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Design Framework for Comparing Wind Turbine Tower Erection Methods

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Project LDA-1405

DESIGN FRAMEWORK FOR COMPARING WIND TURBINE TOWER ERECTION METHODS

A Major Qualifying Project Report
Submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
Degree of Bachelor of Science
in Civil Engineering
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Abstract

Costs associated with turbine towers can account for more than half of the total project cost. The goal of this project was to compare two erection methods (crane and tilt-up) by analyzing stresses on the tower during construction and operation. An *Excel* spreadsheet was created to perform design calculations, considering stresses in the tower wall. These analyses were applied to existing turbine towers in Princeton, MA, and alternative tower designs. Cost estimates were prepared, and results were compared in $/kW.

Acknowledgements

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Authorship

This Major Qualifying Project was edited and authorized by all members of the project team. The table below displays the group member(s) primarily responsible for each section.

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Background	All
Methodology	All
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Baseline Results: Dynamic Loading Analysis	Melissa Samaroo
Baseline Results: Combined Stresses Analysis	Siena Mamayek
Baseline Results: Buckling Analysis	Dana Wolkiewicz
Baseline Results: Tilt-Up Analysis	Siena Mamayek
Baseline Results: Economic Analysis	Holly Ganser
Alternative Results: Tilt-Up Analysis	Holly Ganser
Alternative Results: Operational Analysis	Siena Mamayek
Decision Tool Instructions	Melissa Samaroo
Conclusion/Discussion	Melissa Samaroo, Siena Mamayek
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Capstone Design Statement

The Accreditation Board for Engineering and Technology (ABET) has set standards that each engineering student must reach to be prepared for engineering practice. Students demonstrate this through a Capstone Design Experience. The Capstone Design Experience must include a majority of the following considerations: economic, environmental, sustainability, manufacturability, ethical, health and safety, social and political. This Major Qualifying Project fulfilled the ABET standards by including the considerations listed below.

Economic

A cost analysis of tower designs and construction methods determined the feasibility of each of the different methods. The cost analysis examined factors such as construction costs, time of construction and a comparison of price per kilowatt. The final conclusion of the project depended heavily on this economic analysis.

Environmental and Sustainability

Wind turbines are increasing in popularity because of their low environmental impact during construction and operation. Harnessing wind power is beneficial to the environment because it does not produce carbon emissions, thus leaving no carbon footprint. Wind turbine projects require relatively low amounts of land, therefore the remainder of the land may be used for other uses. This project sought to find a more cost effective method to erect a wind turbine tower. If a less expensive method is found, it is possible to construct more wind turbines and lessen the dependence on fossil fuels.

Manufacturability

The major focus of this project was a comparison of two erection processes for wind turbine towers: crane and tilt-up. A smaller tower design requires less steel, therefore is more cost effective and reduces the time of construction. The tilt-up erection method required a smaller tower design, which included thinner walls and less steel, that was analyzed to determine associated costs. The conclusion of this project provided recommendations on which erection process would be appropriate.

Ethical

This project followed the code of ethics for engineers in order to ensure that the designs are held to the highest degree of honesty and integrity. Safety and reliability for the construction of the turbine tower will not be compromised at the expense of an optimized erection method.

Health and Safety

Each tower was designed to withstand the maximum wind speeds with a factor of safety. The tower was taken through a series of checks to ensure the tower can withstand the stresses exerted on it without falling or endangering the surrounding environment.

Social

Renewable energy, specifically from wind turbines, is becoming a more socially acceptable source of power. However, some cases experience a low return on investment. Slow payback rates discourage the community because they are not reaping the benefits as quickly as anticipated. By optimizing the construction process, this project aimed to lower startup costs which would allow for a faster payback period.

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1.0 Introduction

In the United States, the majority of our power comes from fossil fuels such as coal and oil. This source of energy is not renewable and will eventually run out. Mining these fuels also causes significant damage to the environment. Therefore many people are searching for alternative means to produce power. One alternative power source is renewable energy.

Renewable energy is a continually replenished source of energy and has a significantly lower environmental impact than fossil fuels. Many state governments have implemented renewable energy initiatives into their state plans. For example, Alaska State Legislature has adopted a goal to have 50% of its energy production come from renewable sources by 2025 (Parnell, 2012). As seen by Figure 1, these initiatives have resulted in an increase in U.S. renewable energy consumption over the last 10 years, and officials have projected that the increase will continue.

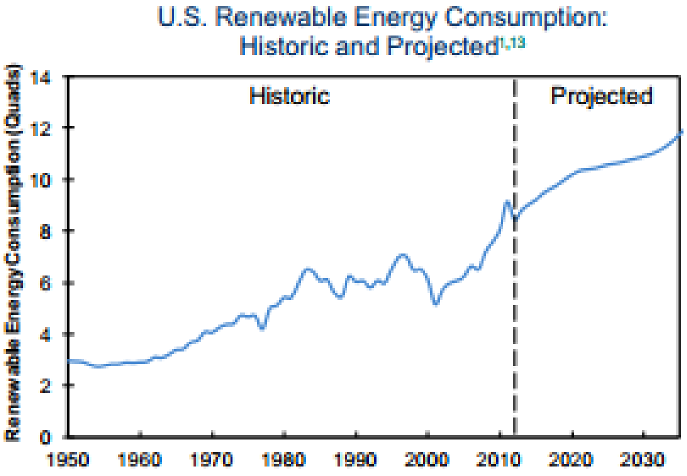


Figure 1: U.S Renewable Energy Consumption. ("U.S. Renewable Energy," 2013).

Wind energy is a renewable energy source that is growing in popularity throughout the United States. At the end of 2012, there were 45,100 wind turbines operating throughout the country (AWEA, 2013). In 2006, the Department of Energy and American Wind Energy Association set the goal to produce 20% of America's electricity with wind power by 2030. If the country maintains developing projects at this rate, this goal will be attainable.

There are many obvious advantages to developing wind energy projects, such as generating clean renewable electricity. There is a strong wind resource across the entire country that makes wind projects feasible at almost every location. However, according to a study performed by the U.S. Department of Energy, 10-25% of the proposed wind projects are never built because of environmental concerns (Jodziewicz, Ram, Walker, & Walker, 2008). Many of these concerns surround the construction process of wind turbines and the infrastructure required to transport the equipment to the site. For example, some wind projects require special cranes that are larger than normal. These cranes may require special access roads and additional open space for assembly, which increases the environmental footprint of the entire project.

These cranes also pose another problem to the construction of wind turbine projects. Due to their large size, there are additional limitations as to when the crane can operate. Weather conditions are one of these limitations; if it is too windy, the crane cannot be used and the progress of the project is negatively impacted. These cranes are expensive to rent and the project will lose money if they are not used in a timely manner.

The goal of this project is to provide a framework of comparison between two erection methods, the crane and tilt up methods, to further promote wind turbines as a renewable energy source. This report will present research that provides a baseline understanding of the elements that contribute to a wind turbine project and a methodology for how the design and analysis calculations were completed. This report also includes chapters outlining the Princeton, Massachusetts wind turbine project that was used as a case study. The chapters following discuss the design and cost estimation for an alternative tower erection method. The conclusion chapter presents key findings and recommendations of future work related to the project.

2.0 Background

As the surface of the earth heats up, wind is created. The sun heats areas of land and the air above it. The warmer, fast-moving air particles exert more pressure and thus less air is needed to maintain a constant air pressure. Air with a low density rises while colder, more dense air rushes to fill in the empty spaces; creating wind (Layton, 2006). It is typically more windy in the afternoon and early evening after the sun has warmed the air all day than it is in the morning when the sun has been down for several hours. The moving air particles contain energy and when an object is placed in the path of wind, energy will be transferred and the objects will move.

The modern day wind turbine evolved from earlier windmills used to process grain. Early windmills generally had a set of four blades rotating about a horizontal axis, attached to a post, which held all of the milling equipment. The entire system could be rotated to face the blades in the correct wind orientation (Shepherd, 2008). In the 1880s, Denmark and the United States began experimenting with different methods to generate electricity using windmill technology. By the 1930s, wind turbines were generating electricity for farms that were a long distance from the main power system. The development of electricity systems and power grids saw a decline in wind turbine use, but the fuel shortage scare in the 1970s caused Americans to seek alternative energy sources (Layton, 2006). At the end of 2012, there were 60,000 wind turbines installed in the United States, which could power 15 million residential buildings (DOER). Figure 2 shows the total energy consumption in the United States in 2013 by source as well as a further percentage breakdown of renewable energy source consumption.

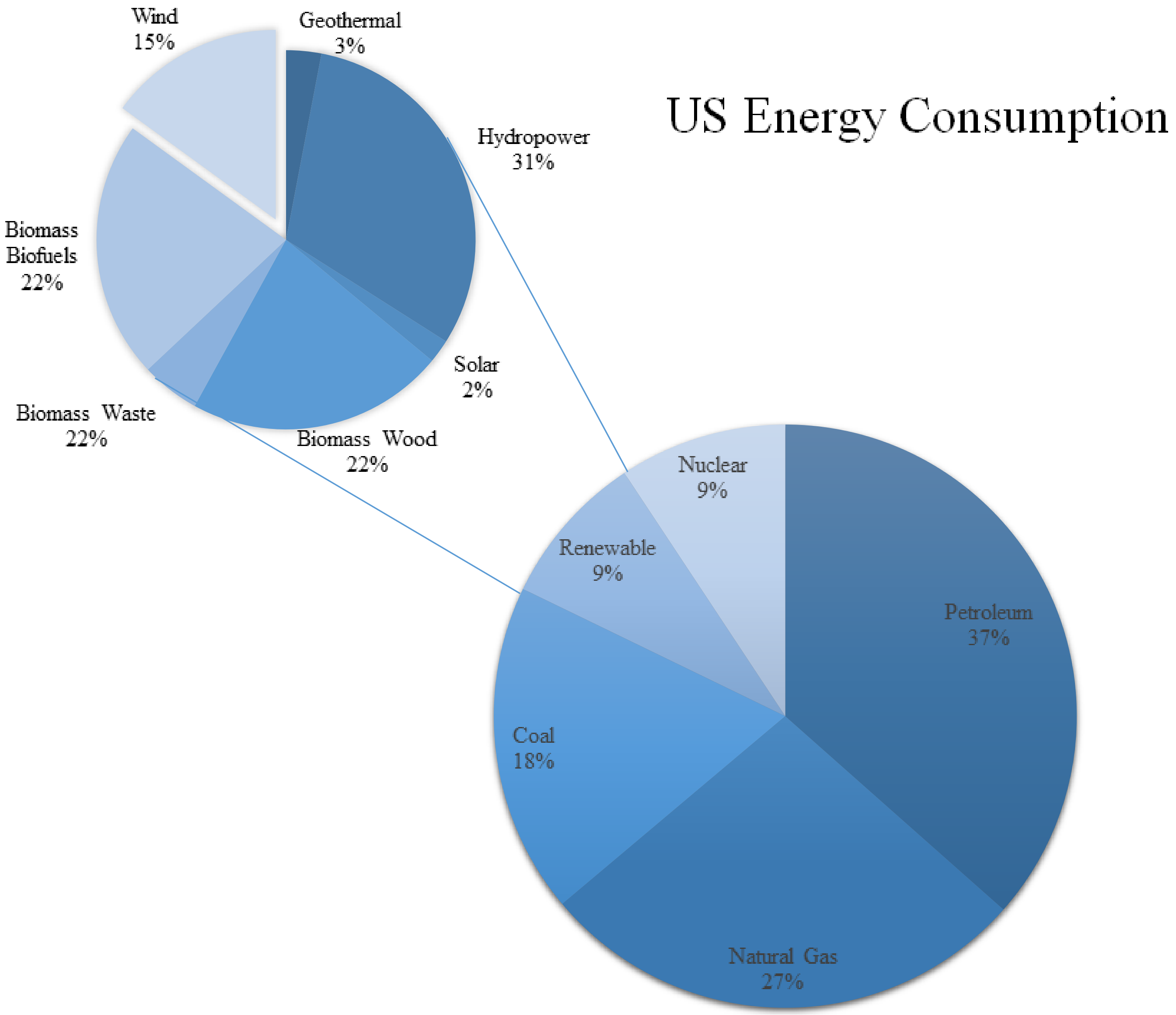


Figure 2: U.S. Energy Consumption by Source. (EIA, 2013b).

As of 2013, wind power accounts for only 1.86% of total electric energy and 15% of renewable energy in the United States. However, future growth projections show that wind energy will account for 23% of energy produced in the United States by 2040 (EIA, 2013a).

In order to develop a baseline understanding of the elements that contribute to a wind turbine project, each aspect of the project must be investigated. The following sections outline the background information necessary for understanding and completing the analysis of a wind turbine tower construction project. Design requirements and alternative erection methods for wind turbine towers are discussed, as well as the economics of the construction process.

2.1 Stages of Wind Turbine Projects

The following process described below and seen in Figure 3 lists the major tasks performed during each stage of a publicly owned wind turbine project. Privately owned wind turbines may omit some of the steps listed in Figure 3 because they do not have as many regulations or the coordination requirements with various project stakeholders that are necessary for public projects. For the purpose of this project, the focus will remain on publicly owned wind turbine projects.

