# Analysis of the Strength of Wind Turbine Towers Under Aerodynamic Loads

**Emmanuel Anios Fils Mompremier**
National Taiwan University (NTU)
E-mail: b06502138@ntu.edu.tw

## ABSTRACT

Wind turbines have been widely utilized over the last decades as the favorite mechanism to transform wind energy into electrical power. While the aerodynamic properties of the turbine rotor blades under all wind conditions are extensively studied, less enthusiasm is arguably shown for the structural analysis of the turbine towers. The wind turbine tower holds the wind turbine at the necessary elevation and supports all the loads that the wind turbine experiences. It also plays an important role in further reducing the cost of harvesting wind energy. As there are increasing demands for higher towers, making safe structure with reasonable cost and conducting tower optimization analyses have become a primary concern. In the present study, we use Finite Element Analysis to model 6 different types of wind turbine tower and assess their performance under a given set of loads. The finite element models of these 10m-tall towers are analyzed using ABAQUS. Comparison of the deformations, stresses and stability under rotor excitation indicates that the conical steel towers can achieve the best structural performance.

KEYWORDS: Wind Turbine, Tower, Aerodynamic Loads, Natural Frequency, Finite Element Analysis

## 1. INTRODUCTION

In our course of study as mechanical engineers, we seem arguably more concerned with the analysis of the aerodynamic parameters of a wind turbine. This can be asserted by the volume of studies that are available for the wind turbine rotor or blades compared to the wind turbine tower. However, one should not conclude that the towers are less important or less critical to the overall structure of the wind turbine. In fact, the tower makes up 26.3% of the total cost of a wind turbine (compared to 22.2 % for the rotor blades) (Fig 1.1). And an optimally designed tower can help reduce the cost of wind energy by placing the turbine at higher elevations where more wind can be captured [6]. In addition, wind energy becomes one of the fastest growing sector in the alternative sources of energy meaning that over all the continents, countries are racing to install and integrate wind turbines to their power grids. Thereby, these turbines become commonplace. The tower, being the main structure that supports the wind turbine and with an additional cost of US $15,000 on average to increase the height by 10 m [6], its damage or collapse may cause serious physical harm to bystanders and significant economic loss to the managing communities/companies. These elements suggest that engineers should look into the structural stability of the towers so that causes of plausible failures can be well understood and avoided. A recurrent type of tower failure is shown in Fig 1.2.

The primary objectives of this research is two-fold: 1) to understand the impact of aerodynamic loads on the wind turbine tower and 2) to compare the performance of several tower designs under a set of given loads.

## 2. LITERATURE REVIEW

Several researchers have dealt with the analysis of wind turbine towers using finite element analysis. More specifically, Ozdemir et al [3] have conducted a static analysis of cylinder towers with steel, concrete and hybrid materials. Lee et al [4] investigated a tower failure and compared the results from their numerical analysis to the actual collapse mode observed at the scene of accident. They found out the buckling limit load of the failed wind turbine tower and the wind speed at buckling point; their FEM model exhibited similar behavior as the actual situation at the acccident. Gwon [6] used Abaqus to perform static and dynamic analyses on 3 kW small wind turbine with a model created with beam, shell and inertia elements. Smith [7] studied wind turbine models under a variety of loads combinations and earthquake records to show that certain turbine models are more susceptible to the applied loads than others.

In this paper, cylindrical and conical towers made of steel, concrete and hybrid (steel + concrete) materials modeled using homogeneous solid in Abaqus and subjected to aerodynamic loads are analyzed and compared.

## 3. RESEARCH METHOD

To achieve the objectives set in the introduction, two wind turbine towers (cylindrical and conical) are designed using the commercial CAD software Solidworks. Each one of these designs is assigned three different sets of materials (steel, concrete, hybrid) while the loads applied to the towers remain constant in all instances.

