
ASEL,S,AREA,,21,30,1 !STIFFENER
AATT,1,2,1
AMESH,ALL
ASEL,ALL

!ANALYSIS
/SOLU

ANTYPE,STATIC
NLGEOM,ON
AUTOTS,ON
SSTIF,ON
NSUBST,2,500,2,ON
NROPT,AUTO
NEQIT,20
```

```
CNVTOL,F,,0.001,,1
CNVTOL,M,,0.001,,1
CNVTOL,U,,0.04,,0
TIME,8000
!BOUNDARY CONDITIONS
NSEL,S,LOC,Y,0
D,ALL,UZ,0,0,,,UX,UY,ROTX,ROTY,ROTZ
NSEL,ALL
!====================================================
!Applying Gravity
!====================================================
ACEL,,9800
!====================================================
!Applying wind load parallel to Z Direction between 0-5m
!====================================================
ASEL,S,AREA,,6
ASEL,A,AREA,,7
ASEL,A,AREA,,8
ASEL,A,AREA,,9
ASEL,A,AREA,,10
NSLA,S,0
NSEL,R,LOC,Y,0,5000
*GET,NCOUNT,NODE,0,COUNT
F,ALL,FZ,A1/NCOUNT
!====================================================
!Applying wind load parallel to Z Direction between 5-10m
!====================================================
ASEL,S,AREA,,6
ASEL,A,AREA,,7
ASEL,A,AREA,,8
ASEL,A,AREA,,9
ASEL,A,AREA,,10
NSLA,S,0
NSEL,R,LOC,Y,5001,10000
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A2/Ncnt
!====================================================
!Applying wind load parallel to Z Direction between 10-15m
!====================================================
ASEL,S,AREA,,6
ASEL,A,AREA,,7
ASEL,A,AREA,,8
ASEL,A,AREA,,9
ASEL,A,AREA,,10
```

```
NSLA,S,0
NSEL,R,LOC,Y,10001,15000
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A3/Ncnt
!====================================================
!Applying wind load parallel to Z Direction between 15-20m
!====================================================
ASEL,S,AREA,,6
ASEL,A,AREA,,7
ASEL,A,AREA,,8
ASEL,A,AREA,,9
ASEL,A,AREA,,10
NSLA,S,0
NSEL,R,LOC,Y,15001,20000
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A4/Ncnt
!====================================================
!Applying wind load parallel to Z Direction between 20-H m
!====================================================
ASEL,S,AREA,,6
ASEL,A,AREA,,7
ASEL,A,AREA,,8
ASEL,A,AREA,,9
ASEL,A,AREA,,10
NSLA,S,0
NSEL,R,LOC,Y,20001,H
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A5/Ncnt


!Applying Rotor Load at the top of Tower
!====================================================
NSEL,S,LOC,Y,H
*GET,Ncnt,NODE,0,COUNT
FYAV=FYY/Ncnt
F,ALL,FY,FYAV
NSEL,ALL
!
!MX IN TERM OF COUPLE MOMENT
FMX=MXX/(RT*2)

!MY IN TERM OF COUPLE MOMENT
FMY=MYY/(RT*4)
```

```
!MZ IN TERM OF COUPLE MOMENT
FMZ=MZZ/(RT*2)