SITE SELECTION
- Analyze Market
- Primary Wind Assessment
- Interconnection & Transmission Assessment
- Market Assessment
- Landowner Assessment/Meetings
- Grid Capacity
- Construction Issues

INITIAL DEVELOPMENT
- Interconnection Application
- Environmental Studies & Analysis
- Land Easements
- Permit Applications
- Preliminary Design/Layout
- Title Searches

FINAL DEVELOPMENT
- Interconnection Agreement
- Permit Approvals
- Final Design/Layout
- Landowner Coordination
- Construction Contracts
- Due Diligence
- Turbine Selection

CONSTRUCTION
- Project Management (includes hiring approx. 60-80 locals)
- Review Construction Plan with the Public
- Landowner Coordination
- Performance Tests
- Road Repairs
- Site Restoration and Clean-up

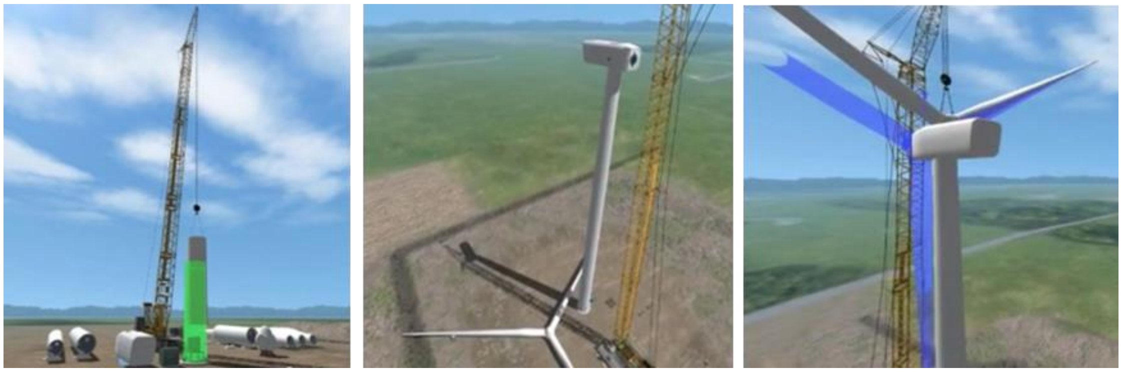
OPERATION
- Hire Staff (workers to operate & maintain the wind farm)
- Optimize Performance
- Ongoing Service & Maintenance
- Ongoing Wind Assessment

Figure 3: Stages of Wind Turbine Project Development. (EverPower Wind Holdings, 2013).

A successful project will engage the municipality early in the planning process and maintain open dialogues throughout the project stages. Next, engineers and scientist will assess wind conditions for up to a year to ensure the quality of the site and to estimate the amount of energy the project will generate (EverPower Wind Holdings, 2013). This data allows experts to determine the site's wind resource level. The wind resource levels range from 1 to 7, with 7 being the best wind resource. The wind resource combined with an assessment of the wind turbulence and extreme wind conditions allow experts to determine if a site is suitable for a wind turbine. Once this has been determined, engineers design to consider topography, turbine performance and sound levels. More detailed site plans for construction documents will include the exact location of the turbine, access roads, foundation and connection to the grid.

During these early stages, an environmental impact study is also performed to resolve design issues which would negatively impact the landscape, plants and wildlife, as well as soil and water conditions. Land negotiations between the developer and landowner also happen relatively early in the planning process. Most often landowners sign long-term lease agreements and are compensated by the developer. As the project progresses, public consultation and permitting is needed. It is important to hear the local community's feedback and ensure their support. The developer must also perform financial feasibility analyses on the turbine not only to predict the cost of construction of a large design but also to estimate the income and return on investment.

Once final designs are approved from engineers, the turbine parts are manufactured. The following narrative describes the process of wind turbine projects as seen in the film created by Jay Groccia for the Princeton Municipal Light Department (Groccia, 2010). Turbine parts are pre-assembled into the main components and shipped to the project site. During the fabrication, the construction company hired for the site work builds the access roads, excavates the foundation and places the concrete. After the turbine components have arrived on site, the crane is assembled and the erection process begins. The first tower section is secured to the foundation, with each subsequent tower section being hoisted and connected to the previous section (Figure 4a). After the tower is fully erect, the nacelle is hoisted and connected to the topmost tower section. The blades and hub are assembled on the ground (Figure 4b), lifted up and positioned at the front of the nacelle (Figure 4c). Both mechanical and electrical components are tested by a commissioning agency before operational start up and full connection to the substation. Following approval, the turbine can start producing energy and deliver electricity to the grid. Throughout the life cycle of the turbine, operation and maintenance is needed to monitor the performance, perform preventative repairs and oversee environmental impacts.



(a) (b) (c)

Figure 4: Assembly of a Wind Turbine. (Vortex, 2012).

2.2 Anatomy of Wind Turbines

There are two main designs for wind turbines; vertical axis wind turbines and horizontal axis wind turbines. Vertical Axis Wind Turbines (VAWTs) are designed with a vertical shaft stemming from the gear box with blades anchored to the top and bottom of the shaft (Figure 5). The greatest advantage of VAWTs is the mechanical component; the generator and gearbox can be installed at the base of the tower. The shaft structure does not have to account for the dead load of these components, and they are easily accessible for service and maintenance. A disadvantage to these systems is the lack of a stable tower structure: the system relies on guy wires for support, which limits the maximum elevation of the rotor. With a lower elevation, the rotor is unable to reach optimal wind speeds and hence operates at a lower efficiency. VAWTs are ideal for small scale application, such as residential or private uses (Jha, 2011).

Horizontal Axis Wind Turbines (HAWTs) are the most commonly used design in the wind power industry. HAWTs are primarily designed upwind to allow wind to pass through the rotor blades at a 90-degree angle allowing the system to rotate to align with the wind (Figure 6). These systems are capable of reaching higher elevations and their power output is directly proportional to the tower height. Larger turbines operate efficiently in winds around 33 miles per hour. The power output for common utility scale wind turbines ranges from 700KW to 1.8MW (Layton, 2006). The advantage of HAWTs is that these systems are capable of automatically adjusting to the wind direction (Jha, 2011). Because the horizontal axis wind turbine is the most commonly used design in the commercial industry, this project focuses solely on this design. The following sections discuss the principal elements and their design considerations for a horizontal wind turbine.

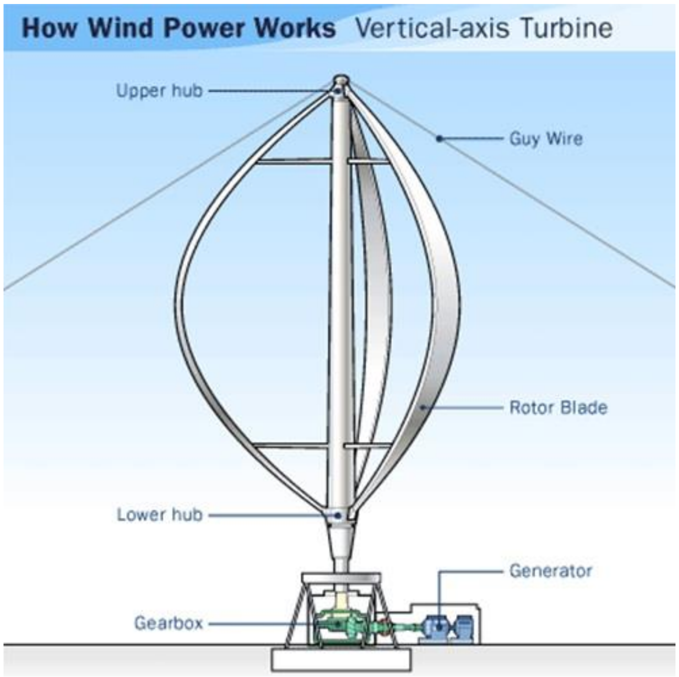


Figure 5: Vertical Axis Wind Turbine. (Layton, 2006).

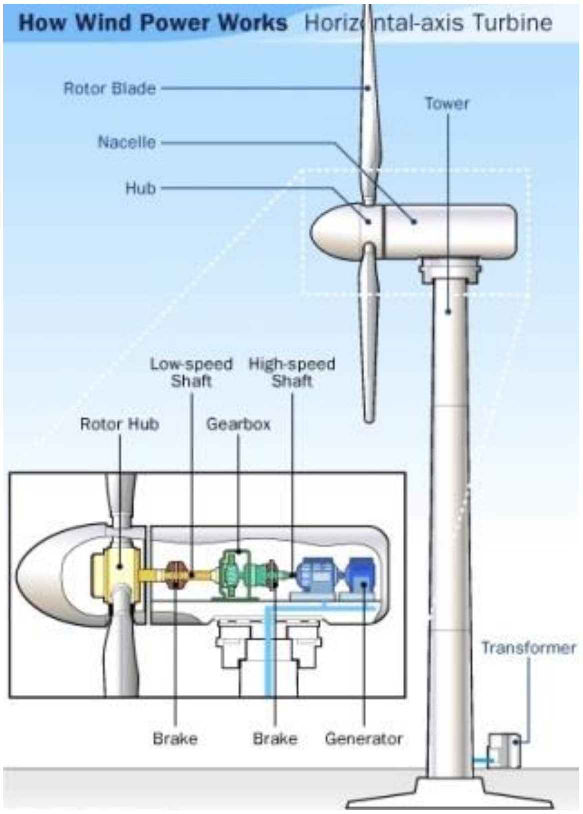


Figure 6: Horizontal Axis Wind Turbine. (Layton, 2006).

2.2.1 Foundation

The key design requirement for wind turbine foundations is the resistance to overturning forces. The foundation, typically a concrete footing, must provide adequate strength to resist extreme wind load conditions. Although there is no universal set of specified standards for the design of wind turbine foundations, certain design criteria must be addressed: stiffness, strength, stability, differential settlement, durability and the economic impact (Morgan, 2008).

2.2.2 Tower

The tower is the main support for the wind turbine. Typically the tower is made of tubular steel, prefabricated in a factory and transported to the site. Commercial turbine tower heights range from 65 feet to 450 feet (Windustry, 2012). The heights are mainly determined by surrounding geographical conditions such as soil type and terrain, as to provide adequate stability for the foundation. From a design perspective, factors to consider include the anticipated wind loading and desired power output. The tower must provide adequate stiffness as to not buckle from these incurred loads. This is typically done by manufacturing towers with thicker walls. However, thicker walls are more expensive resulting in an industrial push to make the walls as thin as possible without causing buckling. Also from a safety perspective, a tower should not be built within a radial distance of the tower height (plus a safety factor) to existing structures to avoid potential damage (Gipe, 2004). The following sections describe the standards and factors associated with the design of a turbine tower.

Standards for Tower Design

There are currently no American standards in place for the specific design of wind turbine towers. The American Society of Civil Engineers and the American Wind Energy Association developed the *Recommended Practice for Compliance of Large Land-based Wind Turbine Support* (2011). The purpose of this document is to:

> *"Enable those responsible for the permitting process to achieve consistency by clarifying the relevant and appropriate standards that have been used in the design process and should be applied when assessing structural capacity, and insure that wind turbine structures so permitted have an appropriate minimum level of protection against damage from hazards during the planned lifetime."*

According to the *Recommended Practice*, each wind turbine is designed and evaluated to uphold the international standards in place and must also satisfy the local requirements in the location of installation. The *Recommended Practice* is designed with the intention to be used alongside various standards that are referenced throughout the text. For each section of the turbine project (i.e. support structure, foundation, and external conditions) the *Recommended Practice* explains which of the standards or codes should be applied. For example, the external conditions a wind turbine tower experiences are outlined in IEC6400-1 and the design checks are explained in ASCE-7 (ASCE & SEI, 2013; IEC, 2008). The *Recommended Practice* aims to clarify any discrepancies between the local standards to generate one commonly used document to aid in the design of wind turbine projects.

Tower Design Factors

When designing a turbine tower, three basic assumptions can be made about the structure:

1. The tower acts as a cantilever beam that is made up of sections which have different but uniform cross-sectional properties;
2. The mass at the top of the tower (the nacelle/rotor unit) is assumed to be a dead load;
3. The cross section of the tower is assumed to be thin-walled and circular (Negm & Maalawi, 2000).

The loads and stresses acting on the turbine tower are described below and must also be considered in the design.

Loading

According to the IEC (2008), loads that shall be considered in the design calculations are: gravitational and inertial loads, aerodynamic loads, actuation loads and other loads such as wake loads, impact loads, ice loads, etc. These loads lend themselves to local buckling and flexural stresses. Because the loads and stresses associated with the turbine tower are dynamic, they must be dealt with as a combined loading problem (Savilonis, personal communication, 2013).

The IEC standards (2008) set in place explain that the design load cases shall be calculated by combining:

- Normal design situations and appropriate normal or extreme external conditions;
- Fault design situations and appropriate external conditions;

- Transportation, installation and maintenance design situations and appropriate external conditions.

The IEC uses these design load cases to verify the structural integrity of the wind turbine by designing loads for worst case scenarios.

In addition to these load cases, the following factors should be taken into account where they are relevant:

- Wind field perturbations due to the wind turbine itself (wake induced velocities, tower shadow, etc.);
- The influence of three dimensional flow on the blade aerodynamic characteristics;
- Structural dynamics and the coupling of vibration modes;
- Aero elastic effects;
- The behavior of the control and protection system of the wind turbine (IEC, 2008).

Dynamic simulations with a structural dynamics model are usually used to calculate wind turbine loads. The IEC dictates parameters specific to site and tower design in order to ensure the structure is reliable.

Dynamic Loading

The dynamic load is a result of periodic loading from the turbine rotation as the blades pass in front of the tower (Sørensen & Sørensen, 2011). The tower must be designed to allow minimum vibrations for stability, increased fatigue life, and minimal noise levels (Negm & Maalawi, 2000). To avoid large amplitude vibrations, the tower's natural frequencies are separated from the frequency spectrum of the dynamic loads. Large amplitude vibrations are caused by resonance, and can be minimized by measuring the performance index. Another way to reduce vibrations is by maximizing the natural frequencies of the system, since higher natural frequencies are favorable for reducing both the steady-state and transient responses of the tower (Fahad, Saad, Parvez, & Ansari, 2012).

The factors for the power output of the wind turbine are directly related to the dynamic loading of the turbine tower. The investigation of dynamic loading includes a comparison of the natural frequency of the turbine tower to the frequency of the thrust force. The natural frequency of a system (in this case, the wind turbine tower) is the frequency at which a system oscillates when not subjected to a continuous or repeated external force (Oxford University, 2014). The thrust force is caused by the rotor and tower resisting the bending loads due to wind passing over the blades (Earnest & Wizelius, 2011). Because the blades on the turbine rotate, the thrust force occurs in intervals, creating the excitation frequency. When the excitation frequency and the natural frequency of the tower are close together, there will be a large dynamic effect and the structure will be in resonance. This means that the structure would self-excite, causing it to undergo large oscillations and possibly overturn. If the two frequencies are relatively far apart, it would yield a small dynamic effect and approach a static loading condition. A static state is ideal for wind turbine towers because it ensures that the tower will not oscillate and is therefore stable.