Therefore, this study relies on 6 models (Fig 4.1) to conduct the finite element analysis using the commercial software ABAQUS. First, a static analysis with emphasis on the resultant stress on the overall tower and the deflection caused on the structure by the loads is conducted. Second, in order to assess the structural stability of the 6 towers under the wind turbine rotor's excitation forces, a natural frequency analysis is also performed.

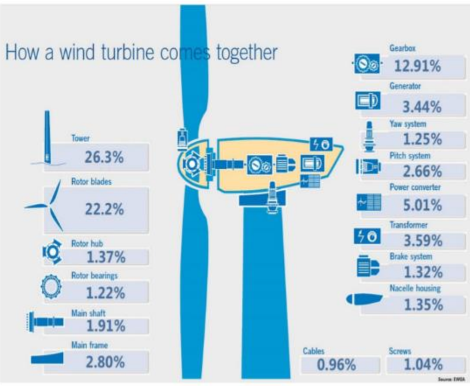


Fig 1.1 Wind Turbine Components and Costs [8]

Fig 1.2 Failure of a Wind Turbine Tower [9]

## 4. FINITE ELEMENT MODELS

A. Design Specifications

For convenience of design and simulation, this study considers a small 10-m high wind turbine tower. This small tower is first modeled as a cylindrical tubular tower i.e. with a uniform diameter and thickness throughout the length of the tower. The second design is of a conical tubular tower whose diameter and thickness decrease from bottom to top as we move along the tower. Table 4.1 shows the different design parameters.

In addition, each of these towers is partitioned into 4 sections to mimic the 4 sections that make up an actual wind turbine and also in order to be able to apply the desired material at the desired section along the length of the tower.

Table 4.1 Tower Design Parameters

| | |
|---|---|
| Height | 10 m |
| Tower Bottom Diameter | 450 m |
| Tower Head diameter (Cylindrical) | 450 mm |
| Tower Head Diameter (Conical) | 251.8 mm |
| Thickness | 5 mm |

B. Materials

Most of the wind turbine towers are manufactured from steel due to its advantages during manufacture, transport and erection of the turbine towers [1]. Steel can also be galvanized or painted to protect it from environmental damage such as corrosion. In this study, structural steel S355 whose mechanical properties are defined in Table 4.2 is used.

Additionally, in order to compare the performance of the towers with respect to the material used, the tower design described in Section 4.A are also analyzed with reinforced concrete C16/20 and a hybrid structure made of S355 and C16/20 is also considered. In the hybrid configuration, the lower 3 sections of the tower (starting from the bottom) are assigned reinforced concrete C16/20 whereas the uppermost section is assigned structural steel S355.

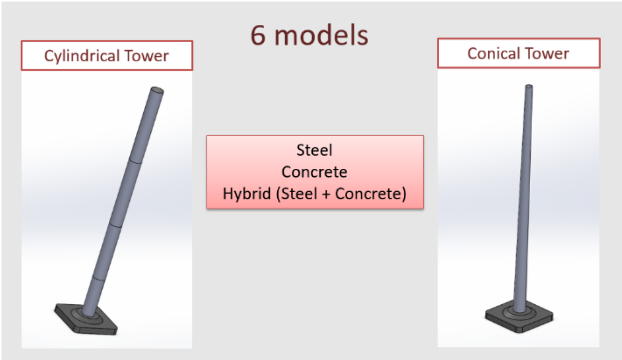


Fig 4.1 The 6 models analyzed in this study (2 shapes X 3 sets of materials)

Table 4.2 Materials Used for the Towers

| | Steel (S355) | Reinforced Concrete C16/20 |
|---|---|---|
| Density (kg / m$^3$) | 7850 | 2500 |
| Young's Modulus (GPa) | 210 | 29 |
| Poisson's Ratio | 0.3 | 0.18 |

C. Loads and Boundary Conditions

During operation, a combination of different types of loads is applied to relevant parts of a wind turbine. And the tower supports a significant portion of these loads. In the literature [2], these is consensus that the majority of the loads supported by the tower are induced by the rotor. In the analysis of wind turbine towers, the following types of loads are usually considered:

- Inertial and gravitational loads resulting from vibration, rotation, gravity and seismic activity.
- Aerodynamic loads which are caused by the airflow and its interaction with the stationary and moving parts of wind turbines.
- Operational loads, which result from the operation and control of wind turbines
- Other loads, such as wake loads, impact loads, ice loads.