 KSEL,S,,,10
FK,ALL,FX,FMY
FK,ALL,FY,-FMX
FK,ALL,FZ,FZZ/4
KSEL,ALL

KSEL,S,,,20
FK,ALL,FX,-FMY
FK,ALL,FY,FMX
FK,ALL,FZ,FZZ/4
KSEL,ALL

KSEL,S,,,6
FK,ALL,FZ,FMY
FK,ALL,FY,-FMZ
KSEL,ALL

KSEL,S,,,16
FK,ALL,FZ,-FMY
FK,ALL,FY,FMZ
KSEL,ALL

KSEL,S,,,38
FK,ALL,FZ,FZZ/4
KSEL,ALL

KSEL,S,,,28
FK,ALL,FZ,FZZ/4
KSEL,ALL

LSWRITE,1
LSSOLVE,1
SAVE
FINISH
```

# Appendix B5

The analysis of 12-cell sections

**12-cell section trail # 1:** For trial # 1, the following geometric parameters are selected.

Bottom diameter: 1300 mm c/c

Top diameter: 800 mm c/c

Inner diameter: 600 mm c/c

Wall thickness: 7.5 mm

Rotor loads: Referred in Table 4.3: Rotor load combination in service for deflection determination of the tower

Wind loads: The governing wind loads for 50 year recurrence period according CSA-S37-01 corresponding to the trial # 1 are mentioned in Table B13

**Table B13:** Wind loads for 12-cell section trial # 1

| Height Range, m | Projected Area ($m^2$) | Exposure Factor, (Ce) | Gust Factor (Cg) | Pressure,(P), Kpa | Wind Force (F), N |
|---|---|---|---|---|---|
| 0-5 | 6.28 | 1.00 | 2.50 | 1.95 | 6124 |
| 5-10 | 5.77 | 1.00 | 2.50 | 1.95 | 5625 |
| 10-15 | 5.26 | 1.08 | 2.50 | 2.11 | 5558 |
| 15-20 | 4.74 | 1.15 | 2.50 | 2.24 | 5313 |
| 20-24.39 | 4.26 | 1.20 | 2.50 | 2.33 | 4967 |

For 12-cell section trial # 1, from finite element analysis it is found that the deflection is 462 mm (Figure B13) and weight of the structure is 2891 Kg.

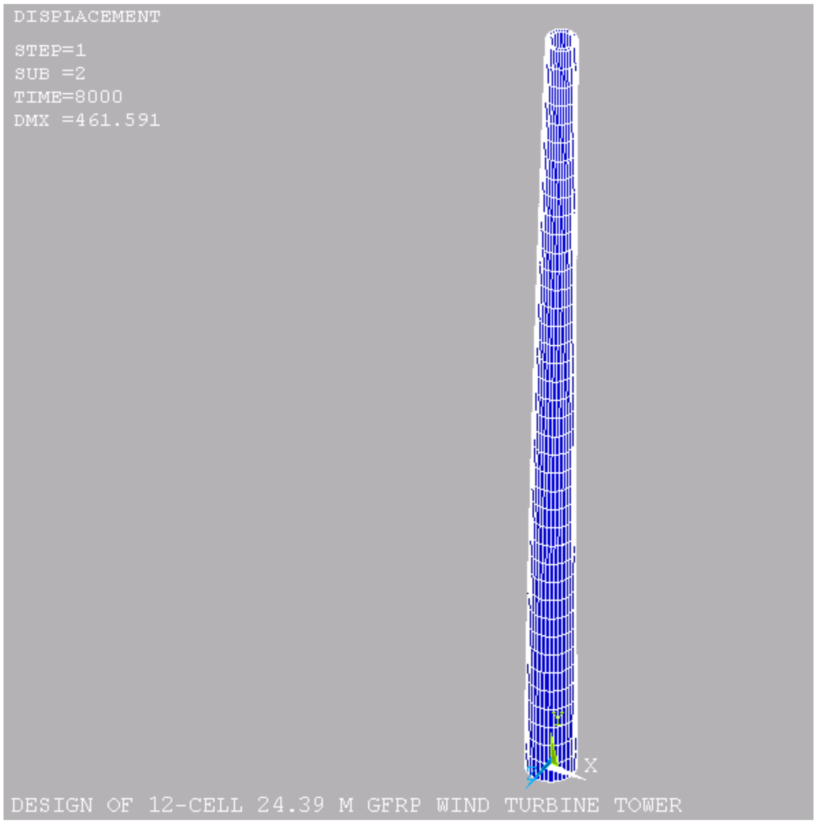


**Figure B13:** Deflection for 12-cell section trial # 1

**12-cell section trail # 2:** For trial no 2, the following geometric parameters are selected.

Bottom diameter: 1300 mm c/c

Top diameter: 800 mm c/c

Inner diameter: 600 mm c/c

Wall thickness: 8.75 mm

Rotor loads: Referred in Table 4.3: Rotor load combination in service for deflection determination of the tower

Wind loads: The governing wind loads for 50 year recurrence period according CSA-S37-01 corresponding to the trial # 2 are mentioned in Table B14.

**Table B14:** Wind loads for 12-cell section trial # 2

| Height Range,m | Projected Area ($m^2$) | Exposure factor, (Ce) | Gust Factor (Cg) | Pressure,(P) Kpa | Wind Force (F), N |
|---|---|---|---|---|---|
| 0-5 | 6.29 | 1.00 | 2.50 | 1.95 | 6130 |
| 5-10 | 5.77 | 1.00 | 2.50 | 1.95 | 5631 |
| 10-15 | 5.26 | 1.08 | 2.50 | 2.11 | 5564 |
| 15-20 | 4.75 | 1.15 | 2.50 | 2.24 | 5320 |
| 20-24.39 | 4.27 | 1.20 | 2.50 | 2.33 | 4974 |

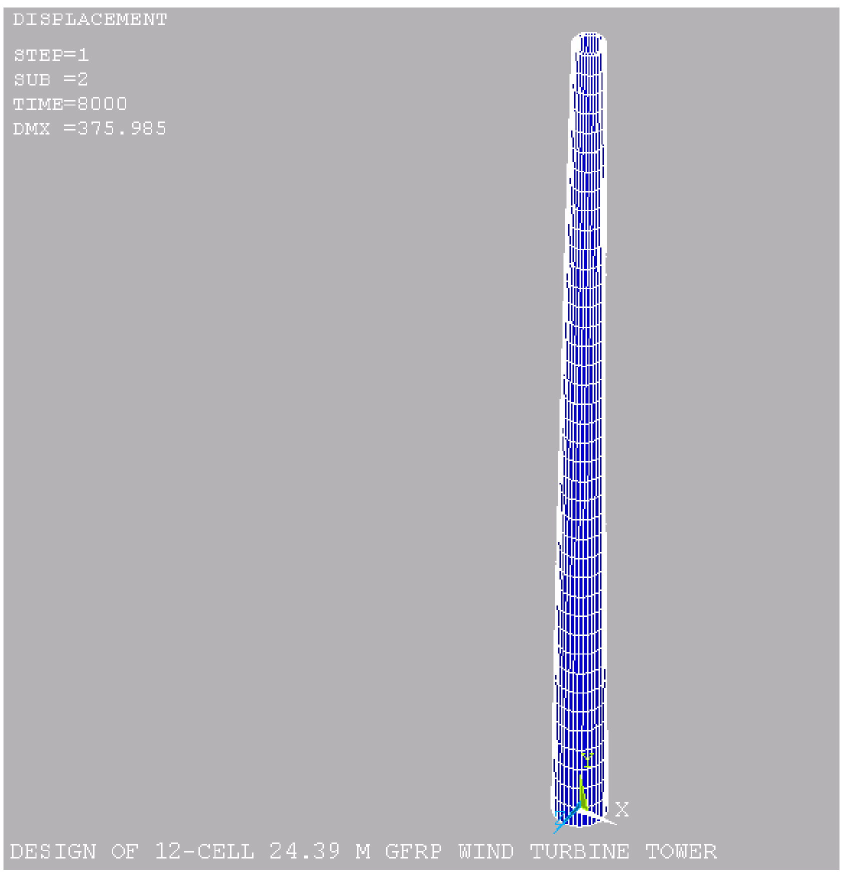


**Figure B14:** Deflection for 12-cell section trial # 2

For 12-cell section trial # 2, from finite element analysis it is found that the deflection is 376 mm (Figure B14) and weight of the structure is 3375 Kg.

**12-cell section trail # 3:** For trial # 3, the following geometric parameters are selected.

Bottom diameter: 1300 mm c/c

Top diameter: 800 mm c/c

Inner diameter: 600 mm c/c

Wall thickness: 10 mm

Rotor loads: Referred in Table 4.3: Rotor load combination in service for deflection determination of the tower

Wind loads: The governing wind loads for 50 year recurrence period according CSA-S37-01 corresponding to the trial # 3 are mentioned in Table B15

**Table B15:** Wind loads for 12-cell section trial # 3

| Height Range, m | Projected Area ($m^2$) | Exposure factor, (Ce) | Gust Factor (Cg) | Pressure,(P), Kpa | Wind Force (F), N |
|---|---|---|---|---|---|
| 0-5 | 6.29 | 1.00 | 2.50 | 1.95 | 6136 |
| 5-10 | 5.78 | 1.00 | 2.50 | 1.95 | 5637 |
| 10-15 | 5.27 | 1.08 | 2.50 | 2.11 | 5571 |
| 15-20 | 4.76 | 1.15 | 2.50 | 2.24 | 5327 |
| 20-24.39 | 4.27 | 1.20 | 2.50 | 2.33 | 4982 |

For 12-cell section trial # 3, from finite element analysis it has been found that the deflection is 317 mm (Figure B15) and weight of the structure is 3855 Kg.

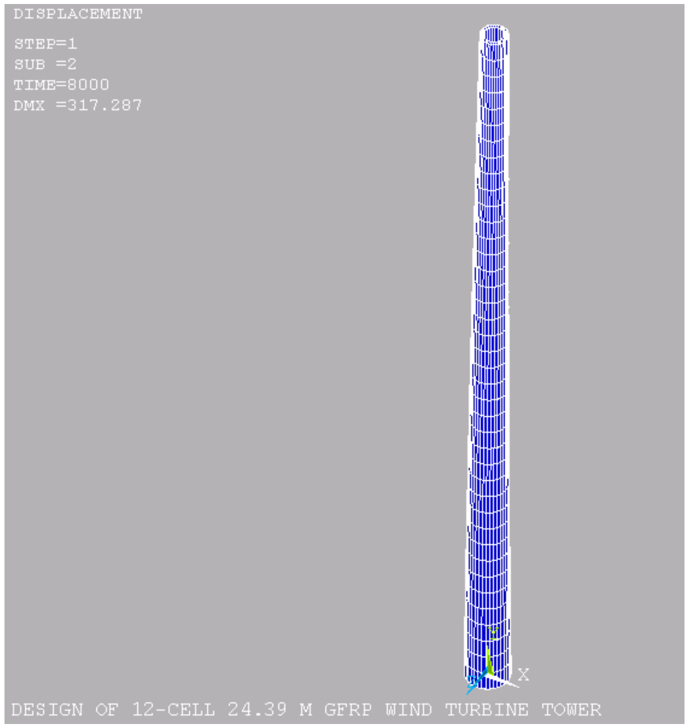


**Figure B15:** Deflection for 12-cell section trial # 3

**12-cell section trail # 4:** For trial # 4, the following geometric parameters are selected.

Bottom diameter: 1300 mm c/c

Top diameter: 800 mm c/c

Inner diameter: 600 mm c/c

Wall thickness:  11.25 mm

Rotor loads: Referred in Table 4.3: Rotor load combination in service for deflection determination of the tower

Wind loads: The governing wind loads for 50 year recurrence period according CSA-S37-01 corresponding to the trial # 4 are mentioned in Table B16

**Table B16:** Wind loads for 12-cell section trial # 4

| Height Range, m | Projected Area (m2) | Exposure factor, (Ce) | Gust Factor (Cg) | Pressure,(P), Kpa | Wind Force (F), N |
|---|---|---|---|---|---|
| 0-5 | 6.30 | 1.00 | 2.50 | 1.95 | 6142.50 |
| 5-10 | 5.79 | 1.00 | 2.50 | 1.95 | 5642.81 |
| 10-15 | 5.27 | 1.08 | 2.50 | 2.11 | 5577.56 |
| 15-20 | 4.76 | 1.15 | 2.50 | 2.24 | 5333.89 |
| 20-24.39 | 4.28 | 1.20 | 2.50 | 2.33 | 4989.03 |

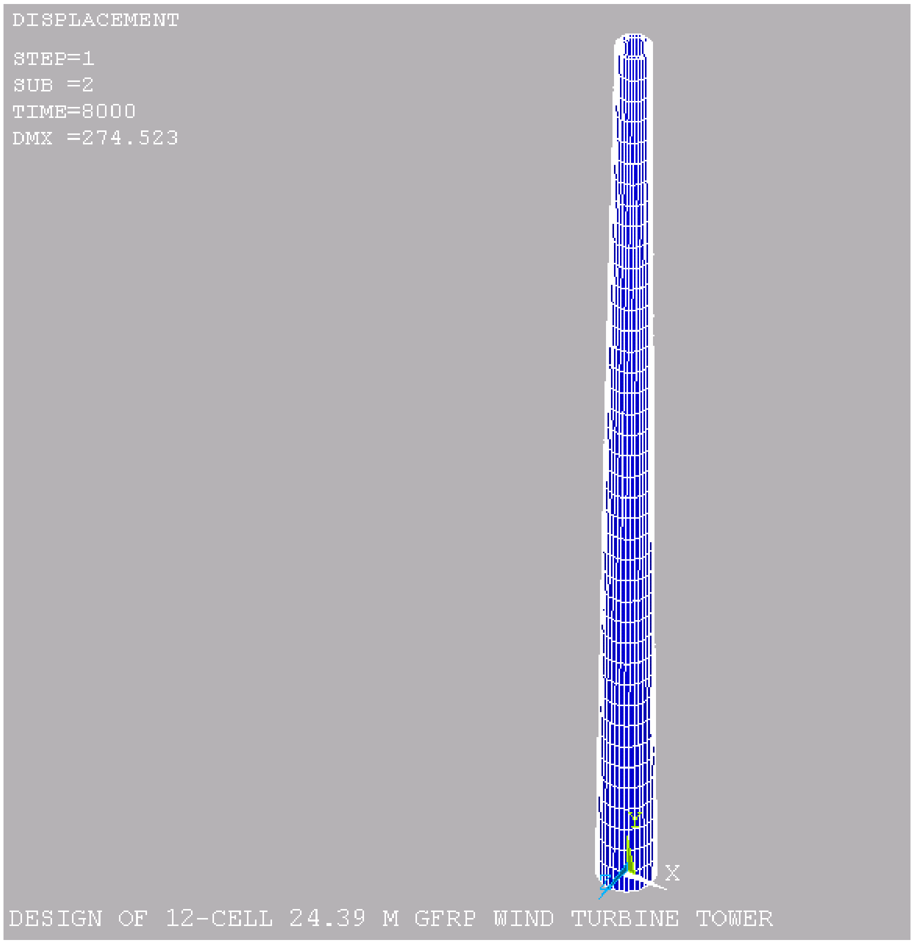


**Figure B16:** Deflection for 12-cell section trial # 4

For 12-cell section trial # 4, from finite element analysis it is found that the deflection is 275 mm (Figure B16) and weight of the structure is 4337 Kg. Sample ANSYS codes related to trail # 4 are included in the Appendix B6.

# Appendix B6

A sample ANSYS codes for 12-cell (trial # 4)