The dynamic magnification factor is used to convert dynamic loading into a an equivalent static load (Paz & Leigh, 2004). The factor depends on the ratio of the excitation frequency of the thrust force to the natural frequency of the structure as well as the levels of damping in the system. For a steel tube (the wind turbine tower) with a weight on the top of it, natural damping occurs. The chart in Figure 7 shows the relationship of the frequency ratio and damping to the dynamic magnification factor.

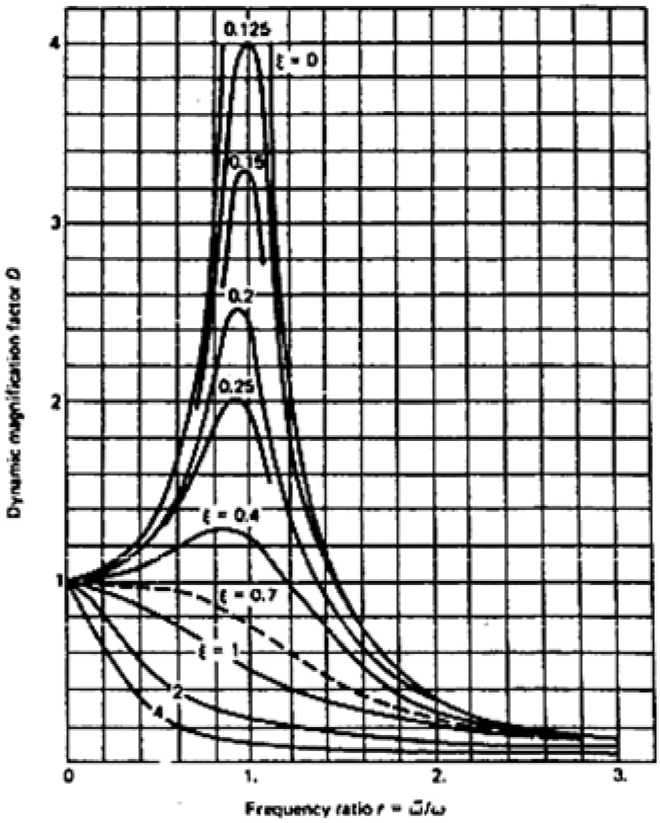


Figure 7: Dynamic Magnification Factor. (Paz & Leigh, 2004).

Each of the curves in the figure above represents the levels of natural damping in a system. As the frequency ratio of a system approaches a value of one, the system is in resonance and the response grows unbounded as the natural damping approaches zero.

Combined Stresses

The combined stresses acting on the tower are the axial and bending stress. The axial force is the normal stress over a cross-sectional area, which is the ability of a structural member to resist loading conditions parallel to its longitudinal axis (Hibbeler, 2010). The bending strength (or flexural strength), is the ability of a structural member to resist bending under loading conditions perpendicular to its longitudinal axis. In essence a wind turbine tower can be analyzed similar to a cantilever beam where stresses in the tubular steel will be a resultant of the vertical and lateral loadings. Equation (1) defines the maximum bending stress as it relates to the internal bending moment acting over the cross sectional area of the tower:

$$\sigma_{bending} = \frac{Mc}{I} \tag{1}$$

Where:

$\sigma_{bending}$ = Normal stress that occurs at the farthest point from the neutral axis on the cross-sectional area (N/m^2)

M = The resultant internal moment calculated about the neutral axis of the cross section (N*m)

c = The perpendicular distance from neutral axis to the point farthest away where σ_{max} acts (m)

I = The moment of inertia of the cross-sectional area about neutral axis (m^4).

The axial stress is a result of an applied force on the tower section divided by the area of said section as defined in Equation (2):

$$\sigma_{axial} = \frac{P}{A} \tag{2}$$

Where:

σ_{axial} = The axial stress as a force per unit area (N/m^2)

P = Applied force (N)

A = Cross-sectional area (m^2).

The sum of equations (1) and (2) gives the combined normal stress on an element of material along the length of the wind turbine tower:

$$\boldsymbol{\sigma = \frac{P}{A} \pm \frac{MC}{I}} \tag{3}$$

Buckling

Important areas for defining failure criteria are buckling failure due to extreme loading and fatigue failure (Sørensen & Sørensen, 2011). “Buckling is instability of equilibrium in structures that can occur from compressive load or stresses” (Guang Teng,1996). It is ideal to make the tower thickness as thin as possible to reduce its weight and material costs; however, this may lead to (i) overall column buckling or (ii) local instability. Turbine designers must find a proper balance of these factors in order to have a cost efficient structure.

Slenderness Ratio

The slenderness ratio (λ) is defined as the ratio of the length of a structural member to its least radius of gyration (Merriam-Webster, 2013). As the slenderness ratio increases, the ability to withstand higher loads decreases. Equation (4) represents the slenderness ratio:

$$\boldsymbol{\lambda = \frac{KL}{r}} \tag{4}$$

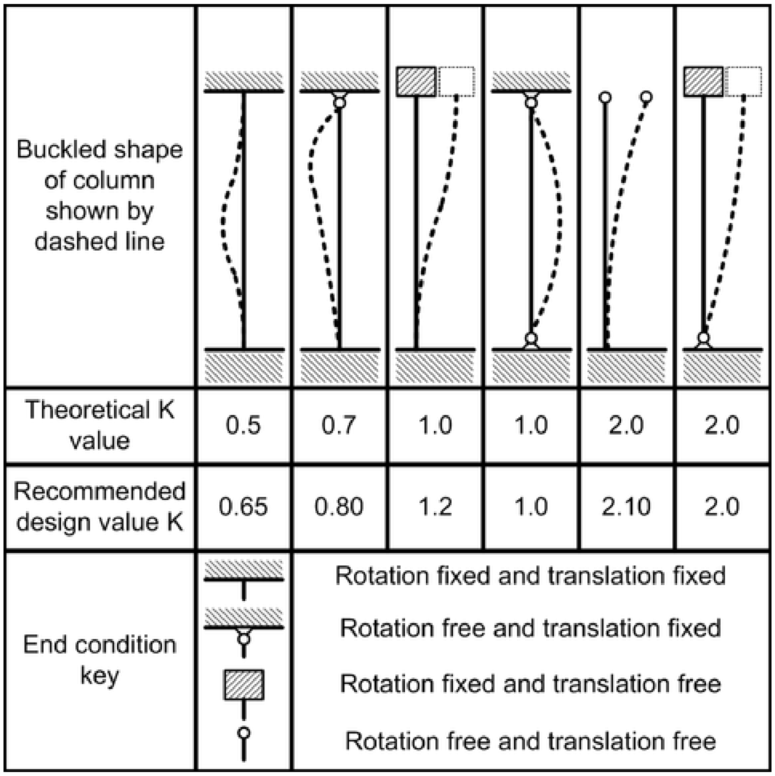
Where:

K = 2.1 (recommended design value)

L = length (m)

r = radius of gyration (m).

The K value in the slenderness ratio equation can be decided from Figure 8.



Buckled shape of column shown by dashed line						
Theoretical K value	0.5	0.7	1.0	1.0	2.0	2.0
Recommended design value K	0.65	0.80	1.2	1.0	2.10	2.0
End condition key		Rotation fixed and translation fixed Rotation free and translation fixed Rotation fixed and translation free Rotation free and translation free				

Figure 8: K Values for Buckling in Columns. (AISC, 2005).

Critical Column Buckling

As tower height increases, the combination of the dynamic and lateral loads and self-weight cause the tower to experience column buckling. Figure 9 illustrates the different fixed end types and their corresponding column buckling equation.

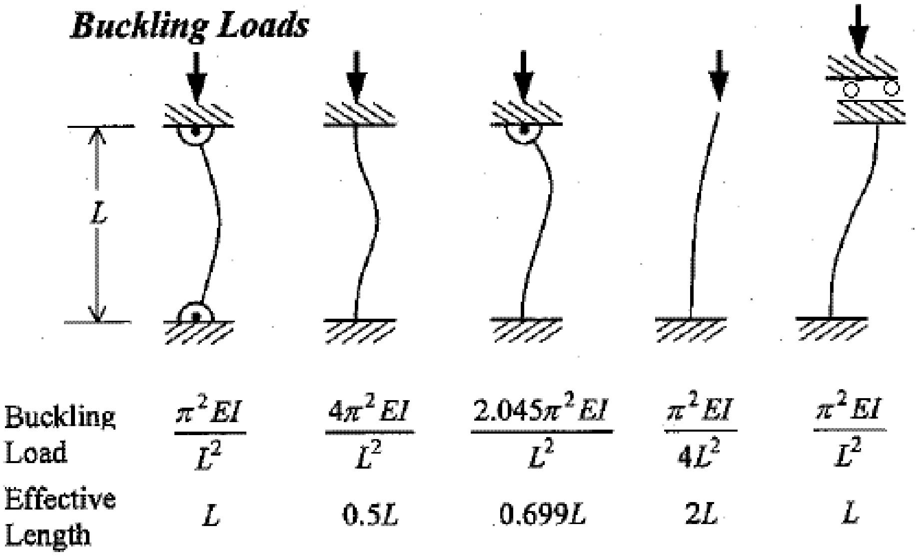


Figure 9: Buckling Load Equations. ("Stability Analysis," 2013).

Since the wind turbine has a fixed base and a free top with a dynamic load, K=2 is a simple approximation from Figure 9, and Equation (5) is used to represents the Euler elastic buckling stress:

$$\boldsymbol{F_e = \frac{\pi^2 E}{\left(\frac{KL}{r}\right)^2}} \tag{5}$$

Where:

F_e = Euler elastic buckling stress (ksi)

E = modulus of elasticity (ksi)

I = second (area) moment of inertia (m^4)

K = 2

L = column length (m)

r = radius of gyration (m).

AISC Column Buckling Theory

As the structure varies in column size, so does the global buckling stress (McCormac & Csernak, 2012). Euler's buckling theory (Equation (6) is only valid for elastic buckling. Short to intermediate length columns buckle by a mix of elastic and inelastic effects, therefore the Euler model must be adjusted as seen in the following equations from the 2010 *AISC Specifications for Structural Steel Buildings*:

Intermediate/Short Columns:

$$\boldsymbol{F_{cr} = \left[.658^{\left(\frac{F_y}{F_e}\right)}\right] * F_y \quad \text{for} \quad \frac{L}{r} \leq 4.71\sqrt{\frac{E}{F_y}} \ \left(\text{or } \frac{F_y}{F_e} \leq 2.25\right)} \tag{6}$$

Long Columns:

$$\boldsymbol{F_{cr} = .877 * F_e \quad \text{for} \quad \frac{L}{r} > 4.71\sqrt{\frac{E}{F_y}} \left(\text{or } \frac{F_y}{F_e} \leq 2.25\right)} \tag{7}$$

Where:

F_{cr} = Critical Column Buckling Stress (ksi)

E = Elastic Modulus (ksi)

F_y = Yield Strength (ksi)

F_e = From Equation (5)—Euler Elastic Buckling Stress (ksi).

Timoshenko Theory for Column Buckling of a Tapered Tower

Although the wind turbine tower is considered a column in this scenario, using Euler's model does not account for the taper angle (Timoshenko & Gere, 1961). Therefore, an additional method is used in order to determine an appropriate effective length factor, *K*, when determining the critical allowable stress. Based on Figure 10, case "c" with a respective *n* value of 2 is used.

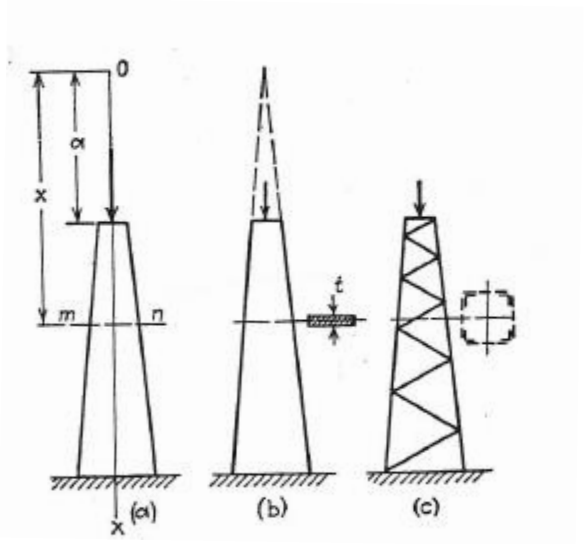


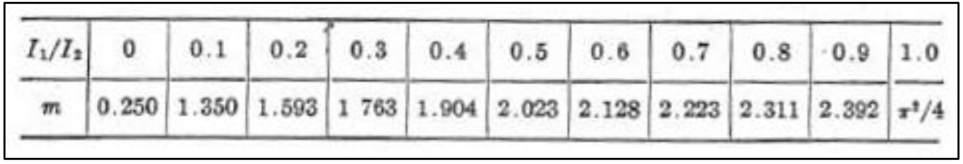
Figure 10: Moment of Inertia Cross Section. (Timoshenko & Gere, 1961).

Also based on Figure 10, the expression for the critical load, P_{cr}, is given below. The "K" value is embedded for the "m" factor.

$$P_{cr} = \frac{mEI}{l^2} \tag{8}$$

Using the ratio for the moment of inertia at the top to the bottom of the tower, the value for "m" is determined from Table 1.

Table 1: Values of the Factor "m". (Timoshenko & Gere, 1961).