In the present study, a pre-calculated set of loads for small wind turbines published by Ozdemir et al [3] is applied to the tower designs. This set includes the rotor weight, the turbine thrust, the wind load and the tower's own weight (Fig 4.2).

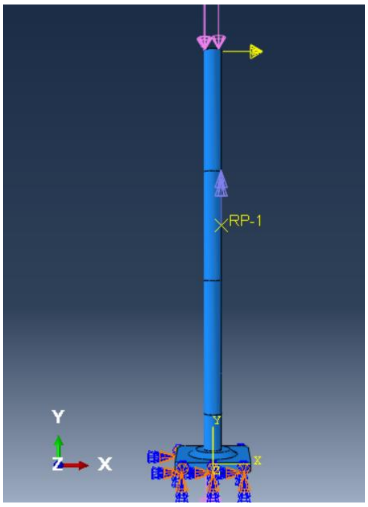


Fig 4.2 The loads and boundary conditions applied to all the 6 models

Rotor Weight

In Ozdemir et al's paper [3], the suggested rotor weight amounts to 2302.6 N; however, in our case it is more practical to apply this load as a pressure distributed on the tower head's surface area. Thus, the resulting pressure from the rotor weight is equal to 0.328 MPa for the cylindrical towers (tower head surface area of 0.007 m$^2$) and 0.592 MPa for the conical towers (surface area of 3.885x10$^{-3}$ m$^2$).

Turbine thrust

The thrust considered in [3] is equal to 12.890 kN. The thrust is the axial force applied by the wind on the rotor. It is dependent upon the rotational speed of the rotor, the average wind speed across the rotor plane, the turbulence intensity, the density of the air, and the aerodynamic shapes of the wind turbine components [2]. The thrust $F$ is found using the following equation:

$$F = \frac{1}{2}\rho C_T V^2 A \quad (1)$$

where $\rho$ stands for density of air, $C_T$ thrust coefficient, $V$ average wind speed and $A$ swept area of the blades.

In our models, the thrust is applied as a concentrated load on the uppermost edge of the tower head in the positive x-direction. This is because this direction is taken as the prevailing wind direction (Fig 4.2).

Wind Load

As the wind is blowing and passing by the tower, it applies a load on the outer surface area of the tower. This load is modeled as a moment of magnitude 2909.64 N/m [3] and with direction perpendicular to the thrust applied in the +x direction, i.e. the wind load is defined as a moment with a +y direction.

In Abaqus, a reference point (RP-1) is defined on the outer surface of the tower at half its height and coupled with the entire surface area of the tower. The moment that represents the wind load is subsequently applied on that reference point (Fig 4.2).

Tower's Own Weight

Since the suggested tower weight in [3] amounts to 456.16 N, in our case, we model this load as a pressure distributed on the bottom surface area of the towers (same bottom surface area for both cylindrical and conical towers). Thus, the resulting pressure from the tower weight is equal to -2868.93 Pa.

Boundary Conditions

In Abaqus, the tower foundation's boundary condition is created in the initial step with a type denoted as Symmetry/Antisymmetry/Encastre. This condition is appropriate because the foundation is expected to remain grounded to the soil during the operation of the wind turbine.

## 5. STATIC ANALYSIS

Static analysis is performed on the 6 models described earlier. The stress and deflection of the towers are calculated and reviewed.