```
FINISH
/CLEAR
/TITLE, DESIGN OF 12-CELL 24.39 M GFRP WIND TURBINE TOWER
/PREP7
/PBC,F,,1
/PBC,U,,1
/NERR,5,50000000
/PNUM,KP,1
/PNUM,LINE,1
/PNUM,AREA,1
/VIEW,1,3500,6000,5000

!ROTOR LOADS
FYY=-6376.50!Fz N ROTOR DEAD LOAD
FZZ=-8522.68  !Fx N
MXX=1434.71e3 !My N.MM
MYY=5319e3!Mz N.MM
MZZ=0!Mx N.MM

!WIND LOAD
A1=	-6142.50
A2=	-5642.81
A3=	-5577.56
A4=	-5333.89
A5=	-4989.03

RB=650
RT=400
IR=300
H=24390

!GEOMETRY
K,1,0,0,0
K,2,0,H,0
K,3,IR,0,0
K,4,IR,H,0
K,5,RB,0,0
K,6,RT,H,0

L,3,4
L,5,6
AROTAT,2,,,,,,1,2,360,12
AROTAT,1,,,,,,1,2,360,12
```

```
A,4,6,5,3
A,30,8,7,29
A,32,10,9,31
A,34,12,11,33
A,36,14,13,35
A,38,16,15,37
A,40,18,17,39
A,42,20,19,41
A,44,22,21,43
A,46,24,23,45
A,48,26,25,47
A,50,28,27,49

!
!ELEMENT TYPE
ET,1,SHELL99,,0,0,0,1,3

!REAL CONSTANT
t=1.25

R,1,8,0
RMORE,
RMORE,1,0,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,0,t
R,2,8,0
RMORE,
RMORE,1,0,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,0,t
!MATERIAL PROPERTIES
MP,EX,1,34125 !N/MM^2 (MPA)
MP,EY,1,6852 !N/MM^2 (MPA)
MP,EZ,1,6852
MP,GXY,1,3330 !N/MM^2 (MPA)
MP,GYZ,1,3330
MP,GXZ,1,3330
MP,PRXY,1,0.2865
MP,PRYZ,1,0.2865
MP,PRXZ,1,0.2865
MP,DENS,1,2.005E-9 !ton/MM^3
```

```
!MATERIAL PROPERTIES
MP,EX,2,34125 !N/MM^2 (MPA)
MP,EY,2,6852 !N/MM^2 (MPA)
MP,EZ,2,6852
MP,GXY,2,3330 !N/MM^2 (MPA)
MP,GYZ,2,3330
MP,GXZ,2,3330
MP,PRXY,2,0.2865
MP,PRYZ,2,0.2865
MP,PRXZ,2,0.2865
MP,DENS,2,2.005E-9 !ton/MM^3

!MASHING CONTROL
LSEL,S,LOC,Y,H/2
LESIZE,ALL,,,40,1
LSEL,ALL
!
ESIZE,0,2
ASEL,S,AREA,,13,24,1 !INNER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,1,12,1 !OUTER
AATT,1,1,1
AMESH,ALL
ASEL,ALL
!
ESIZE,0,3
ASEL,S,AREA,,25,36,1 !STIFFENER
AATT,1,2,1
AMESH,ALL
ASEL,ALL

!ANALYSIS
/SOLU
ANTYPE,STATIC
NLGEOM,ON
AUTOTS,ON
SSTIF,ON
NSUBST,2,500,2,ON
NROPT,AUTO
NEQIT,20
```

```
CNVTOL,F,,0.001,,1
CNVTOL,M,,0.001,,1
CNVTOL,U,,0.04,,0
TIME,8000
!BOUNDARY CONDITIONS
NSEL,S,LOC,Y,0
D,ALL,UZ,0,0,,,UX,UY,ROTX,ROTY,ROTZ
NSEL,ALL
!=====================================================
!Applying Gravity
!=====================================================
ACEL,,9800
!=====================================================
!Applying wind load parallel to Z Direction between 0-5m
!=====================================================
ASEL,S,AREA,,7
ASEL,A,AREA,,8
ASEL,A,AREA,,9
ASEL,A,AREA,,10
ASEL,A,AREA,,11
ASEL,A,AREA,,12
NSLA,S,0
NSEL,R,LOC,Y,0,5000
*GET,NCOUNT,NODE,0,COUNT
F,ALL,FZ,A1/NCOUNT
!=====================================================
!Applying wind load parallel to Z Direction between 5-10m
!=====================================================
ASEL,S,AREA,,7
ASEL,A,AREA,,8
ASEL,A,AREA,,9
ASEL,A,AREA,,10
ASEL,A,AREA,,11
ASEL,A,AREA,,12
NSLA,S,0
NSEL,R,LOC,Y,5001,10000
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A2/Ncnt
!=====================================================
!Applying wind load parallel to Z Direction between 10-15m
!=====================================================
ASEL,S,AREA,,7
ASEL,A,AREA,,8
ASEL,A,AREA,,9
```