I_1/I_2	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
m	0.250	1.350	1.593	1.763	1.904	2.023	2.128	2.223	2.311	2.392	$\pi^2/4$

Once the "m" factor has been determined, the effective length factor can be calculated using the equation below:

$$K = \sqrt{\frac{\pi^2}{m}} \tag{9}$$

Using this “K” value, the column slenderness can be determined using the following equation, which will account for the taper of the tower.

$$\lambda = \frac{KL}{R_2} \tag{10}$$

Where:

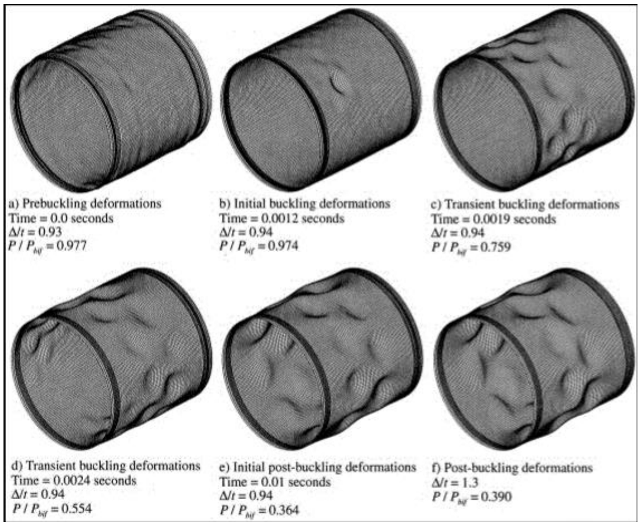
K = Effective Length Factor (As Previously Calculated)

L = Length of Tower (m)

R_2 = Radius of Gyration of the tower cross section at the base of tower.

Critical Local Buckling

Tall, tubular towers are susceptible to not only column buckling, but local buckling as well. Local buckling commonly occurs when there are initial imperfections in the material, causing a wave-like crumbling pattern of failure to appear throughout the structure (Figure 11).



a) Prebuckling deformations
Time = 0.0 seconds
$\Delta/t = 0.93$
$P / P_{bif} = 0.977$

b) Initial buckling deformations
Time = 0.0012 seconds
$\Delta/t = 0.94$
$P / P_{bif} = 0.974$

c) Transient buckling deformations
Time = 0.0019 seconds
$\Delta/t = 0.94$
$P / P_{bif} = 0.759$

d) Transient buckling deformations
Time = 0.0024 seconds
$\Delta/t = 0.94$
$P / P_{bif} = 0.554$

e) Initial post-buckling deformations
Time = 0.01 seconds
$\Delta/t = 0.94$
$P / P_{bif} = 0.364$

f) Post-buckling deformations
$\Delta/t = 1.3$
$P / P_{bif} = 0.390$

Figure 11: Local Buckling on a Slender Column. (Hilburger, Starnes, 2004).

Currently, there is no standardly used equation to calculate the local buckling of a tubular cylinder. The following theories illustrate different methods of calculating the local buckling stresses.

Burton, Bossanyi, Jenkins, Sharpe Local Buckling Theory

An elastic critical buckling stress of a cylindrical steel tube is first calculated (Equation (11) (Burton, Sharpe, Jenkins, & Bossanyi, 2001):

$$\sigma_{cr.elastic} = 0.605E_s\left(\frac{t}{r}\right)$$

(11)

Where:

E_s= modulus of elasticity of steel (ksi)

t = wall thickness (m)

r = mean radius of the wall (m).

Next, the critical stress reduction coefficients for axial and bending loading are calculated from the following equations below. Note: there are set parameters for the axial coefficient equation depending on the ratio of radius to thickness ($\frac{r}{t}$).

$$\alpha_0 = \frac{0.83}{\sqrt{1+0.01\left(\frac{r}{t}\right)}} \;\; for \; \left(\frac{r}{t}\right) < 212 \quad ; \quad \alpha_0 = \frac{0.70}{\sqrt{1+0.01\left(\frac{r}{t}\right)}} \;\; for \; \left(\frac{r}{t}\right) \geq 212$$

(12)

$$\alpha_\beta = 0.1887 + 0.8113(\alpha_0)$$

(13)

Where:

α_0 = axial loading coefficient

α_β = bending coefficient.

By combining these coefficients with the yield strength and the critical elastic buckling strength, the maximum principal stress in the structure should not exceed the critical local buckling stress value provided by the equation below in order to avoid failure:

$$\sigma_{buckling} = F_y\left[1 - 0.4123\left(\frac{F_y}{\alpha_\beta \sigma_{cr.elastic}}\right)^{0.6}\right] \;\; \text{for} \;\; \alpha_\beta \sigma_{cr.elastic} > \frac{F_y}{2}$$

(14)

$$\sigma_{buckling} = 0.75\alpha_\beta \sigma_{cr} \;\; \text{for} \;\; \alpha_\beta \sigma_{cr.elastic} \leq \frac{F_y}{2}$$

(15)

Troitsky Local Buckling Theory

A second theory to determine the local buckling capacity of a cylindrical can be seen in equations (16) and (17):

$$\boldsymbol{\sigma_{allow} = .6 * Fy \quad \text{for} \quad \frac{D}{t} \leq \frac{3300}{F_y}} \tag{16}$$

$$\boldsymbol{\sigma_{allow} = \frac{662}{\frac{D}{t}} + .399 * F_y \quad \text{for} \quad \frac{3300}{F_y} < \frac{D}{t} < \frac{13{,}000}{F_y}} \tag{17}$$

Where:

D = Mean diameter of cylinder wall (m)

t = wall thickness (m)

F_y = yield strength (ksi)

σ_{allow} = allowable column stress (ksi).

Allowed Column and Local Buckling

A Factor of Safety (FoS) is applied for the Burton, Bossanyi, Jenkins and Sharpe buckling theory equations to ensure that failure is not reached. These new values represent the allowed column and local buckling stresses on the tower and are used to determine the design requirements. This value can range depending on how conservative the designer wants to values to be. For steel, a common FoS is 1.67. For a tower to withstand buckling stresses, the actual combined stresses (as discussed later in this chapter) must be less than the allowable buckling stress that the tower is designed for:

$$\boldsymbol{\sigma_{combined} \leq \sigma_{allowable}} \tag{18}$$

Where:

$\sigma_{combined}$ = Actual combined stress due to dead loads and lateral wind forces (ksi)

$\sigma_{allowable}$ = Allowable stress on tower (ksi).

AISC Tower Yielding Check

In addition to local buckling, wind turbine towers are susceptible to failure due to yielding. Using the AISC method, the interaction equation for combined axial and bending effects must be below 1.0 to avoid a failure by yielding (Equation (19).

$$\frac{P_r}{P_c} + \frac{M_r}{M_c} \leq 1.0$$

(19)

Where:

P_r = Axial Load (N)

M_r = Moment (N-m)

P_c = Axial Capacity

M_c = Bending Capacity

While it is expected that the highest stress of the tower during erection would be seen at the base, a check must be performed along the length of the tower to ensure that the tower does not yield at a location other than the base. If Equation (19) is satisfied along the tower, then the tower will not fail due to yielding.

In order for the wind turbine tower to withstand various loadings and stresses, the tower design factors previously outlined were used to determine the actual and allowable design values the tower can withstand. Chapter 3.0 outlines the structural analysis that was completed using the defined design factors.

2.2.3 Wind Turbine Mechanics

The nacelle is the large casing that sits atop of the tower which holds all the mechanical components (including the turbine) that converts wind into electrical energy. The hub, attached to the front of the nacelle, is where the blades stem outwards. The blades can be up to 150 feet in length. As the wind turns the blades, the rotor hub turns the gearbox. The faster the gearbox rotates, the generator produces more electricity. All structures below the nacelle are designed to withstand the dead loads and vibrations produced by the turbine.

Wind Turbine Sizes

Wind turbine sizes range from small residential use to large commercial use, depending on desired power output. Generally, as turbine size increases, so does the turbine tower height (Figure 12). Because wind speeds increase at higher elevations, there is potential for harnessing more wind power at these elevations. As demonstrated in Figure 12, wind turbine heights have increased over the last 30 years. With an increase in height, rotor diameter increases causing an increase in power capacity (Layton, 2006). As improvements in designs are made, officials predict that tower height can increase further and thus increase output capacity.

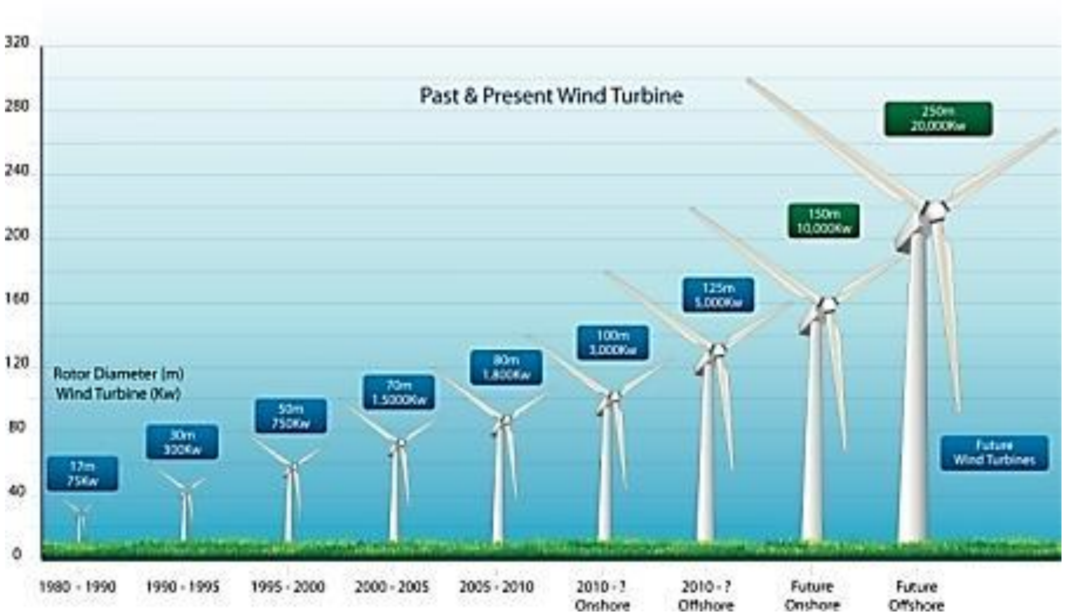


Figure 12: Predicted Tower Heights. ("Leading the Energy Transition: Wind Power," 2013).

Small turbine designs, mainly for residential use, have much lower tower heights. Design requirements take into account surrounding obstacles to maximize efficiencies. Each project must meet community and other local standards. As defined by the Massachusetts Department of Energy Resources (2012), wind turbines may not be sited within:

> *"(a) a distance equal to one and one-half (1.5) times the maximum tip height (MTH) of the wind turbine from buildings, critical infrastructure—including Critical Electric Infrastructure and above-ground natural gas distribution infrastructure—or private or public ways that are not part of the wind energy facility;*
> *(b) a distance equal to three (3.0) times the maximum tip height (MTH) of the turbine from the nearest existing residential or commercial structure; or*
> *(c) a distance equal to one and one-half (1.5) times the maximum tip height (MTH) of the turbine from the nearest property line, and private or public way."*

Power Output

There are many important components that comprise a wind turbine; however, not all of them are directly responsible for harnessing the wind energy. Although the tower height is capable of reaching higher wind speeds and the generator is responsible for converting the kinetic wind energy into electricity, it is the rotor diameter that relates to power output and ultimately the size of the turbine (Gipe, 2004).

The power output of wind turbines is calculated with the Swept Area Method (Manwell, 2002). Equation 20 determines the mass flow of air through the projected area of the rotor disk.

$$P = \frac{1}{2} \rho U^3 A C_P \tag{20}$$

Where:

P = Available Wind Power (W)

ρ = Air Density (kg/m^3)

U = Air Velocity (m/s)

A = Projected Sweep Area (m^2)

C_p = Power Coefficient.

It is important to note that for standard conditions, the density of air is 1.225 kg/m^3. Also that power is proportional to the area swept by the rotor. In such cases for a conventional wind turbine, the formula for sweep area is that of a circle (Manwell, 2002). Since wind passes through the rotor blades, the turbine does not capture 100% of the energy. Thus, a power coefficient, $C_{p,}$ is used to determine the attainable amount of wind energy depending on the turbine type.

The maximum power coefficient, C_{pmax} is used for ideal multi-blade turbines and has a capacity of 59.3% as defined by the Betz Limit (Gipe, 2004). Wind turbines are not designed to harness the maximum potential wind energy; the power coefficient is unique to each turbine type and is a function of the wind speed during operation. Figure 13 shows the graph that is used to obtain the corresponding power coefficient based on the type of turbine and ratio of blade tip speed to wind speed.

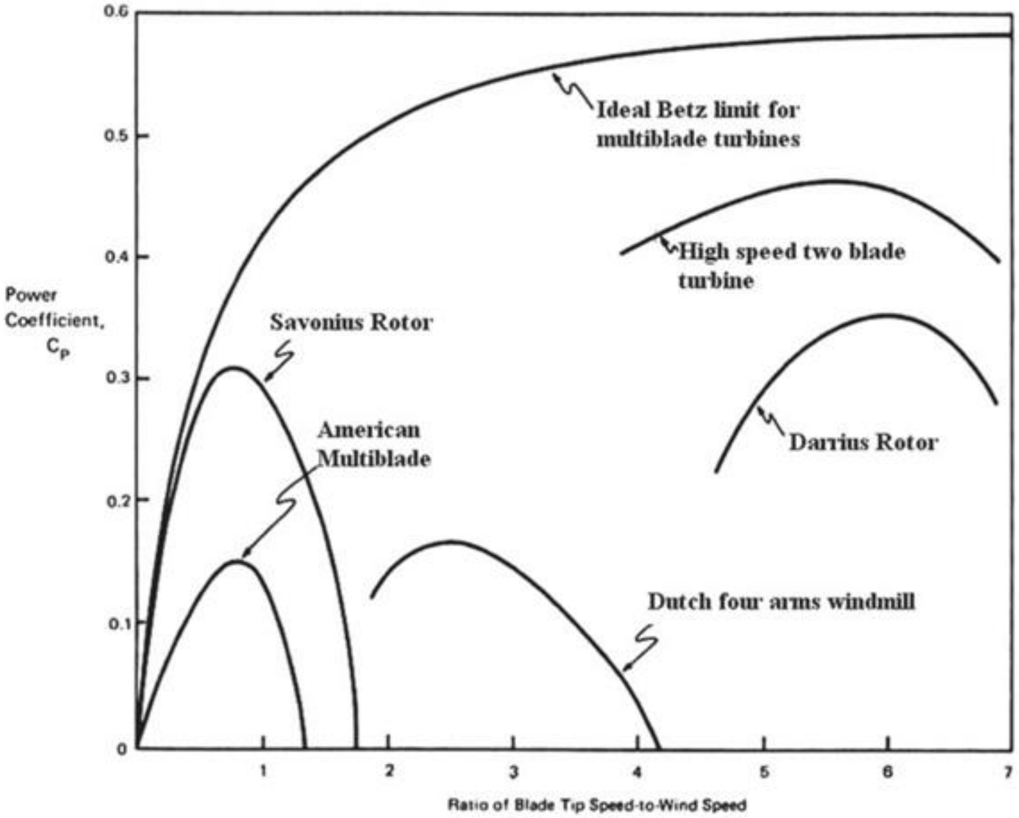


Figure 13: Betz Limit Diagram. (Ragheb & Ragheb, 2011).