### A. Mesh

To conduct the static analysis, a "Static,General" step was implemented in Abaqus. A very fine mesh was also applied on the tower structure, it served to ensure the accuracy of the results that will be obtained. The characteristics of the tower mesh are as follows:

Table 5.1 Tower Mesh Properties

| | |
|---|---|
| Approxiamte Global Size | 50 |
| Number of Elements | 36752 |
| Element Shape | Tet |
| Element Type | C3D10 |

Because in this study, the foundation is not of significant interest, much effort was not spent to validate its structure and calibrate its mesh. This has the advantage of speeding up the simulation process with little impact on the tower structure simulation.

### B. Modeling Assumptions

The following list sums up the assumtions made for the finite element analyses in this study:

1. Linear elastic analysis – the structure response is assumed to be linear and elastic, materials will reman in the elastic region and applied loads remain constant in direction and magnitude.
2. The wind turbine towers are modeled as uniform structures partitioned into 4 sections (Fig 4.1 and 4.2).
3. The ground is assumed to be rigid.

### C. Stress and Deflection Analyses

During the simulation in Abaqus, all the loads on the tower are kept identical to those described in Section 4.C i.e. rotor weight, turbine thrust, wind load and tower's own weight.

As shown in Fig 5.2, the maximum stress on the cylindrical steel tower was found to be 0.221 MPa and located on the tower head region. The corresponding maximum deflection was about 0.083 mm (Fig 5.3). The overall length of the tower is 10m, so the deflection is small, accounting for 0.00083% of the overall tower length.

The subsequent figures (Fig 5.2 to 5.5) show the stress distribution and deflection for additional towers among the 6 models analyzed in this study.

Table 5.2 Summary of Max Stress and Deflection on all the 6 Tower models

| Tower Type | | Maximum Stress (MPa) | Maximum Deflection (mm) |
|---|---|---|---|
| Cylindrical | Steel | 0.221 | 0.083 |
| | Concrete | 0.225 | 0.113 |
| | Hybrid | 0.221 | 0.104 |
| Conical | Steel | 0.532 | 0.097 |
| | Concrete | 0.721 | 0.210 |
| | Hybrid | 0.532 | 0.130 |

Table 5.2 shows that in both cylindrical and conical tower types, the concrete towers stood out as those experiencing the maximum stresses (0.225MPa and 0.721MPa, respectively) and the maximum deflections (0.113 mm and 0.210 mm, respectively). On the other hand, cylindrical steel and conical steel towers have proven to be the least deflected by the loads with a maximum deflection of 0.083 mm and 0.097mm, respectively.

Consequently, based on these results, better performance is obtained for our 10-m tall wind turbine tower with steel material, hybrid material and concrete (in that order) (Fig 5.1).


Fig 5.1 Overall Performance of the towers with respect to materials used

## 6. DOMINANT FORCE ON THE TOWER

The static analysis described earlier provides a comparison of the behavior of the 6 models under the given loads with respect to the tower types and the materials used. However, there is another important question that remains unanswered. Observation of the deflection distribution of the towers highlights the fact that the regions most at risk in the tower structure are mainly the tower head or the uppermost section of the towers. This observation contrasts with the majority of the tower failures that occur in real life (Fig 1.2). In order to shed light on this discrepancy, it is important that we determine the dominant force that is the most likely to cause large deflections or even failure of the towers.

Among the loads applied to the tower, the rotor thrust appears to be the largest in magnitude by far (Section 4.C). And since it is applied on the tower head, it can be deduced that the thrust is largely responsible for the maximum stresses and deflections located at the tower head (Table 5.2). Additionally, inspection of its formula (1) reveals that the thrust $F$ is proportional to the square of the wind speed (while the other parameters involved in the calculation can be considered roughly constant over the lifetime of a wind turbine). This means that if the rotor rotates at an excessive speed, a thrust beyond the limit load of the tower can be generated and buckling will result.

According to Lee et al [4], buckling of a column occurs when its length is greater than its cross-sectional dimension and the column is under a compressive load. Any force greater than the critical load will result in an elastic collapse of the material. It can be readily shown that our 6 models fall under that category (L>>D and tower subjected to compressive loads), yet we do not observe any signs of buckling at any sections of the towers.