```
ASEL,A,AREA,,10
ASEL,A,AREA,,11
ASEL,A,AREA,,12
NSLA,S,0
NSEL,R,LOC,Y,10001,15000
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A3/Ncnt
!=====================================================
!Applying wind load parallel to Z Direction between 15-20m
!=====================================================
ASEL,S,AREA,,7
ASEL,A,AREA,,8
ASEL,A,AREA,,9
ASEL,A,AREA,,10
ASEL,A,AREA,,11
ASEL,A,AREA,,12
NSLA,S,0
NSEL,R,LOC,Y,15001,20000
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A4/Ncnt
!=====================================================
!Applying wind load parallel to Z Direction between 20-H m
!=====================================================
ASEL,S,AREA,,7
ASEL,A,AREA,,8
ASEL,A,AREA,,9
ASEL,A,AREA,,10
ASEL,A,AREA,,11
ASEL,A,AREA,,12
NSLA,S,0
NSEL,R,LOC,Y,20001,H
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A5/Ncnt

!Applying Rotor Load at the top of Tower
!=====================================================
NSEL,S,LOC,Y,H
*GET,Ncnt,NODE,0,COUNT
FYAV=FYY/Ncnt
F,ALL,FY,FYAV
NSEL,ALL
!
!MX IN TERM OF COUPLE MOMENT
FMX=MXX/(RT*2)
```

```
!MY IN TERM OF COUPLE MOMENT
FMY=MYY/(RT*4)

!MZ IN TERM OF COUPLE MOMENT
FMZ=MZZ/(RT*2)

KSEL,S,,,12
FK,ALL,FX,FMY
FK,ALL,FY,-FMX
FK,ALL,FZ,FZZ/4
KSEL,ALL

KSEL,S,,,24
FK,ALL,FX,-FMY
FK,ALL,FY,FMX
FK,ALL,FZ,FZZ/4
KSEL,ALL

KSEL,S,,,6
FK,ALL,FZ,FMY
FK,ALL,FY,-FMZ
KSEL,ALL

KSEL,S,,,18
FK,ALL,FZ,-FMY
FK,ALL,FY,FMZ
KSEL,ALL

KSEL,S,,,46
FK,ALL,FZ,FZZ/4
KSEL,ALL

KSEL,S,,,34
FK,ALL,FZ,FZZ/4
KSEL,ALL

LSWRITE,1
LSSOLVE,1
SAVE
FINISH
```

# Appendix B7

Maple codes for the integration of analytical solution of deflection determination for the proposed section.

$with(Student[Calculus1]):$

$Ix := 7.1864x^2 + 214637x + 3e09;$

$$7.1864x^2 + 214637x + 3.\ 10^9$$

$v1 := \int \left(-\frac{p \cdot x}{E \cdot Ix}\right) dx;$

$$-\frac{1}{E}\left(0.06957586552 p \ln\left(8983. x^2 + 2.68296250 10^8 x + 3.750000000 10^{12}\right)\right) + \frac{0.1490233787 p \arctan(0.00007171377514 x + 1.070941609)}{E}$$

$v2 := \int (v1 + 0.2828513450) dx;$

$$-\frac{1}{E}\left(0.06957586552 p\, x \ln\left(8983. x^2 + 2.68296250 10^8 x + 3.750000000 10^{12}\right)\right) + \frac{0.1391517310 p\, x}{E} - \frac{1}{E}\left(1039.015018 p \ln\left(8983. x^2 + 2.68296250 10^8 x + 3.750000000 10^{12}\right)\right) + \frac{285.072232 p \arctan(0.00007171377514 x + 1.070941609)}{E} + \frac{0.1490233787 p \arctan(0.00007171377514 x + 1.070941609)\, x}{E} - \frac{1}{E}\left(1039.015018 p \ln\left(1. + (0.00007171377514 x + 1.070941609)^2\right)\right) + 0.2828513450 x$$

$uma := v2 + 4410.095885;$

$$-\frac{1}{E}\left(0.06957586552 p\, x \ln\left(8983.\, x^2 + 2.6829625010^8\, x + 3.75000000010^{12}\right)\right) + \frac{0.1391517310 p\, x}{E}$$

$$- \frac{1}{E}\left(1039.015018 p \ln\left(8983.\, x^2 + 2.6829625010^8\, x + 3.75000000010^{12}\right)\right)$$

$$+ \frac{285.072232 p \arctan(0.00007171377514 x + 1.070941609)}{E}$$

$$+ \frac{0.1490233787 p \arctan(0.00007171377514 x + 1.070941609)\, x}{E}$$

$$- \frac{1}{E}\left(1039.015018 p \ln\left(1. + (0.00007171377514 x + 1.070941609)^2\right)\right) + 0.2828513450 x + 4410.095885$$

$E := 34125;$

34125

$p := 5000;$

5000

$x := 0;$

0

$umax := uma;$

−79.655679

# Appendix C1

ANSYS codes for the deflection analysis of the proposed design section.

```
FINISH
/CLEAR
/PREP7
/PBC,F,,1
/PBC,U,,1
/NERR,5,50000000
/PNUM,KP,1
/PNUM,LINE,1
/PNUM,AREA,1
/VIEW,1,3500,6000,5000

!ROTOR LOADS
FYY=-6376.50!Fz N ROTOR DEAD LOAD
FZZ=-8522.68  !Fx N
MXX=1434.71e3 !My N.MM
MYY=5319e3!Mz N.MM
MZZ=0!Mx N.MM

!WIND LOAD
A1=-6160.78 !0-5M HEIGHT,N
A2=-5661.09 !5-10M HEIGHT,N
A3=-5597.39 !10-15M HEIGHT,N
A4=-5354.89 !15-20M HEIGHT,N
A5=-5010.88 !20-H M HEIGHT,N

RB=650 !MM,BOTTOM RADIUS centre to centre
RT=400 !MM,TOP RADIUS  centre to centre
IR=300 !MM,INNER RADIUS  centre to centre
H=24390 !MM,HEIGHT OF THE TOWER

!GEOMETRY
K,1,0,0,0
K,2,0,H,0
K,3,IR,0,0
K,4,IR,H,0
K,5,RB,0,0
K,6,RT,H,0

L,3,4
L,5,6
AROTAT,2,,,,,,1,2,360,8
AROTAT,1,,,,,,1,2,360,8

A,3,4,6,5
A,21,22,8,7
```

```
A,23,24,10,9
A,25,26,12,11
A,27,28,14,13
A,29,30,16,15
A,31,32,18,17
A,33,34,20,19
!
!ELEMENT TYPE
ET,1,SHELL99,,0,0,0,1,3
KEYOPT,1,11,2
ET,2,SHELL99,,0,0,0,1,3
KEYOPT,2,11,1
ET,3,SHELL99,,0,0,0,1,3

!REAL CONSTANT
t=1.25

R,1,12,0
RMORE,
RMORE,1,0,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,0,t

R,2,6,0
RMORE,
RMORE,1,0,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,0,t

R,3,6,0
RMORE,
RMORE,1,0,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,0,t

!MATERIAL PROPERTIES
MP,EX,1,34125 !N/MM^2 (MPA)
MP,EY,1,6852 !N/MM^2 (MPA)
MP,EZ,1,6852
MP,GXY,1,3330 !N/MM^2 (MPA)
MP,GYZ,1,3330
MP,GXZ,1,3330
MP,PRXY,1,0.2865
MP,PRYZ,1,0.2865
```

```
MP,PRXZ,1,0.2865
MP,DENS,1,2.005E-9 !ton/MM^3

!MATERIAL PROPERTIES
MP,EX,2,34125 !N/MM^2 (MPA)
MP,EY,2,6852 !N/MM^2 (MPA)
MP,EZ,2,6852
MP,GXY,2,3330 !N/MM^2 (MPA)
MP,GYZ,2,3330
MP,GXZ,2,3330
MP,PRXY,2,0.2865
MP,PRYZ,2,0.2865
MP,PRXZ,2,0.2865
MP,DENS,2,2.005E-9 !ton/MM^3