In reality, even in optimal designs, the limit is significantly lower than the Betz Limit in the range of 0.35-0.45. Once other factors are accounted for within the wind turbine system, roughly 10-30% of the available wind energy converts into electricity.

2.3 Tower Erection Methods

Depending on varying site conditions, tower height and desired power output, there are different methods for erecting the wind turbine tower. The most traditional method is the use of a crane. The following sections describe the crane erection method and nontraditional alternative erection methods, along with the advantages and disadvantages of each.

2.3.1 Traditional Crane

One of the most common methods of erecting a wind turbine is with the use of two cranes: a crawler crane and a tower crane (Biggie Crane and Rigging Co., 2013). These cranes are combined to lift and suspend each segment of the tower and slowly place them in the correct location. The tower crane is the main piece of equipment used during the erection of a wind turbine tower. These cranes can reach up to 550 feet high, and can carry loads as heavy as 3.6

million kilograms. The crawler crane (reaching up to 400 feet with a lifting capacity of approximately three million kilograms) supplements the tower crane and acts as a balancing support for suspended tower segments.

The combinations of these two cranes have advantages and disadvantages. Tower cranes give the best combination of height and lifting capacities, especially for projects such as wind turbines (Khaleej Times, 2009). However, these cranes can be quite costly, and have limited mobility once they are on-site. The main advantages of crawler cranes are their ability to mobilize (with or without a load) around the construction site and to perform lifts with little setup needed (Biggie Crane and Rigging Co., 2013). Some disadvantages include its heavy weight, and its inability to relocate from one site to another easily and for low cost.

Princeton, MA Wind Turbine

The Princeton Municipal Light Department (PMLD) installed two 1.5MW wind turbines (named “North” and “South”) in 2009, located in Princeton, MA. Originally made by German wind turbine manufacturer, *Fuhrländer Wind*, these turbines cost Princeton $5 million. The two turbines reach a height of just under 70 meters, and have the potential to generate an annual energy consumption of 800 homes. The erection method chosen for these turbines was the traditional crane method. As mentioned earlier, this method can be costly. Figure 14 shows the cost breakdown for all aspects of transportation and construction of the two turbines.

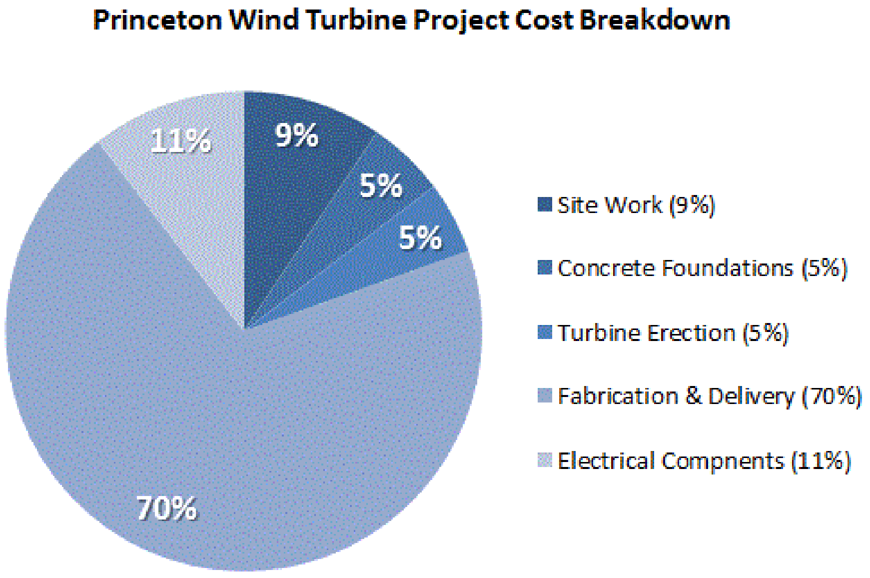


Figure 14: Princeton Wind Turbine Project Cost Breakdown. (Methuen Construction, 2009).

Costs associated with the turbine erection include, but are not limited to, the crane and labor of the crew.

In 2012, Fuhrländer filed for bankruptcy, leaving the ongoing maintenance to the PMLD. These turbines are losing more money than they are making; as of 2013, there was an $800,000 net loss because of the required maintenance necessary to the turbines. This loss falls to the PMLD customers by increasing their rates. In 2011, PMLD customers paid an additional $774,000 compared to the average Massachusetts customer (Allen, 2012).

2.3.2 Alternative Erection Methods

Alternative erection methods are being explored so as to find ways to reduce time and costs associated with using the traditional crane method. Below are four nontraditional methods that have been suggested for use in the industry.

Jack-Up with Offshore Platform Towers for Lifting

The erection methods for offshore drilling platforms could be used for the erection of wind turbines. Legs that are anchored to the ocean floor support the offshore oil-drilling platforms. The platforms are mounted on the legs which allow them to move up and down. This would relate to a wind turbine because the turbine would be assembled while it is on its side. Then, two lifting towers (which are much like the support legs for the offshore oil-drilling platforms) are erected along with two towers on each side of the wind turbine. The frame connected to the turbine tower is raised up the lifting towers using a rack-and-pinion mechanism. A final frame would guide the bottom of the tower as well. In this way, the entire wind turbine tower could be erected simultaneously. Figure 15 illustrates this concept.

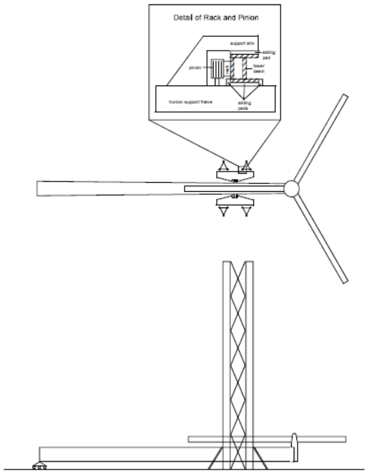


Figure 15: Jack-Up with Offshore Platform Towers. (Global Energy Concepts, 2001).

The advantages to this self-erection method is that the time to assemble and erect the wind turbine would decrease significantly because it could all be done at once as opposed to in stages. However, site conditions will be a driving factor for this method because in order for the entire turbine to be assembled on its side, there needs to be a lot of open space. Furthermore, the frame that helps guide the turbine up the two lifting towers would have to be built into the tower and would also have to be taken into consideration for the design and fabrication of the tower.

Slip-Form Approach

The slip-form design involves erecting the tower from the top down. The top tower section is placed into a frame with a bearing that creates a horizontal couple that prevents the tower from tipping. The next tower section is placed into the frame and pushes the previously placed section upwards. This process is repeated for each tower section until the tower is completely constructed (Global Energy Concepts, 2008). An illustration of this method can be found below in Figure 16.

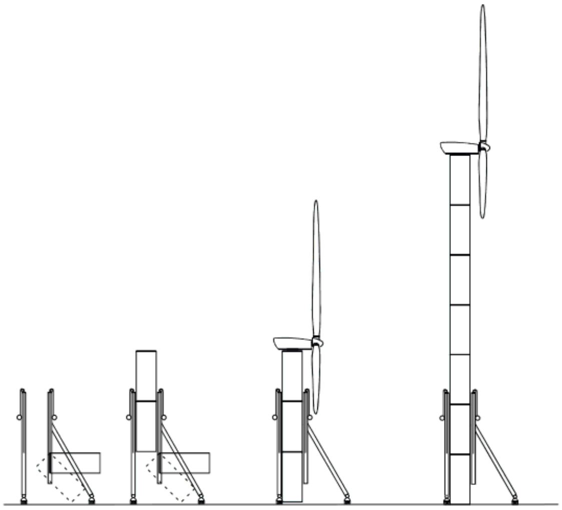


Figure 16: Slip Form Erection Method. (Global Energy Concepts, 2001).

The slip-form method has been implemented in oil rigs but studies claim that the use of the frame allows for the erection of a 5MW turbine. The use of this method eliminates the need for a crane and allows for construction in a location where land area is limited. However, there is one major disadvantage to this method. In order for the frame to maintain a constant cross-sectional bearing on the tower section, the tower cannot be tapered.

Telescoping Tower

One alternative method for self-erecting a tower would be through telescoping. Multiple tower sections would be pre-fabricated to fit inside one another and eventually extruded upwards. The topmost tower section, which would also be the innermost section, would require a greater length than the other sections so as to install the nacelle on top of the tower while at a relatively low elevation. This elevation must also be predetermined to ensure that the blades do not touch the ground. To finalize the installation of the wind turbine, a lifting mechanism would be required to extrude each section and raise the tower to its full height. Figure 17 illustrates this process. Challenges with this method include determining the type of lifting mechanism that would be feasible, and designing each connection point of the individual tower sections to ensure tower stability.

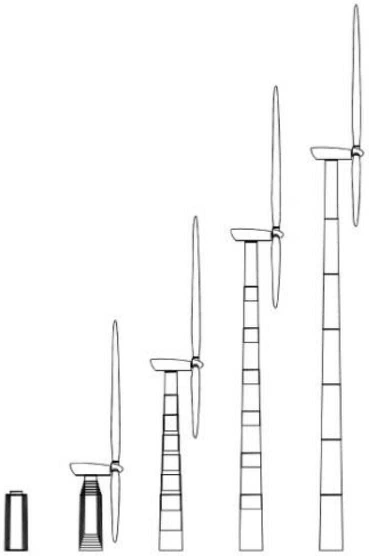


Figure 17: Telescoping Tower. (Global Energy Concepts, 2001).

Tilt-Up Method

Similar to the process of offshore tower installation, the tilt-up method is another alternative to using cranes. There are two ways to tilt up the tower: with guy wires or with a hydraulic jack. When using guy wires, the turbine tower has a self-supporting frame and is fully assembled on the ground. The turbine and tower are then hooked to several anchors and guy wires, and the tower pivots around a base as the guy wires pull the fully assembled structure up into a vertical position (Figure 18).

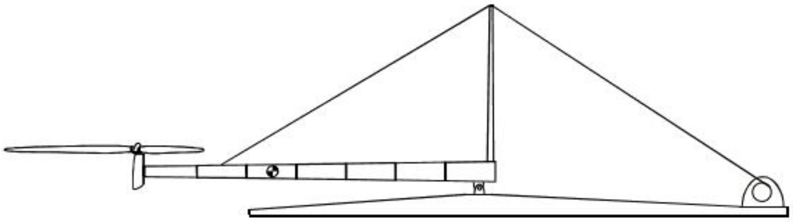


Figure 18: Tilt-Up Method with Self-Supporting Frame. (Global Energy Concepts, 2001).

Using a hydraulic jack eliminates the need for guy wires, and hydraulic pistons and winches raise the tower into place (Manwell, 2002).

When using this method of tower erection, there are some limitations that the contractor might face. In order for this method to work successfully, the tower cannot exceed a specific height and weight because the bending moment created by the self-weight of the tower causes tower failure. In addition, special equipment may be needed in order to assemble the tower before tilting up, such as a platform or small crane. Additionally, the site must have a large area of open space for the tower to lie flat before erection. Therefore, only small scale wind turbines could be erected by using the tilt up method. However, there are some benefits to this method. For example, because this method includes a self-supporting frame, a tower crane would not be needed to lift the segments on top of each other, thus potentially reducing the cost.

The focus of this project will be on the efficiency of the traditional crane erection method described earlier in this chapter compared to the tilt-up method using guy wires. Parameters that define efficiency included cost of equipment and time of construction. Comparisons of these parameters regarding the two erection methods and turbine towers were used to determine if current practices can be optimized. Chapter three outlines the methods used to analyze two turbine towers with regard to design, construction and erection.

3.0 Methodology

In order to determine a decision framework to aid in the structural design of a wind turbine tower and the selection of the best erection method, four objectives were created to outline the methodology:

1. Understand the design and construction process for wind turbine towers;
2. Perform a structural (construction and operation) analysis and economic analysis of a baseline wind turbine tower erected using a crane and using the tilt-up method;
3. Develop framework tool for design and analysis based on the baseline analyses (objective 2);
4. Repeat structural and economic analyses of alternative wind turbine towers using decision tool for the tilt-up method.

The flowchart in Figure 19 illustrates how the above objectives are related. The study of a baseline case helped to identify driving factors for design and construction. These factors were used to create a decision tool to investigate alternative tower designs and construction methods. This investigation of the tilt-up method was important to understand the correlation between tower design and construction factors. The methods for performing these objectives are discussed in Sections 3.1-3.5 below.