This can be explained by pointing out that in the Modeling Assumptions (Section 5.B-2), the towers are modeled as a continuous uniform structure partitioned in Abaqus in order to apply different materials to the different sections. In contrast, the tower sections in real life have bolted connections which should be checked for shear, bearing and tension on net sections [5]. In other words, for a thrust out of bounds, the tower models in this study will deflect as a single structure whereas in reality the deflections will be exacerbated at the joints linking the sections of the tower. It is, thus, very likely that buckling be observed in real life turbine towers and less likely in the models considered in this study.

To prevent the rotor thrust to exceed the limit load of the tower and cause failure, the wind turbine manufacturers integrate rotor speed control with cut-out speed i.e. speed at which the turbine shuts down to avoid damage.

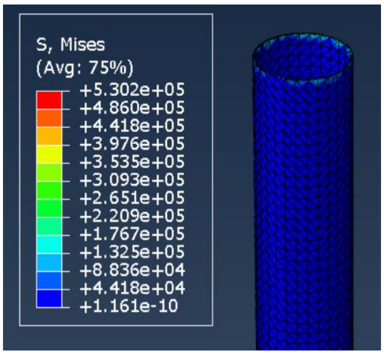


Fig 5.2 Stress Distribution of the Cylindrical Steel Tower

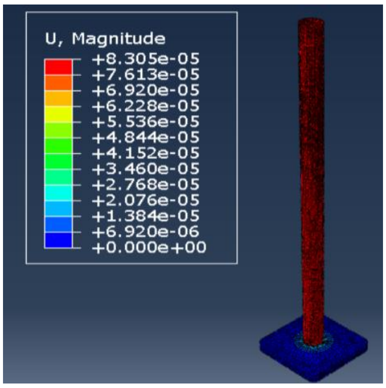


Fig 5.3 Deflection Distribution of the Cylindrical Steel Tower

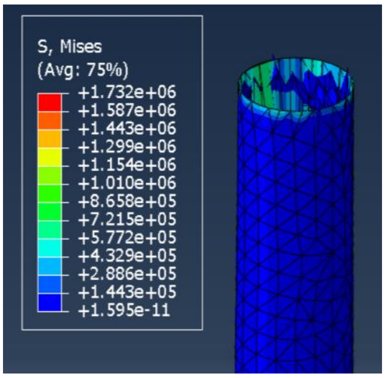


Fig 5.4 Stress Distribution of the Conical Concrete Tower

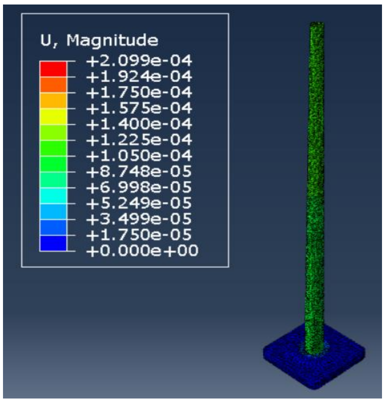


Fig 5.5 Deflection Distribution of the Conical Concrete Tower

## 7. DISCUSSIONS ON THE TOWER MATERIALS

From Table 5.2, it is clear that the steel towers performed better than the other materials considered in this study. In fact, as of today, the majority of wind turbines are supported by conical steel towers. Even though the cylindrical steel towers display more strength among all the possible designs, manufacturers prioritize conical steel towers (Fig 7.1) because the latter helps save material (diameter of the tower decreases with the length), thus reducing manufacturing costs for an acceptable overall performance (in our simulation, the deflection observed on the conical steel tower is only 0.00014% higher that of the cylindrical steel tower, see Table 5.2).

Fig 7.1 Conical Tower Model

On the contrary, the concrete towers have shown the least strength among our models. It is worthwhile mentioning that concrete has excellent compressive strength, but is very brittle, and fractures easily under tension. Various sections along the height of the towers in our models exhibit tensile stresses in the y-direction (S22). That would help explain why deflection is more important in concrete than in steel.