!MASHING CONTROL
LSEL,S,LOC,Y,H/2
LESIZE,ALL,,,40,1
LSEL,ALL
!
ESIZE,0,2
ASEL,S,AREA,,1,1,1 !INNER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,3,3,1 !INNER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,5,5,1 !INNER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,7,7,1 !INNER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,2,2,1 !INNER
AATT,2,2,1
```

```
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,4,4,1 !INNER
AATT,2,2,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,6,6,1 !INNER
AATT,2,2,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,8,8,1 !INNER
AATT,2,2,1
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,9,9,1 !OUTER
AATT,2,2,2
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,11,11,1 !OUTER
AATT,2,2,2
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,13,13,1 !OUTER
AATT,2,2,2
AMESH,ALL
ASEL,ALL
ESIZE,0,3
ASEL,S,AREA,,15,15,1 !OUTER
AATT,2,2,2
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,10,10,1 !OUTER
AATT,1,1,2
```

```
AMESH,ALL
ASEL,ALL
ESIZE,0,3
ASEL,S,AREA,,12,12,1 !OUTER
AATT,1,1,2
AMESH,ALL
ASEL,ALL
ESIZE,0,3
ASEL,S,AREA,,14,14,1 !OUTER
AATT,1,1,2
AMESH,ALL
ASEL,ALL
ESIZE,0,3
ASEL,S,AREA,,16,16,1 !OUTER
AATT,1,1,2
AMESH,ALL
ASEL,ALL
!
ESIZE,0,3
ASEL,S,AREA,,17,24,1 !STIFFENER
AATT,2,3,3
AMESH,ALL
ASEL,ALL

!ANALYSIS
/SOLU
/TITLE, DESIGN OF 8-CELL 24.39 M GFRP WIND TURBINE TOWER
ANTYPE,STATIC
NLGEOM,ON
AUTOTS,ON
SSTIF,ON
NSUBST,2,500,2,ON
NROPT,AUTO
NEQIT,20
CNVTOL,F,,0.001,,1
CNVTOL,M,,0.001,,1
CNVTOL,U,,0.04,,0
TIME,8000
!BOUNDARY CONDITIONS
NSEL,S,LOC,Y,0
D,ALL,UZ,0,0,,,UX,UY,ROTX,ROTY,ROTZ
NSEL,ALL
!==================================================
!Applying Gravity
!==================================================
ACEL,,9800
!==================================================
```

```
!Applying wind load parallel to Z Direction between 0-5m
!==========================================================
ASEL,S,AREA,,5
ASEL,A,AREA,,6
ASEL,A,AREA,,7
ASEL,A,AREA,,8
NSLA,S,0
NSEL,R,LOC,Y,0,5000
*GET,NCOUNT,NODE,0,COUNT
F,ALL,FZ,A1/NCOUNT
!==========================================================
!Applying wind load parallel to Z Direction between 5-10m
!==========================================================
ASEL,S,AREA,,5
ASEL,A,AREA,,6
ASEL,A,AREA,,7
ASEL,A,AREA,,8
NSLA,S,0
NSEL,R,LOC,Y,5001,10000
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A2/Ncnt
!==========================================================
!Applying wind load parallel to Z Direction between 10-15m
!==========================================================
ASEL,S,AREA,,5
ASEL,A,AREA,,6
ASEL,A,AREA,,7
ASEL,A,AREA,,8
NSLA,S,0
NSEL,R,LOC,Y,10001,15000
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A3/Ncnt
!==========================================================
!Applying wind load parallel to Z Direction between 15-20m
!==========================================================
ASEL,S,AREA,,5
ASEL,A,AREA,,6
ASEL,A,AREA,,7
ASEL,A,AREA,,8
NSLA,S,0
NSEL,R,LOC,Y,15001,20000
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A4/Ncnt
!==========================================================
!Applying wind load parallel to Z Direction between 20-H m
!==========================================================
ASEL,S,AREA,,5
```

```
ASEL,A,AREA,,6
ASEL,A,AREA,,7
ASEL,A,AREA,,8
NSLA,S,0
NSEL,R,LOC,Y,20001,H
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A5/Ncnt

!Applying Rotor Load at the top of Tower
!=====================================================
NSEL,S,LOC,Y,H
*GET,Ncnt,NODE,0,COUNT
FYAV=FYY/Ncnt
F,ALL,FY,FYAV
NSEL,ALL
!
!MX IN TERM OF COUPLE MOMENT
FMX=MXX/(RT*2)

!MY IN TERM OF COUPLE MOMENT
FMY=MYY/(RT*4)

!MZ IN TERM OF COUPLE MOMENT
FMZ=MZZ/(RT*2)
KSEL,S,,,10
FK,ALL,FX,FMY
FK,ALL,FY,-FMX
FK,ALL,FZ,FZZ/4
KSEL,ALL

KSEL,S,,,18
FK,ALL,FX,-FMY
FK,ALL,FY,FMX
FK,ALL,FZ,FZZ/4
KSEL,ALL

KSEL,S,,,6
FK,ALL,FZ,FMY
FK,ALL,FY,-FMZ
KSEL,ALL

KSEL,S,,,14
FK,ALL,FZ,-FMY
FK,ALL,FY,FMZ
KSEL,ALL

KSEL,S,,,32
```

```
FK,ALL,FZ,FZZ/4
KSEL,ALL

KSEL,S,,,24
FK,ALL,FZ,FZZ/4
KSEL,ALL

LSWRITE,1
LSSOLVE,1
SAVE
FINISH
```

# Appendix C2

ANSYS codes for the stress analysis of the proposed section.

```
FINISH
/CLEAR
/PREP7
/PBC,F,,1
/PBC,U,,1
/NERR,5,50000000
/PNUM,KP,1
/PNUM,LINE,1
/PNUM,AREA,1
/VIEW,1,3500,6000,5000

!ROTOR LOADS
FYY=-7014.15!Fz N ROTOR DEAD LOAD
FZZ=-8522.68  !Fx N
MXX=1578.18e3 !My N.MM
MYY=5319e3!Mz N.MM
MZZ=0!Mx N.MM

!WIND LOAD
A1=-9241.17 !0-5M HEIGHT,N
A2=-8491.63 !5-10M HEIGHT,N
A3=-8396.08 !10-15M HEIGHT,N
A4=-8032.33 !15-20M HEIGHT,N
A5=-7516.33 !20-H M HEIGHT,N

RB=650 !MM,BOTTOM RADIUS
RT=400 !MM,TOP RADIUS
IR=300 !MM,INNER RADIUS
H=24390 !MM,HEIGHT OF THE TOWER


!GEOMETRY
K,1,0,0,0
K,2,0,H,0
K,3,IR,0,0
K,4,IR,H,0
K,5,RB,0,0
K,6,RT,H,0

L,3,4
L,5,6
AROTAT,2,,,,,,1,2,360,8
AROTAT,1,,,,,,1,2,360,8

A,3,4,6,5
A,21,22,8,7
A,23,24,10,9
```

```
A,25,26,12,11
A,27,28,14,13
A,29,30,16,15
A,31,32,18,17
A,33,34,20,19
!
!ELEMENT TYPE
ET,1,SHELL99,,0,0,0,1,3
KEYOPT,1,11,2
ET,2,SHELL99,,0,0,0,1,3
KEYOPT,2,11,1
ET,3,SHELL99,,0,0,0,1,3
!REAL CONSTANT
t=1.25

R,1,12,0
RMORE,
RMORE,1,0,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,0,t

R,2,6,0
RMORE,
RMORE,1,0,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,0,t
!MATERIAL PROPERTIES
MP,EX,1,34125 !N/MM^2 (MPA)
MP,EY,1,6852 !N/MM^2 (MPA)
MP,EZ,1,6852
MP,GXY,1,3330 !N/MM^2 (MPA)
MP,GYZ,1,3330
MP,GXZ,1,3330
MP,PRXY,1,0.2865
MP,PRYZ,1,0.2865
MP,PRXZ,1,0.2865
MP,DENS,1,2.005E-9 !ton/MM^3