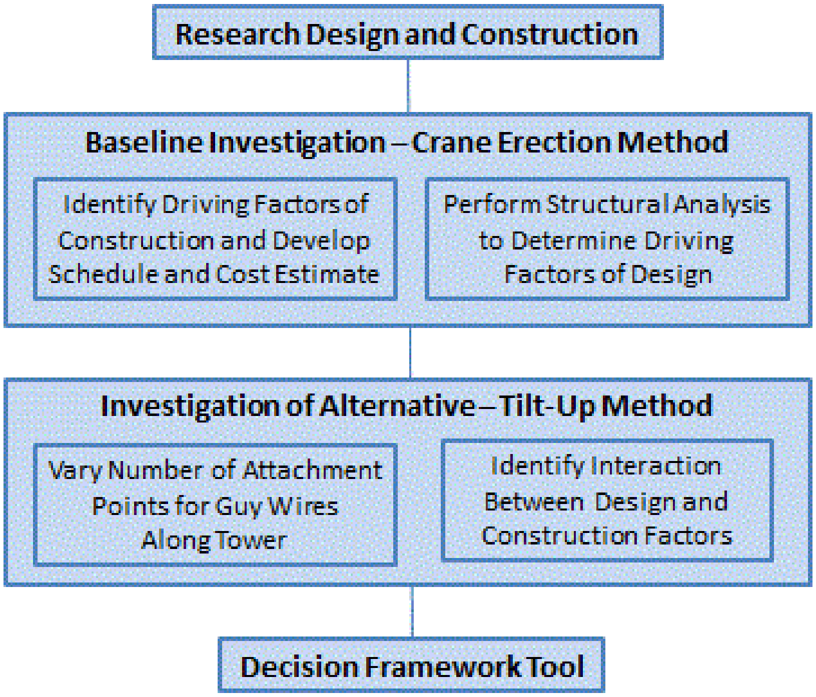


Figure 19: Objective Flowchart

3.1 Understanding the Design and Construction Process

Research and interviews with industry contacts were used to develop an understanding of the critical factors considered in the design and construction planning for a wind turbine tower. This included exploring existing design standards for wind turbine towers and similar structures as specified by the *Specification for Structural Steel Buildings* (AISC, 2013), the *Recommended Practice for Compliance of Large Land-Based Wind Turbine Support* (AWEA, 2013) the *Minimum Design Loads for Buildings and Other Structures* (ASCE & SEI, 2013), and the *Wind Turbines—Part I: Design Requirements* (IEC, 2008).

To better understand the erection process and challenges that may arise, a visit to an existing wind turbine site in Princeton, Massachusetts served as the baseline investigation. Wind data, environmental conditions and design specifications were gathered from this facility to serve as constants throughout this project, and the key data are summarized in Table 2.

Table 2: Criteria for Baseline Investigation and Alternative Cases

Turbine	
Power Output	1.5 MW
Number of Blades	3
Design Type	Upwind
Tower	
Material	A-36 Steel
Shape	Tubular
Environmental Factors	
Wind Speed	3 - 13.4 m/s
Location	Princeton, MA
Exposure Factor*	D

**As identified by ASCE-7-10 Standards (ASCE & SEI, 2013).*

3.2 Operational Analysis for Tower Structures

Similar structural design and analysis activities were performed for the baseline and alternative towers and the results were compared. To accomplish this, calculations were completed using *Microsoft Excel*, and the results were cross-checked and confirmed with hand calculations for the first few meters of the turbine tower. The load cases on the tower included dead loads from the structure, lateral loads from the wind profile, and dynamic loads produced from the rotation of the blades. The allowable stresses on the tower were identified by considering column and local buckling and yielding limits for A-36 steel. Completing a structural analysis of a wind turbine tower was necessary to understand the critical loading and stresses applied to the tower during operation.

3.2.1 Wind Loading

In order to determine the wind loads that act along the height of the wind turbine tower, the criteria outlined in the *Minimum Design Loads for Buildings and Other Structures: ASCE/SEI 7-10* (ASCE 7-10) were used. Chapter 29 of this standard describes wind loads on other structures and building appurtenances, and therefore the equations defined in that chapter were applied to the tower. The design wind force is:

$$F = q_z G C_f A_f \tag{21}$$

Where:

q_z = the velocity pressure (N/m^2)

G = the gust-effect factor

C_f = the force coefficients

A_f = the projected area normal to the wind (m^2).

The velocity pressure (q_z) is:

$$q_z = 0.613 K_z K_{zt} K_d V^2 \tag{22}$$

Where:

K_z = velocity pressure exposure coefficient

K_{zt} = topographic factor

K_d = wind directionality factor

V = basic wind speed (m/s).

The velocity pressure exposure coefficient is constant for the first five meters of the tower. For the rest of the tower the value is:

$$K_z = 2.01\left(\frac{z}{213.36}^{\left(\frac{2}{11.5}\right)}\right) \tag{23}$$

Where:

z = height of analyzed tower section (m).

3.2.2 Dynamic Loading

In order to determine the dynamic loading, the thrust force and its excitation frequency must be identified. The thrust force is dependent on the rotation of the blades, wind speed, blade tip speed and the optimal tip speed ratio. All of the equations correlating to dynamic loading were derived from the Ragheb et al. (2011) article. Equation (24) shows the optimal tip speed ratio ($\lambda_{optimal}$) of blade tip speed to wind speed to yield the maximum power efficiency:

$$\lambda_{optimal} \approx \frac{4\pi}{n}$$

(24)

Where:

n = number of blades on the wind turbine.

The actual tip speed ratio, λ_{actual}, can be substituted with $\lambda_{optimal}$ from Equation (24) to solve for the wind speed for a given tip speed (Equation (25):

$$\boldsymbol{Wind\ Speed} = \frac{(\lambda_{actual}) = (\lambda_{optimal})}{\boldsymbol{Tip\ Speed}}$$

(25)

Equation (26) is then used to determine the time for the blades to make one revolution:

$$T = \frac{2\pi r}{Tip\ Speed}$$

(26)

Where:

T = time per revolution (seconds)

r = rotor radius (meters).

The excitation frequency for the thrust force is then equal to $\frac{1}{T}$. The magnitude of the thrust force was calculated with respect to the wind speed and power equation:

$$F_t = \frac{P = \frac{1}{2}\rho U^3 A C_P}{V_w}$$

(27)

Where:

F_t = thrust force (N)

P = power output (N)

V_w = wind velocity (m/s).

The thrust force was calculated as a dynamic load; therefore, the dynamic magnification factor (discussed in Chapter 2) was used to convert the load into an equivalent static load acting at the center of the hub with the following equation:

$$\mathbf{P}_{\mathbf{static}} = F_t * DMF \tag{28}$$

Where:

P_{static} = Equivalent Static Load

DMF = Dynamic Magnification Factor.

The dynamic magnification factor was identified from comparing the frequency ratio ($\frac{Wind\ Frequency}{Natural\ Frequency}$) of the tower to the level of damping in the system using the chart in Figure 7.

The dynamic loading condition was analyzed as a single lateral load for the combined stress analysis. The load conditions outlined in sections 3.2.1 and 3.2.2 were determined to calculate the combined stresses exerted on the tower structure.

3.2.3 Combined Stresses

To calculate the combined stresses, the tower was segmented into one-meter sections. The combined stresses during turbine operation account for the bending stress caused by the lateral loading as well as the axial stress from the dead load. For each tower section, cross-sectional properties were identified to account for the taper angle and change in wall thickness.

The tower analysis started at the center of the hub and continued down the tower. As additional sections were analyzed, the section weights accumulated to account for the dead load while the wind load accumulated for more exposure to the wind profile. Bending, axial and combined stresses were calculated at the mid-height of each one-meter section using the following equations:

Table 3: Combined Stress Equations

Equation Description	Equation
Bending Stress	$\sigma = \frac{Mc}{I}$
Axial Stress	$\sigma = \frac{P}{A}$
Combined Stress	$\sigma = \frac{P}{A} + \frac{Mc}{I}$

3.2.4 Tower Buckling

The steps taken to calculate the allowable column and local buckling stresses on the turbine tower are outlined below:

Column Buckling

The Timoshenko theory was used when calculating the column buckling stress because it accounts for the taper in the tower. A single value for the critical column buckling stress was then determined using the steps below:

1. Determine "m" factor in Table 1 using the moments of inertia of the base and top of the tower.
2. Solve for K using Equation (9):

$$\boldsymbol{K} = \sqrt{\frac{\boldsymbol{\pi}^2}{\boldsymbol{m}}}$$

3. Determine the column slenderness, λ using Equation (10):

$$\lambda = \frac{\boldsymbol{KL}}{\boldsymbol{R}_2}$$

4. Use the Euler Equation (5) to determine the critical column buckling stress:

$$\boldsymbol{F}_e = \frac{\boldsymbol{\pi}^2\boldsymbol{E}}{\boldsymbol{\lambda}^2}$$

For wind turbine towers, column buckling is rarely the cause of failure.

Local Buckling

To determine local buckling, the theories explained in Section 2.4.4 were used. Both the Troitsky and *Wind Energy Handbook* methods were used to calculate the allowable local buckling stress for the baseline investigation. In order to make a consistent comparison for each tower design, the equations from Troitsky's local buckling theory, as seen below, were used in the analysis of alternative towers.

$$\textbf{When} \quad \frac{D}{t} \le \frac{3300}{F_y} \quad \textbf{use} \quad \sigma_{allow} = .6 * Fy$$

$$\textbf{When} \quad \frac{3300}{F_y} < \frac{D}{t} < \frac{13{,}000}{F_y} \quad \textbf{use} \quad \sigma_{allow} = \frac{662}{\frac{D}{t}} + .399 * F_y$$

The column and local buckling allowable stresses were then compared to the calculated combined stresses for the operational analyses. If the calculated stresses exceeded the allowable stresses, the tower would fail due to buckling.

The methods above comprised the operational analyses for the investigated towers.

3.3 Decision Framework Tool

An *Excel* spreadsheet was created as a decision framework tool after the analyses in 3.2 were completed for the baseline tower. Conducting analyses on the baseline tower served as the foundation for the operational and construction analyses of the alternative towers. All of the calculations for the alternative tower designs were completed in the *Excel* spreadsheet, which are further explained in Chapter 5.

3.4 Construction Analysis for Tower Structures

The construction analysis was applied to a tower for tilt-up erection. Tower sections were assumed to be connected on the ground and the assembled tower was erected using a crane to pull the tower vertical. Analyses revealed the minimum tension in the guy wires necessary to lift the tower. This was found when the calculated tension moment was greater than the moment produced from the weight of the tower. Calculated bending stresses were compared to the allowable bending stresses in 10º increments with relation to the ground. Using the interaction equation from Equation (19), $\frac{P_r}{P_c} + \frac{M_r}{M_c} \le 1$, the calculated bending stress was compared to the allowable yielding limit to further ensure that the towers would not fail. In addition, the calculated stresses were compared to allowable bending and local buckling stresses. The resultant forces at the base of the tower were calculated by analyzing the dead weight of the tower as point loads located at the attachment points. As the number of attachment points increased, the point loads were distributed based on tributary width principles (Figure 20).

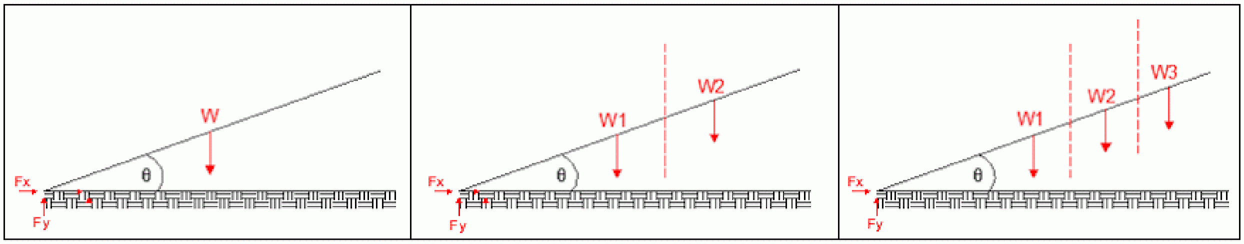


Figure 20: Resultant Forces Along Tower Height.

When calculating the moment along the tower height, the dead weight was analyzed as a uniform distributed load. As calculations progressed from the tip of the tower to the base, the resultant of the dead load increased as more of the tower was accounted for, as seen in Figure 21.

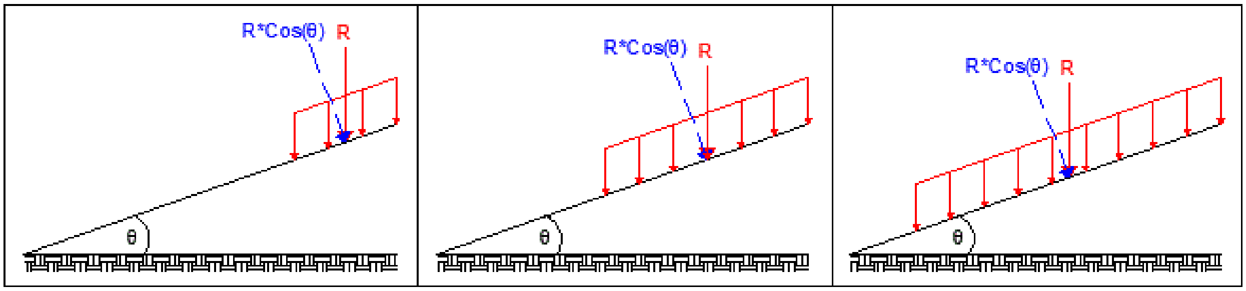


Figure 21: Distributed Dead Load Along Tower.

3.4.1 Baseline Tower

The Princeton turbine was investigated upon completion of the initial structural analysis to determine whether the tilt-up erection method was feasible. Three analyses were considered for the baseline tower using varying guy wires. The following diagrams represent the varying guy wire placements (note: drawings not to scale).

1. One guy wire; attached at the center of gravity (CoG):

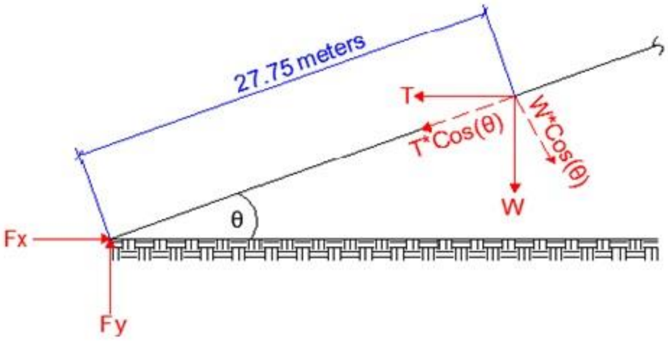


Figure 22: Tilt-Up Method Using One Guy Wire.