Since the hybrid towers are made up of concrete (3/4) and steel (1/4), and based on the abovementioned discussions, it is understandable that the overall performance of the hybrid towers fall in between that of the steel and the concrete (Fig 7.2).

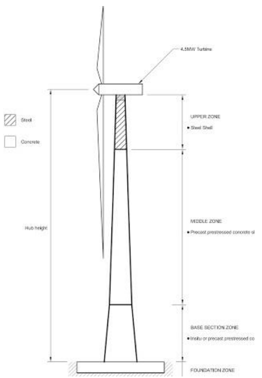


Fig 7.2 Cross-section of a hybrid tower

That being said, it may seem unlikely that other materials except than steel will ever be used in tower structures. However, constructing conical steel towers taller than 90 meters proves challenging mainly because as the tower gets taller the base diameter of the tower should be increased such that as it decreases along the height, the resulting diameter at the tower head remain large enough to prevent failure of the tower. But the maximum thickness of a cylindrical steel structure that can be manufactured today is limited to 40 mm. That is, if a thickness beyond 40 mm is needed, steel cannot be used. On the other hand, hybrid (concrete and steel) towers have shown improved performance over standard tubular steel at tower heights of 120 meters and above.

Another challenge faced by the steel towers is related to the transportation. These massive structures can reach an outer diameter of 4m which make their transportation across streets in the cities as we know them very difficult. To palliate this concern, concrete is being considered since it allows for precast sections to be assembled on site, thus avoiding the challenges steel faces during transportation.

Even though steel is unquestionably the best material for application in wind turbine towers, given some constraints related to steel tower thickness, outer diameter and transportation, concrete or hybrid towers may rise as viable alternatives.

## 8. NATURAL FREQUENCY ANALYSIS

To assess the structural stability of the tower models analyzed in this study, beside the static analysis, a natural frequency analysis is conducted.

A. Theoretical Considerations

According to [2], to keep the vibrational behavior of a wind turbine under control, the stiffness and mass parameters of all its components must be carefully matched. The most important design requirement concerning vibrations of the turbine as a whole is to prevent the exciting rotor forces from resonating with the natural tower bending frequencies.

The critical source of the turbine rotor's exciting forces is the aerodynamic imbalances that result from the asymmetrical air flow against the rotor. It is critical since it cannot be avoided nor can it be minimized through precise manufacturing [2].

The dynamic characteristics of the towers include their natural frequency $f_n$ and their relationship with excitation frequencies: the rotor frequency $f_{rotor}$ - It is the first frequency of excitation and usually called 1P [2] - and the blade passing frequency $f_{bp}$ - higher harmonics that appear for multi-blade turbines, in the case of this study 3P.

A tower should be designed so that $f_n$ does not coincide with $f_{rotor}$ nor $f_{bp}$ in order to prevent premature fatigue damage or catastrophic failure of the tower. Designation soft-soft, soft or stiff tower corresponds to the position of the tower's first natural frequency relative to $f_{rotor}$ and $f_{bp}$.

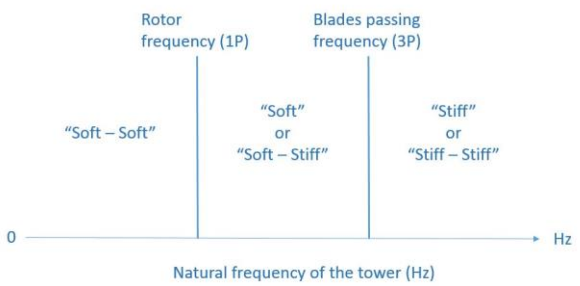


Fig 8.1 Tower Category Depending on Its Natural Frequency $f_n$ [1]

Stiff towers (towers whose first natural frequency is higher than the rotor frequency and the blades passing frequency) are desirable. This is because during their lifetime they will not be affected neither by the excitation of the rotor nor the blades of the tower. These towers also tend to radiate less sound. However, they may not be cost-effective to build since a bigger mass (more material/more stiffness) is needed to achieve the outcome mentioned.