!MATERIAL PROPERTIES
MP,EX,2,34125 !N/MM^2 (MPA)
MP,EY,2,6852 !N/MM^2 (MPA)
MP,EZ,2,6852
MP,GXY,2,3330 !N/MM^2 (MPA)
MP,GYZ,2,3330
```

```
MP,GXZ,2,3330
MP,PRXY,2,0.2865
MP,PRYZ,2,0.2865
MP,PRXZ,2,0.2865
MP,DENS,2,2.005E-9 !ton/MM^3


!MASHING CONTROL
ESHAPE,2,0
LSEL,S,LOC,Y,H/2
LESIZE,ALL,,,40,1
LSEL,ALL
!
ESIZE,0,2
ASEL,S,AREA,,1,1,1 !INNER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,3,3,1 !INNER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,5,5,1 !INNER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,7,7,1 !INNER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,2,2,1 !INNER
AATT,2,2,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,4,4,1 !INNER
AATT,2,2,1
AMESH,ALL
```

```
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,6,6,1 !INNER
AATT,2,2,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,8,8,1 !INNER
AATT,2,2,1
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,9,9,1 !OUTER
AATT,2,2,2
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,11,11,1 !OUTER
AATT,2,2,2
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,13,13,1 !OUTER
AATT,2,2,2
AMESH,ALL
ASEL,ALL
ESIZE,0,3
ASEL,S,AREA,,15,15,1 !OUTER
AATT,2,2,2
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,10,10,1 !OUTER
AATT,1,1,2
AMESH,ALL
ASEL,ALL
ESIZE,0,3
ASEL,S,AREA,,12,12,1 !OUTER
AATT,1,1,2
AMESH,ALL
ASEL,ALL
```

```
ESIZE,0,3
ASEL,S,AREA,,14,14,1 !OUTER
AATT,1,1,2
AMESH,ALL
ASEL,ALL
ESIZE,0,3
ASEL,S,AREA,,16,16,1 !OUTER
AATT,1,1,2
AMESH,ALL
ASEL,ALL
!
ESIZE,0,3
ASEL,S,AREA,,17,24,1 !STIFFENER
AATT,2,2,3
AMESH,ALL
ASEL,ALL

!ANALYSIS
/SOLU
/TITLE, DESIGN OF 8-CELL 24.39 M GFRP WIND TURBINE TOWER
ANTYPE,STATIC
NLGEOM,ON
AUTOTS,ON
SSTIF,ON
NSUBST,2,500,2,ON
NROPT,AUTO
NEQIT,20
CNVTOL,F,,0.001,,1
CNVTOL,M,,0.001,,1
CNVTOL,U,,0.04,,0
TIME,8000
!BOUNDARY CONDITIONS
NSEL,S,LOC,Y,0
D,ALL,UZ,0,0,,,UX,UY,ROTX,ROTY,ROTZ
NSEL,ALL
!=====================================================
!Applying Gravity
!=====================================================
ACEL,,9800
!=====================================================
!Applying wind load parallel to Z Direction between 0-5m
!=====================================================
ASEL,S,AREA,,5
ASEL,A,AREA,,6
ASEL,A,AREA,,7
ASEL,A,AREA,,8
NSLA,S,0
```

```
NSEL,R,LOC,Y,0,5000
*GET,NCOUNT,NODE,0,COUNT
F,ALL,FZ,A1/NCOUNT
!=====================================================
!Applying wind load parallel to Z Direction between 5-10m
!=====================================================
ASEL,S,AREA,,5
ASEL,A,AREA,,6
ASEL,A,AREA,,7
ASEL,A,AREA,,8
NSLA,S,0
NSEL,R,LOC,Y,5001,10000
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A2/Ncnt
!=====================================================
!Applying wind load parallel to Z Direction between 10-15m
!=====================================================
ASEL,S,AREA,,5
ASEL,A,AREA,,6
ASEL,A,AREA,,7
ASEL,A,AREA,,8
NSLA,S,0
NSEL,R,LOC,Y,10001,15000
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A3/Ncnt
!=====================================================
!Applying wind load parallel to Z Direction between 15-20m
!=====================================================
ASEL,S,AREA,,5
ASEL,A,AREA,,6
ASEL,A,AREA,,7
ASEL,A,AREA,,8
NSLA,S,0
NSEL,R,LOC,Y,15001,20000
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A4/Ncnt
!=====================================================
!Applying wind load parallel to Z Direction between 20-H m
!=====================================================
ASEL,S,AREA,,5
ASEL,A,AREA,,6
ASEL,A,AREA,,7
ASEL,A,AREA,,8
NSLA,S,0
NSEL,R,LOC,Y,20001,H
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A5/Ncnt
```

```
!Applying Rotor Load at the top of Tower
!=====================================================
NSEL,S,LOC,Y,H
*GET,Ncnt,NODE,0,COUNT
FYAV=FYY/Ncnt
F,ALL,FY,FYAV
NSEL,ALL
!
!MX IN TERM OF COUPLE MOMENT
FMX=MXX/(RT*2)
!MY IN TERM OF COUPLE MOMENT
FMY=MYY/(RT*4)
!MZ IN TERM OF COUPLE MOMENT
FMZ=MZZ/(RT*2)
KSEL,S,,,10
FK,ALL,FX,FMY
FK,ALL,FY,-FMX
FK,ALL,FZ,FZZ/4
KSEL,ALL
KSEL,S,,,18
FK,ALL,FX,-FMY
FK,ALL,FY,FMX
FK,ALL,FZ,FZZ/4
KSEL,ALL
KSEL,S,,,6
FK,ALL,FZ,FMY
FK,ALL,FY,-FMZ
KSEL,ALL
KSEL,S,,,14
FK,ALL,FZ,-FMY
FK,ALL,FY,FMZ
KSEL,ALL
KSEL,S,,,32
FK,ALL,FZ,FZZ/4
KSEL,ALL
KSEL,S,,,24
FK,ALL,FZ,FZZ/4
KSEL,ALL
LSWRITE,1
LSSOLVE,1
SAVE
FINISH/POST1
RSYS,SOLU
FC,1,s,xten,587.46
FC,1,s,xcmp,-267.15
FC,1,s,yten,21.27
```

```
FC,1,s,ycmp,-71.05
FC,1,s,zten,1E6
FC,1,s,xy,27.20
FC,1,s,yz,1E6
FC,1,s,xz,1E6
FC,1,s,XYCP,-1
FC,1,s,YZCP,-1
FC,1,s,XZCP,-1
FC,2,s,xten,587.46
FC,2,s,xcmp,-267.15
FC,2,s,yten,21.27
FC,2,s,ycmp,-71.05
FC,2,s,zten,1E6
FC,2,s,xy,27.20
FC,2,s,yz,1E6
FC,2,s,xz,1E6
FC,2,s,XYCP,-1
FC,2,s,YZCP,-1
FC,1,s,XZCP,-1
FINISH
```

## Appendix C3

ANSYS codes for the Free Vibration analysis of the proposed Tower

```
FINISH
/CLEAR
/PREP7
/PBC,F,,1
/PBC,U,,1
/NERR,5,50000000
/PNUM,KP,1
/PNUM,LINE,1
/PNUM,AREA,1
/VIEW,1,3500,6000,5000