2. Two guy wires; the first attached at the CoG and the second half way up the remainder of the tower height:

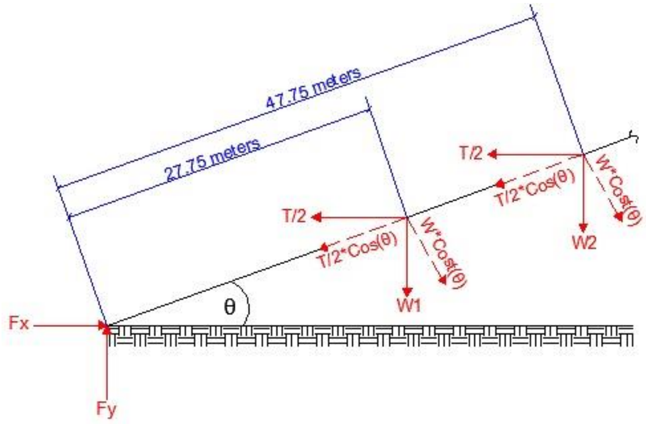


Figure 23: Tilt-Up Method Using Two Guy Wires.

3. Three guy wires; the same guy wire placement as Figure 23 with a third guy wire attached halfway from the base of the tower to the CoG:

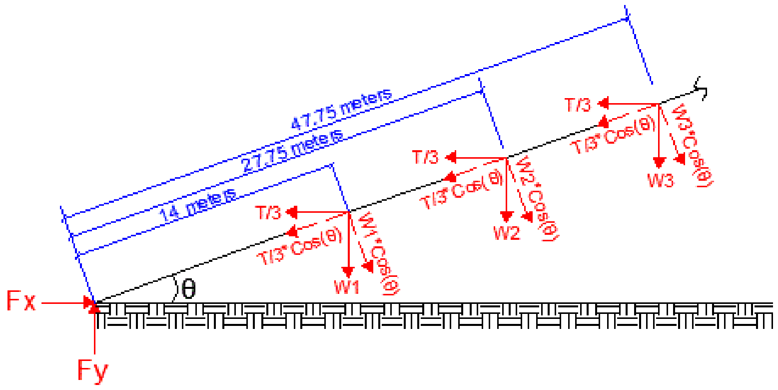


Figure 24: Tilt-Up Method Using Three Guy Wires.

Of these tilt-up scenarios, the guy wire attachment with the smallest margin of failure was used to analyze the subsequent alternative tower designs for consistency. Failure was assessed based on the magnitude of stresses endured along the tower height and the minimum required tension to tilt up the tower. In the event that all three scenarios did not fail, then the scenario with the smallest required tension would be chosen for the alternative tower designs. The construction analysis for the baseline case study included bending and buckling investigations, but only included a yielding check for the optimal guy wire scenario.

3.4.2 Alternative Tower Designs

Three alternative tower designs were prepared for analysis and comparison with the baseline tower. The majority of the specifications were provided by the turbine manufacturers. The upper diameter, lower diameter, and thickness were calculated using the proportions from the baseline tower. Once the optimal guy wire configuration was determined from Section 3.4.1, a structural analysis was performed on the alternative towers using the decision framework tool as described in Section 3.3. The analyses performed on the alternative towers included bending, yielding and buckling investigations.

3.5 Economic Analysis of Tower

An economic analysis was performed for both the baseline and each of the alternative turbine towers. Project costs for the baseline analysis were provided by the experts who worked on the project. These costs included turbine costs, site work, foundation work, and erection costs. The project costs of the baseline turbine served as a point of comparison for the economic analyses of the alternative towers.

The project costs for the alternatives were estimated by contacting the turbine companies to determine the cost of each turbine. After the minimum tension required to lift each alternative was determined, crane companies were contacted to find the necessary rental costs for cranes that met the determined requirements. Because the site and foundation work is so dependent on the site conditions and the type of turbine that is erected, a sufficient cost estimate for broad-based comparison could not be determined. The results are specific to the Princeton site.

4.0 Baseline Study: Princeton Turbine

The Princeton Municipal Light Department (PMLD) currently owns two wind turbines located in Princeton, Massachusetts. These dual wind turbines were installed in 2009 as a way to help lower energy prices for the local residents that the PMLD serves. The wind turbines selected for this site were Fuhrländer Wind FL-1500 machines with a hub height of 70 meters. The total cost of this project including the turbines, towers, and equipment used for erection and construction, was $7.5 million. For this report, these two wind turbines served as a reference for investigating the design of tower and the typical crane erection method. By selecting Princeton as the baseline, it was possible to make a comparison with other design and tilt-up erection alternatives in order to better understand the feasibility and limitations of each.

4.1 Construction Process

The project was awarded to Lumus Construction and Methuen Construction in June 2007—site construction took three months to complete and the foundation was completed in the Fall of 2008 (Shah, personal communication, 2013). Hallamore Crane Company erected the tower in fall 2009 upon arrival of the turbines.

Onsite Studios was hired to make a video of the construction process from start to finish for the PMLD project. The following narrative describes how the turbines were transported to the site and erected as observed from watching the video.

The wind turbine tower was fabricated in three sections offsite and then transported by flatbed truck to Princeton, MA. Once all of the components of the wind turbine (nacelle, blades, hub, and tower sections) arrived on site, two cranes lifted the tower sections into position. The larger crane did the majority of the lifting while a smaller crane stabilized the bottom portion of the tower section. The first section was erected upright over the foundation and anchored into position. Next, workmen climbed inside and at the top of the first section to assemble the necessary bolts for installation of the second section. The nacelle was installed at the top of the tower once the three sections were erected. Finally, workmen attached the three blades to the hub while on the ground, and then raised and installed the hub assembly on the nacelle. Figure 25 highlights the major stages of the construction process.

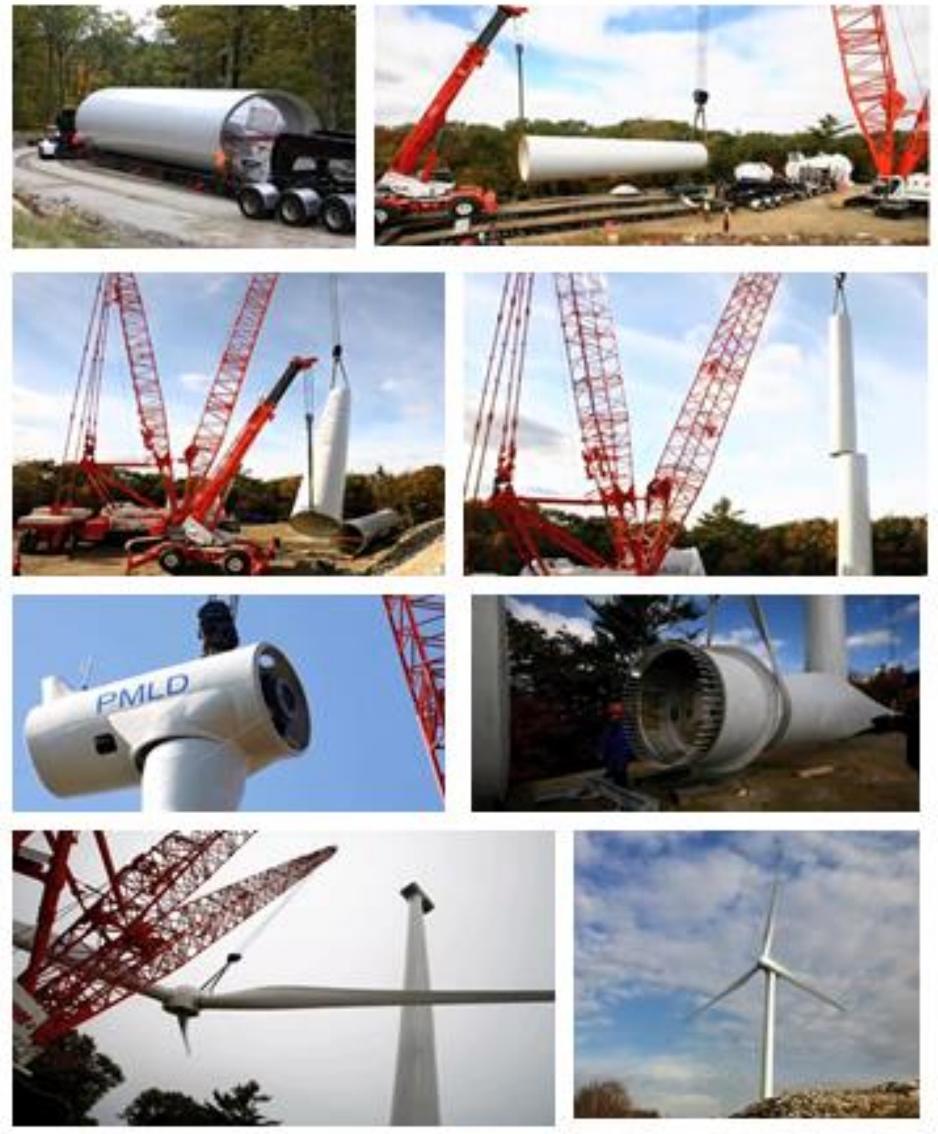
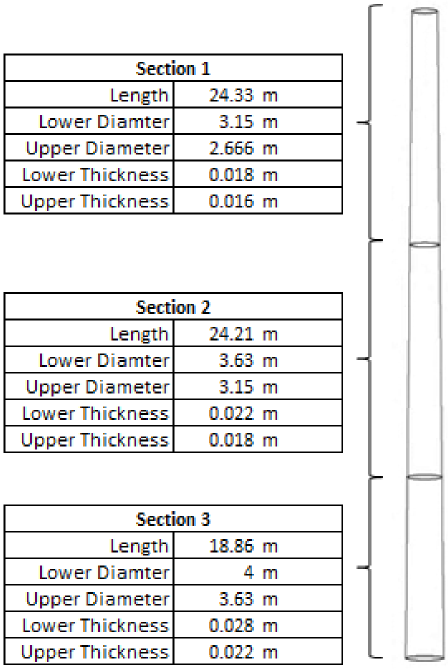


Figure 25: Construction Process of Princeton Turbine. (Groccia, 2010).

4.2 Operational Analysis

The following sections outline the loading and stress results from the structural analysis performed on the baseline wind turbine tower. The structural analysis provided a means to observe how wind, dynamic and dead loads compared with the tower's buckling resistance and capacity to sustain combined stresses. Figure 26 and Figure 27 show the given values for the Princeton, MA turbine tower that were used.

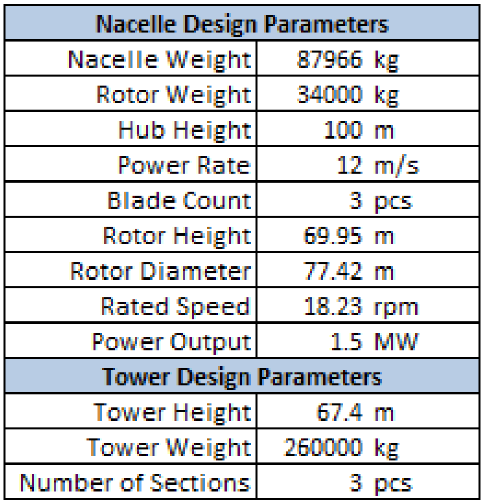


Section 1	
Length	24.33 m
Lower Diamter	3.15 m
Upper Diameter	2.666 m
Lower Thickness	0.018 m
Upper Thickness	0.016 m

Section 2	
Length	24.21 m
Lower Diamter	3.63 m
Upper Diameter	3.15 m
Lower Thickness	0.022 m
Upper Thickness	0.018 m

Section 3	
Length	18.86 m
Lower Diamter	4 m
Upper Diameter	3.63 m
Lower Thickness	0.028 m
Upper Thickness	0.022 m

Figure 26: Princeton Wind Turbine Tower Specifications. (PMLD, 2013).



Nacelle Design Parameters	
Nacelle Weight	87966 kg
Rotor Weight	34000 kg
Hub Height	100 m
Power Rate	12 m/s
Blade Count	3 pcs
Rotor Height	69.95 m
Rotor Diameter	77.42 m
Rated Speed	18.23 rpm
Power Output	1.5 MW
Tower Design Parameters	
Tower Height	67.4 m
Tower Weight	260000 kg
Number of Sections	3 pcs

Figure 27: Princeton Wind Turbine Design Parameters. (PMLD, 2013).

4.2.1 Wind Loading Results

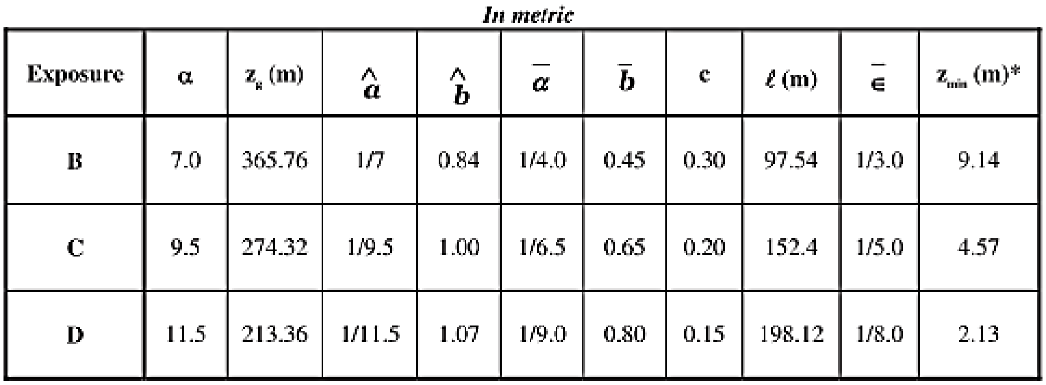
The American Society of Civil Engineers standard *Minimum Design Standards for Buildings and Other Structures* (ASCE 7-10) was used to calculate the lateral wind loading along the height of the wind turbine tower. Chapter 29 of *ASCE 7-10* defines design wind loads on other structures and building appurtenances. Wind loading was calculated at one-meter sections along the tower height to incorporate the tower taper and increasing wind velocity pressure with increasing height above ground. To calculate the wind velocity pressure Equation (22) was used:

$$q_z = 0.613 K_z K_{zt} K_d V^2$$

The exposure category for the Princeton site was determined as Exposure D, according to the following designation within *ASCE 7-10*:

> *"Exposure D shall apply where the ground surface roughness, as defined by Surface Roughness D, prevails in the upwind direction for a distance greater than 5,000ft or 20 times the building height, whichever is greater. Exposure D shall also apply where the ground surface roughness immediately upwind of the site is B or C, and the site is within a distance of 600ft or 20 times the building height, whoever is greater, from an Exposure D condition as defined in the previous sentence"(ASCE & SEI, 2013).*

The corresponding constants for Exposure D can be found in Figure 28. The constants were applied to the given equations to solve for K_z at each one-meter section. The conditions for wind speed-up were not observed at the site, and therefore $K_{zt} = 1$ was used. The basic wind speed of 44.704 m/s was found using the 2009 Massachusetts State Building Code (Standard, 2010). Table 4 summarizes the variables and their values. A sample of the calculated q_z variables is presented in Appendix E.