This cost factor explains that stiff towers are only possible in short steel towers [2] and that most large turbines have soft or soft-soft towers.

B. Results

In this study, the turbine's design rotating speed is around 31.4 rpm which corresponds to the rotor frequency $f_{rotor}$ (1P) of 0.52 Hz and the blades passing frequency $f_{bp}$ (3P) of 1.57 Hz. In the case of the conical steel tower, the 1$^{st}$ mode of the tower is 0.016 Hz which is less than the rotor frequency. Therefore, this tower is categorized as a soft-soft tower, which indicates that it is a relatively light tower susceptible to larger head deflections.

$f_{rotor}$ lies between the 3$^{nd}$ and 4$^{rd}$ mode of the tower natural frequency, avoiding excitation of the tower's natural mode of vibration during the normal operation. Also, the blade passing frequency $f_{bp}$ (1.57 Hz) lies between 6$^{th}$ and 7$^{th}$ mode of vibration. It avoids the excitation during the normal operation; however, the tower may be temporarily excited as the turbine starts up or shuts down.

| Index | Description |
|---|---|
| 0 | Increment 0: Base State |
| 1 | Mode 1: Value = 1.07801E-02 Freq = 1.65246E-02 (cycles/time) |
| 2 | Mode 2: Value = 1.08275E-02 Freq = 1.65609E-02 (cycles/time) |
| 3 | Mode 3: Value = 8.0646 Freq = 0.45197 (cycles/time) |
| 4 | Mode 4: Value = 11.687 Freq = 0.54409 (cycles/time) |
| 5 | Mode 5: Value = 16.180 Freq = 0.64020 (cycles/time) |
| 6 | Mode 6: Value = 16.217 Freq = 0.64092 (cycles/time) |
| 7 | Mode 7: Value = 165.64 Freq = 2.0483 (cycles/time) |
| 8 | Mode 8: Value = 165.73 Freq = 2.0489 (cycles/time) |
| 9 | Mode 9: Value = 168.29 Freq = 2.0647 (cycles/time) |
| 10 | Mode 10: Value = 180.68 Freq = 2.1393 (cycles/time) |

Fig 8.2 Natural Frequencies of Conical Steel Tower

The first and second mode shapes are very similar to the buckling mode of the wind turbine tower (Fig 8.3 and 8.40). This fact indicates that if the rotor freely rotates at its rated speed of 31.4 rpm (0.52Hz) without a controller, it surpasses the natural frequency, causing resonance of the dynamic response.

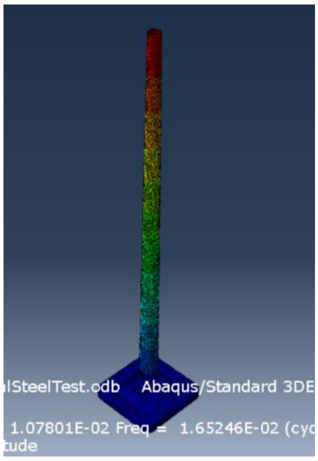


Fig 8.3 1$^{st}$ mode shape of conical steel tower (0.01652Hz)

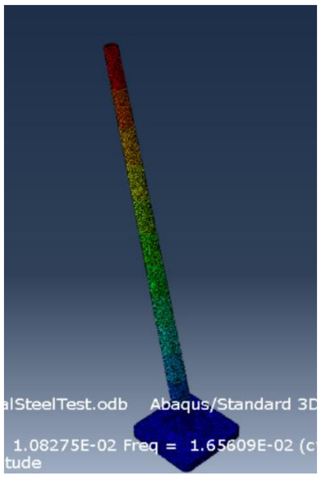


Fig 8.4 2$^{nd}$ mode shape of conical steel tower (0.01656Hz)

A similar analysis was conducted for each one of the 6 models analyzed in this study and the results are summarized in Table 8.1.