RB=650
RT=400
IR=300
H=24390

!GEOMETRY
K,1,0,0,0
K,2,0,H,0
K,3,IR,0,0
K,4,IR,H,0
K,5,RB,0,0
K,6,RT,H,0

L,3,4
L,5,6
AROTAT,2,,,,,,1,2,360,8
AROTAT,1,,,,,,1,2,360,8

A,3,4,6,5
A,21,22,8,7
A,23,24,10,9
A,25,26,12,11
A,27,28,14,13
A,29,30,16,15
A,31,32,18,17
A,33,34,20,19

K,10000,IR,H,1027
K,10001,-IR,H,1027
K,10002,IR,H+100,1027
K,10003,-IR,H+100,1027

A,28,4,20,16
A,10001,16,20,10000
A,10000,10001,10003,10002
!ELEMENT TYPE
```

```
ET,1,SHELL99,,0,0,0,1,3
KEYOPT,1,11,2

ET,2,SHELL99,,0,0,0,1,3
KEYOPT,2,11,1
ET,3,SHELL99,,0,0,0,1,3
!REAL CONSTANT
t=1.25
R,1,12,0
RMORE,
RMORE,1,0,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,0,t
R,2,6,0
RMORE,
RMORE,1,0,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,0,t
R,3,1,0
RMORE,
RMORE,3,90,133.39
R,4,1,0
RMORE,
RMORE,4,90,152.66

!MATERIAL PROPERTIES
MP,EX,1,34125 !N/MM^2 (MPA)
MP,EY,1,6852 !N/MM^2 (MPA)
MP,EZ,1,6852
MP,GXY,1,3330 !N/MM^2 (MPA)
MP,GYZ,1,3330
MP,GXZ,1,3330
MP,PRXY,1,0.2865
MP,PRYZ,1,0.2865
MP,PRXZ,1,0.2865
MP,DENS,1,2.005E-9 !ton/MM^3

!MATERIAL PROPERTIES
MP,EX,2,34125 !N/MM^2 (MPA)
MP,EY,2,6852 !N/MM^2 (MPA)
MP,EZ,2,6852
MP,GXY,2,3330 !N/MM^2 (MPA)
MP,GYZ,2,3330
MP,GXZ,2,3330
```

```
MP,PRXY,2,0.2865
MP,PRYZ,2,0.2865
MP,PRXZ,2,0.2865
MP,DENS,2,2.005E-9 !ton/MM^3

MP,EX,3,200000 ! Young's Modulus
MP,PRXY,3,0.3 ! Poisson's ratio
MP,DENS,3,7.86e-9!ton/MM^3

!MASHING CONTROL
ESHAPE,2,0
LSEL,S,LOC,Y,H/2
LESIZE,ALL,,,40,1
LSEL,ALL
!
ESIZE,0,2
ASEL,S,AREA,,1,1,1 !INNER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,3,3,1 !INNER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,5,5,1 !INNER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,7,7,1 !INNER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,2,2,1 !INNER
AATT,2,2,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,4,4,1 !INNER
```

```
AATT,2,2,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,6,6,1 !INNER
AATT,2,2,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,8,8,1 !INNER
AATT,2,2,1
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,9,9,1 !OUTER
AATT,2,2,2
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,11,11,1 !OUTER
AATT,2,2,2
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,13,13,1 !OUTER
AATT,2,2,2
AMESH,ALL
ASEL,ALL
ESIZE,0,3
ASEL,S,AREA,,15,15,1 !OUTER
AATT,2,2,2
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,10,10,1 !OUTER
AATT,1,1,2
AMESH,ALL
ASEL,ALL
ESIZE,0,3
ASEL,S,AREA,,12,12,1 !OUTER
AATT,1,1,2
```

```
AMESH,ALL
ASEL,ALL
ESIZE,0,3
ASEL,S,AREA,,14,14,1 !OUTER
AATT,1,1,2
AMESH,ALL
ASEL,ALL
ESIZE,0,3
ASEL,S,AREA,,16,16,1 !OUTER
AATT,1,1,2
AMESH,ALL
ASEL,ALL
!
ESIZE,0,3
ASEL,S,AREA,,17,24,1 !STIFFENER
AATT,2,2,3
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,25,25,1 !Nacelle Mass part 1
AATT,3,3,1
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,26,26,1 !Nacelle Mass part 2
AATT,3,3,1
AMESH,ALL
ASEL,ALL

ESIZE,0,1
ASEL,S,AREA,,27,27,1 !Blade Mass
AATT,3,3,1
AMESH,ALL
ASEL,ALL

FINISH
/SOLU
/TITLE, MODAL ANALYSIS OF  8-CELL 24.39 M GFRP WIND TURBINE TOWER

ANTYPE,2                ! Modal analysis
MODOPT,SUBSP,10         ! Subspace, 10 modes
EQSLV,FRONT             ! Frontal solver
MXPAND,10               ! Expand 10 modes

!BOUNDARY CONDITIONS
```

```
NSEL,S,LOC,Y,0
D,ALL,UZ,0,0,,,UX,UY,ROTX,ROTY,ROTZ
NSEL,ALL

SAVE
SOLVE
FINISH

/POST1                         ! List solutions
SET,LIST

SET,FIRST
PLDISP                         ! Display first mode shape
```

# Appendix C4

ANSYS codes for the Eigen Buckling analysis of the proposed design section.

```
FINISH
/CLEAR

/PREP7
/PBC,F,,1
/PBC,U,,1
/NERR,5,50000000
/PNUM,KP,1
/PNUM,LINE,1
/PNUM,AREA,1
/VIEW,1,3500,6000,5000

FYY=-1

RB=650
RT=400
IR=300
H=24390

!GEOMETRY
K,1,0,0,0
K,2,0,H,0
K,3,IR,0,0
K,4,IR,H,0
K,5,RB,0,0
K,6,RT,H,0
L,3,4
L,5,6
AROTAT,2,,,,,,1,2,360,8
AROTAT,1,,,,,,1,2,360,8

A,3,4,6,5
A,21,22,8,7
A,23,24,10,9
A,25,26,12,11
A,27,28,14,13
A,29,30,16,15
A,31,32,18,17
A,33,34,20,19
!
!ELEMENT TYPE
ET,1,SHELL99,,0,0,0,1,3
KEYOPT,1,11,2
ET,2,SHELL99,,0,0,0,1,3
KEYOPT,2,11,1
ET,3,SHELL99,,0,0,0,1,3
```

```
!REAL CONSTANT
t=1.25

R,1,12,0
RMORE,
RMORE,1,0,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,0,t

R,2,6,0
RMORE,
RMORE,1,0,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,0,t

R,3,6,0
RMORE,
RMORE,1,0,t,1,90,t
RMORE,1,90,t,1,90,t
RMORE,1,90,t,1,0,t

!MATERIAL PROPERTIES
MP,EX,1,34125 !N/MM^2 (MPA)
MP,EY,1,6852 !N/MM^2 (MPA)
MP,EZ,1,6852
MP,GXY,1,3330 !N/MM^2 (MPA)
MP,GYZ,1,3330
MP,GXZ,1,3330
MP,PRXY,1,0.2865
MP,PRYZ,1,0.2865
MP,PRXZ,1,0.2865
MP,DENS,1,2.005E-9 !ton/MM^3

!MATERIAL PROPERTIES
MP,EX,2,34125 !N/MM^2 (MPA)
MP,EY,2,6852 !N/MM^2 (MPA)
MP,EZ,2,6852
MP,GXY,2,3330 !N/MM^2 (MPA)
MP,GYZ,2,3330
MP,GXZ,2,3330
MP,PRXY,2,0.2865
MP,PRYZ,2,0.2865
MP,PRXZ,2,0.2865
MP,DENS,2,2.005E-9 !ton/MM^3
```

```
!MASHING CONTROL

LSEL,S,LOC,Y,H/2
LESIZE,ALL,,,40,1
LSEL,ALL
!
ESIZE,0,2
ASEL,S,AREA,,1,1,1 !INNER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,3,3,1 !INNER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,5,5,1 !INNER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,7,7,1 !INNER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,2,2,1 !INNER
AATT,2,2,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,4,4,1 !INNER
AATT,2,2,1
AMESH,ALL
ASEL,ALL