Table 8.1 indicates that all of our 6 models fall under the category "soft-soft tower". Soft-soft towers are relatively lighter than the other categories but experience larger tower head deflections. They are also likely to enter into resonance with the rotor at some point between start-up of the wind turbine and its nominal speed of operation.

Table 8.1 Category of all 6 tower models

| Tower Type | | 1st Mode Natural Frequency $f_n$ (Hz) | Category |
|---|---|---|---|
| Cylindrical | Steel | 0.032 | Soft-Soft |
| | Concrete | 0.050 | Soft-Soft |
| | Hybrid | 0.032 | Soft-Soft |
| Conical | Steel | 0.016 | Soft-Soft |
| | Concrete | 0.026 | Soft-Soft |
| | Hybrid | 0.019 | Soft-Soft |

## 9. LIMITATIONS AND FUTURE WORK

Over the course of this study, a number of simplifications have been made whether for convenience of computation and simulation or for allowing for a lighter design for the 6 models considered. These simplifications may, however, have some impacts on the concordance of our results with other studies.

- Our models are 10m-tall with a maximum diameter of 450 mm and a thickness of 5mm whereas actual wind turbine towers can reach more than 100m in height, 4m in diameter and 40mm of thickness. At this point, it is uncertain whether, the results found in the present study can be extrapolated to large turbines.
- The loads used in this study were pre-calculated by Ozdemir et al [3] without evidence of experimental measurements, and the author of the present study has not taken the extra step of verifying these results. As the loads constitute a critical parameter in the analyses conducted in the present paper, inaccuracies in the magnitude of the loads considered may greatly affect the results.
- Some studies point out the importance of analyzing the tower and the foundation together as the supporting structure of the wind turbine since they mutually impact each other. In the present study, the focus has been put only on the tower with little emphasis on the foundation i.e. little emphasis on its geometry, design parameters or mesh.

The author of this study expects to conduct additional analyses to complement the current results, address the limitations and corroborate the present results.

## 10. CONCLUSIONS

In light of the objectives set and the analyses conducted in this study, the following results can be reported:

(1) The rotor thrust is the dominant force on the tower; it creates the maximum stress and deflection at the tower head and may occasion buckling.
(2) From the six 10m-tall models analyzed in this study, the cylindrical steel tower performed better (in terms of stress, deflections, and stability under excitation), followed by the conical steel tower.
(3) All 6 models are categorized as soft-soft towers which suggests that they are likely to enter into resonance with the rotor at some point between start-up of the wind turbine and its nominal speed of operation.
(4) For 100+m-tall towers, it is the cost and performance needed that dictate the design materials and tower shapes. Even though cylindrical steel towers might reach the best performance, however limitations due to maximum thickness of steel structure and transportation might call for other types of towers such as conical shape or concrete/hybrid towers.

## 11. REFERENCES

[1] Wind farms construction
https://www.windfarmbop.com/type-of-towers-stiff-soft-or-soft-soft/

[2] High-strength steel tower for wind turbines (Histwin_Plus), Veljkovic, 2015
http://www.winercost.com/cost_files/HISTWIN_Plus_Report.pdf

[3] Static analysis of different type of wind turbine towers, Ozdemir et al, 2017

[4] A study on the prediction of lateral buckling load for wind turbine tower structures, Lee et al, 2012

[5] Modeling of bolted connections in tower
http://www.powline.com/products/tow_bolt.html

[6] Structural analyses of wind turbine tower for 3 kw horizontal-axis wind turbine, Gwon, 2011

[7] Evaluation of wind turbine towers under the simultaneous application of seismic, operation and wind loads, Smith, 2013

[8] Tower design and analysis for a small wind turbine, Karmouche, 2016

[9] The truth about the great wind power fraud
https://stopthesethings.com/2019/06/12/top-secret-turmoil-wind-industry-covering-up-catastrophic-300-tonne-wind-turbine-collapses/