ESIZE,0,2
ASEL,S,AREA,,6,6,1 !INNER
AATT,2,2,1
AMESH,ALL
ASEL,ALL
```

```
ESIZE,0,2
ASEL,S,AREA,,8,8,1 !INNER
AATT,2,2,1
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,9,9,1 !OUTER
AATT,2,2,2
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,11,11,1 !OUTER
AATT,2,2,2
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,13,13,1 !OUTER
AATT,2,2,2
AMESH,ALL
ASEL,ALL
ESIZE,0,3
ASEL,S,AREA,,15,15,1 !OUTER
AATT,2,2,2
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,10,10,1 !OUTER
AATT,1,1,2
AMESH,ALL
ASEL,ALL
ESIZE,0,3
ASEL,S,AREA,,12,12,1 !OUTER
AATT,1,1,2
AMESH,ALL
ASEL,ALL
ESIZE,0,3
ASEL,S,AREA,,14,14,1 !OUTER
AATT,1,1,2
AMESH,ALL
ASEL,ALL
ESIZE,0,3
ASEL,S,AREA,,16,16,1 !OUTER
```

```
AATT,1,1,2
AMESH,ALL
ASEL,ALL
!
ESIZE,0,3
ASEL,S,AREA,,17,24,1 !STIFFENER
AATT,2,3,3
AMESH,ALL
ASEL,ALL

FINISH
/SOLU                   ! Enter the solution mode


/TITLE, EIGENVALUE BUCKLING ANALYSIS OF 8-CELL 24.39 M GFRP WIND
TURBINE TOWER
ANTYPE,STATIC
PSTRES,ON
!BOUNDARY CONDITIONS
NSEL,S,LOC,Y,0
D,ALL,UZ,0,0,,,UX,UY,ROTX,ROTY,ROTZ
NSEL,ALL
NSEL,S,LOC,Y,H
*GET,Ncnt,NODE,0,COUNT
FYAV=FYY/Ncnt
F,ALL,FY,FYAV
NSEL,ALL

SOLVE
FINISH
/SOLU                         ! Enter the solution mode again to solve buckling
ANTYPE,BUCKLE                 ! Buckling analysis
BUCOPT,LANB,1                 ! Buckling options - subspace, one mode
SOLVE
FINISH

/SOLU                   ! Re-enter solution mode to expand info - necessary
EXPASS,ON               ! An expantion pass will be performed
MXPAND,1                ! Specifies the number of modes to expand
SOLVE
FINISH

/POST1                  ! Enter post-processor
SET,LIST                ! List eigenvalue solution - Time/Freq listing
                        ! force required for buckling (in N for this case).
SET,LAST                ! Read in data for the desired mode
PLDISP                  ! Plots the deflected shape
```

# Appendix C5

ANSYS codes for 24.3 m steel tower.

```
FINISH
/CLEAR
/PREP7
/PBC,F,,1
/PBC,U,,1
/NERR,5,50000000
/PNUM,KP,1
/PNUM,LINE,1
/PNUM,AREA,1
/VIEW,1,3500,6000,5000


!ROTOR LOADS
FYY=-6376.50!Fz N ROTOR DEAD LOAD
FZZ=-8522.68  !Fx N
MXX=1434.71e3 !My N.MM
MYY=5319e3!Mz N.MM
MZZ=0!Mx N.MM

!WIND LOAD
A1=     -3057.36
A2=     -3017.38
A3=     -3228.91
A4=     -3374.22
A5=     -3465.97
RB=310 !MM,BOTTOM RADIUS centre to centre
RT=290 !MM,TOP RADIUS  centre to centre
H=24390 !MM,HEIGHT OF THE TOWER
!GEOMETRY
K,1,0,0,0
K,2,0,H,0
K,3,RB,0,0
K,4,RT,H,0

L,3,4

AROTAT,1,,,,,,1,2,360,4
!ELEMENT TYPE
ET,1,93
!REAL CONSTANT
R,1,11.25,11.25,11.25,11.25
!MATERIAL PROPERTIES
MP,EX,1,200000 ! Young's Modulus
MP,PRXY,1,0.3 ! Poisson's ratio
```

```
MP,DENS,1,7.86e-9!ton/MM^3


!MASHING CONTROL
LSEL,S,LOC,Y,H/2
LESIZE,ALL,,,40,1
LSEL,ALL
ESIZE,0,3
ASEL,S,AREA,,1,1,1 !OUTER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,2,2,1 !OUTER
AATT,1,1,1
AMESH,ALL
ASEL,ALL

ESIZE,0,3
ASEL,S,AREA,,3,3,1 !OUTER
AATT,1,1,1
AMESH,ALL
ASEL,ALL
ESIZE,0,3
ASEL,S,AREA,,4,4,1 !OUTER
AATT,1,1,1
AMESH,ALL
ASEL,ALL
!ANALYSIS
/SOLU
/TITLE, DESIGN OF 8-CELL 24.39 M STEEL WIND TURBINE TOWER
ANTYPE,STATIC
NLGEOM,ON
AUTOTS,ON
SSTIF,ON
NSUBST,2,500,2,ON
NROPT,AUTO
NEQIT,20
CNVTOL,F,,0.001,,1
CNVTOL,M,,0.001,,1
CNVTOL,U,,0.04,,0
TIME,8000
!BOUNDARY CONDITIONS
NSEL,S,LOC,Y,0
D,ALL,UZ,0,0,,,UX,UY,ROTX,ROTY,ROTZ
NSEL,ALL
```

```
!=====================================================
!Applying Gravity
!=====================================================
ACEL,,9800
!=====================================================
!Applying wind load parallel to Z Direction between 0-5m
!=====================================================
ASEL,S,AREA,,3
ASEL,A,AREA,,4

NSLA,S,0
NSEL,R,LOC,Y,0,5000
*GET,NCOUNT,NODE,0,COUNT
F,ALL,FZ,A1/NCOUNT
!=====================================================
!Applying wind load parallel to Z Direction between 5-10m
!=====================================================
ASEL,S,AREA,,3
ASEL,A,AREA,,4
NSLA,S,0
NSEL,R,LOC,Y,5001,10000
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A2/Ncnt
!=====================================================
!Applying wind load parallel to Z Direction between 10-15m
!=====================================================
ASEL,S,AREA,,3
ASEL,A,AREA,,4
NSLA,S,0
NSEL,R,LOC,Y,10001,15000
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A3/Ncnt
!=====================================================
!Applying wind load parallel to Z Direction between 15-20m
!=====================================================
ASEL,S,AREA,,3
ASEL,A,AREA,,4
NSLA,S,0
NSEL,R,LOC,Y,15001,20000
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A4/Ncnt
!=====================================================
!Applying wind load parallel to Z Direction between 20-H m
!=====================================================
ASEL,S,AREA,,3
ASEL,A,AREA,,4
NSLA,S,0
```

```
NSEL,R,LOC,Y,20001,H
*GET,Ncnt,NODE,0,COUNT
F,ALL,FZ,A5/Ncnt

!Applying Rotor Load at the top of Tower
!=====================================================
NSEL,S,LOC,Y,H
*GET,Ncnt,NODE,0,COUNT
FYAV=FYY/Ncnt
F,ALL,FY,FYAV
NSEL,ALL
!
!MX IN TERM OF COUPLE MOMENT
FMX=MXX/(RT*2)

!MY IN TERM OF COUPLE MOMENT
FMY=MYY/(RT*4)

!MZ IN TERM OF COUPLE MOMENT
FMZ=MZZ/(RT*2)


KSEL,S,,,10
FK,ALL,FX,FMY
FK,ALL,FY,-FMX
FK,ALL,FZ,FZZ/2
KSEL,ALL

KSEL,S,,,6
FK,ALL,FX,-FMY
FK,ALL,FY,FMX
FK,ALL,FZ,FZZ/2
KSEL,ALL
KSEL,S,,,4
FK,ALL,FZ,FMY
FK,ALL,FY,-FMZ
KSEL,ALL
KSEL,S,,,8
FK,ALL,FZ,-FMY
FK,ALL,FY,FMZ
KSEL,ALL
LSWRITE,1
LSSOLVE,1
SAVE
FINISH
```