In metric

Exposure	α	z_g (m)	$\hat{a}$	$\hat{b}$	$\bar{\alpha}$	$\bar{b}$	c	ℓ (m)	$\bar{\epsilon}$	z_{min} (m)*
B	7.0	365.76	1/7	0.84	1/4.0	0.45	0.30	97.54	1/3.0	9.14
C	9.5	274.32	1/9.5	1.00	1/6.5	0.65	0.20	152.4	1/5.0	4.57
D	11.5	213.36	1/11.5	1.07	1/9.0	0.80	0.15	198.12	1/8.0	2.13

Figure 28 Terrain Exposure Constants. (ASCE & SEI, 2013).

Table 4 Velocity Pressure Variables and Values

Variable	Value
K$_z$	1.03 for $z < 4.6m$
	$2.01\left(\frac{z}{213.36}^{\frac{2}{11.5}}\right)$ for $4.6m \leq z \leq 212.36$
K$_{zt}$	1
K$_d$	0.95
V (m/s)	44.704

The given equation for the design wind force is from Equation (21):

$$\boldsymbol{F = q_z G C_f A_f}$$

The gust-effect factor, G, is 0.85 for rigid structures. The force coefficient, C_f, for round, moderately smooth structures is 0.7. The projected area normal to the wind, A_f, was determined by calculating the projected area of each one-meter section that was analyzed. Table 5 summarizes the variables used in the design wind force equation and their values. A sample of the calculated wind force at 1- meter intervals can be found in Table 6 (see Appendix E for full calculations).

Table 5: Design Wind Force Variables and Values

Variable	Value
q$_z$	$0.613K_zK_{zt}K_dV^2$
G	0.85
C$_f$	0.7
A$_f$	Diameter of tower at z

Table 6: Design Wind Force Calculations

Section (m)	k_z	q_z	F (N)
1	1.03	1,199	2,846
2	1.03	1,199	2,832
3	1.03	1,199	2,817
4	1.03	1,199	2,803
5	1.03	1,199	2,789
6	1.06	1,238	2,866
7	1.10	1,275	2,935
8	1.12	1,307	2,993
9	1.15	1,336	3,043
10	1.17	1,362	3,087
11	1.19	1,386	3,124
12	1.21	1,408	3,157
13	1.23	1,428	3,187
14	1.24	1,447	3,212
15	1.26	1,466	3,235
16	1.27	1,483	3,255
17	1.29	1,499	3,273
18	1.30	1,514	3,289
19	1.31	1,529	3,302
20	1.33	1,543	3,314
21	1.34	1,556	3,325
22	1.35	1,569	3,334
23	1.36	1,582	3,341
24	1.37	1,594	3,348
25	1.38	1,605	3,353
26	1.39	1,617	3,357
27	1.40	1,628	3,360
28	1.41	1,638	3,363
29	1.42	1,648	3,364
30	1.42	1,658	3,364
31	1.43	1,668	3,364
32	1.44	1,677	3,363
33	1.45	1,686	3,361
34	1.46	1,695	3,359
35	1.46	1,704	3,356
36	1.47	1,712	3,352
37	1.48	1,721	3,348
38	1.49	1,729	3,343
39	1.49	1,737	3,338
40	1.50	1,745	3,332
41	1.51	1,752	3,326
42	1.51	1,760	3,319
43	1.52	1,767	3,312
44	1.52	1,774	3,304
45	1.53	1,781	3,296
46	1.54	1,788	3,287
47	1.54	1,795	3,278
48	1.55	1,801	3,269
49	1.55	1,808	3,259
50	1.56	1,814	3,249
51	1.56	1,821	3,239
52	1.57	1,827	3,228
53	1.58	1,833	3,217
54	1.58	1,839	3,206
55	1.59	1,845	3,194
56	1.59	1,851	3,183
57	1.60	1,857	3,170
58	1.60	1,862	3,158
59	1.60	1,868	3,145
60	1.61	1,873	3,132
61	1.61	1,879	3,119
62	1.62	1,884	3,105
63	1.62	1,889	3,092
64	1.63	1,895	3,078
65	1.63	1,900	3,063
66	1.64	1,905	3,049
67	1.64	1,910	3,034

The resulting wind loading is displayed in Figure 29. The wind loading increases along the tower until the height of 30 meters is reached. At this point, the wind load begins to decrease as a result of the tower's taper. The tower experiences a cumulative lateral wind force of 215 KN along its height.

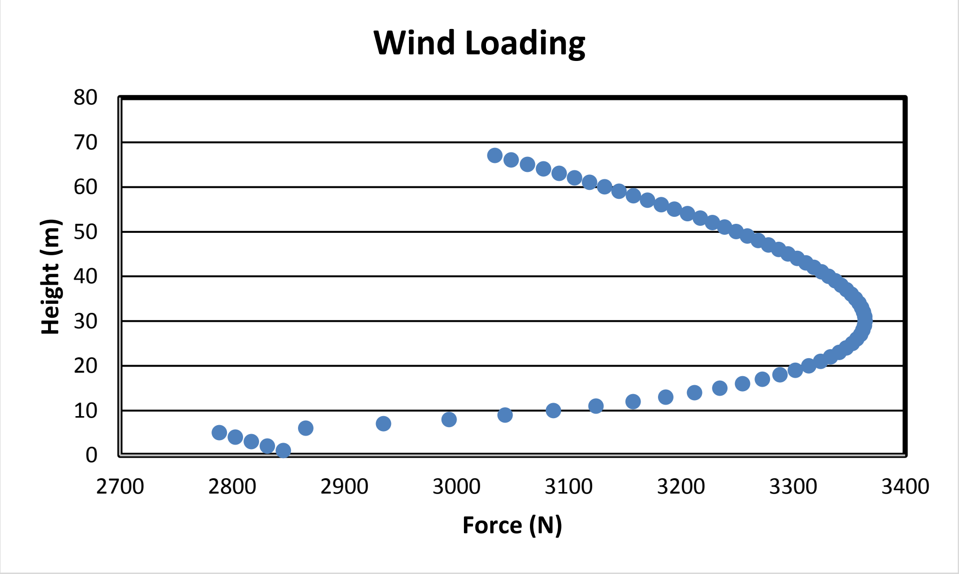


Figure 29: Wind Loading Along Tower Height.

4.2.2 Dynamic Loading Results

To verify the optimal Tip Speed Ratio $\left(\lambda_{optimal}\right)$ for the Princeton turbine, given values were compared with a calculated ratio. PMLD provided the wind turbine specifications which included the blade tip speed, which was 204-mph. The turbine speed was calculated to be within a range of 17-rpm to 21-rpm (Windtec, 2007). Using Equation (24) with an *n* value of 3, the optimal tip speed ratio was calculated as 4.2. To yield conservative values, $\lambda_{optimal}$ was set to equal to λ_{actual}. Given the tip speed, the wind speed was calculated using Equation (25):

$$\boldsymbol{Wind\ Speed = \frac{\lambda_{actual}}{Tip\ Speed}}$$

which resulted in a wind speed of 21.7 m/s. The time needed to complete one rotation was determined by using Equation (26):

$$\boldsymbol{T = \frac{2\pi r}{Tip\ Speed}}$$

which yielded 2.58 seconds, or 23 rpm. Comparing this value to the turbine speed of 17-rpm to 21-rpm, the optimal tip speed ratio yielded a value near this range. Thus, 4.2 was used as λ_{actual} for the remaining calculations. Table 7 summarizes the calculated values from above.

Table 7: Values Obtained from Dynamic Loading

Equation	Value
$\lambda_{optimal} = \lambda_{actual}$	4.2
Wind Speed (m/s)	21.7
Time per rotation	2.58 rps or 23 rpm

For given wind speed values collected from the Princeton turbine facility, the respective rpm and frequencies were calculated and are displayed in Table 8.

Table 8: RPM and Frequency of Princeton Wind Turbine

Ranges (m/s)		RPM	Frequency (Hz)
Critical Wind Speed	13.4 m/s	14.33	0.24
Max Wind Speed	12 m/s	12.83	0.21
Average Wind Speed	7.5 m/s	8.02	0.13
Minimum Wind Speed	3 m/s	3.21	0.05

Using λ_{actual} as 4.2, the power coefficient, C_p, was determined to be 0.56 by interpolating the value from the Betz Limit graph in Figure 30.

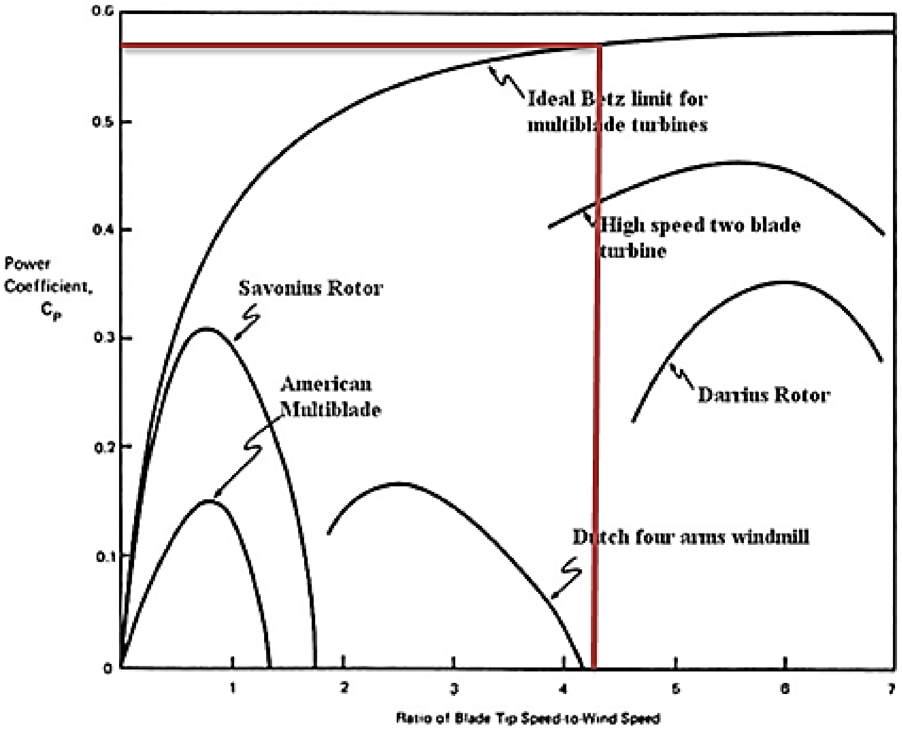


Figure 30: Interpretation of Power Coefficient. (Paz & Leigh, 2004).

The values in Table 9 were calculated using a C_p of 0.56 to determine the power output and thrust force at the wind speeds provided by PMLD. Complete calculations for the dynamic loading can be seen in Appendix F.

Table 9: Power and Thrust Force of Princeton Wind Turbine

Wind Speed Range		Power (W)	Thrust Force (KN)
Critical Wind Speed	13.4 m/s	3.65	272.09
Max Wind Speed	12.0 m/s	2.62	218.21
Average Wind Speed	7.50 m/s	0.64	85.24
Minimum Wind Speed	3.00 m/s	0.04	13.64

4.2.3 Combined Stress Results

Figure 31 illustrates the free body diagram of the forces acting along the tower height. The bending stresses due to the thrust force and lateral wind load were calculated at one-meter sections along the tower height using Equation (1), $\sigma_{bending} = \frac{Mc}{I}$. The dynamic magnification for the thrust force was 1.1 based on a frequency ratio of 0.2 and an assumed 2% damping ratio. The calculation of bending moment began at the top of the tower at the first one-meter section, to include the dynamic loading and the first one-meter section of the wind profile. As the moment calculation continued down the tower height, the dynamic force remained constant with a varying and increasing moment arm. The wind loading varied in magnitude as the analysis progressed down the tower height resulting in a larger moment arm for each analyzed section.

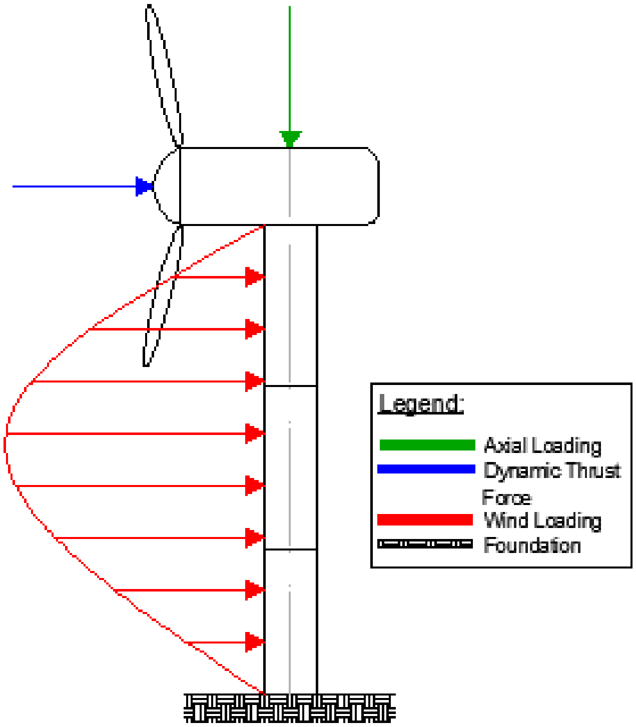


Figure 31: Free Body Diagram - Forces Acting on Tower.

The resulting moment diagram can be seen in Figure 32. The maximum moment was calculated at the mid-height of the first one-meter from the foundation, while the smallest moment was observed at the mid-height of the top one-meter section of the tower. The maximum moment has a magnitude of 28,000 KN-m, while the magnitude of the smallest moment was 1,000 KN-m.

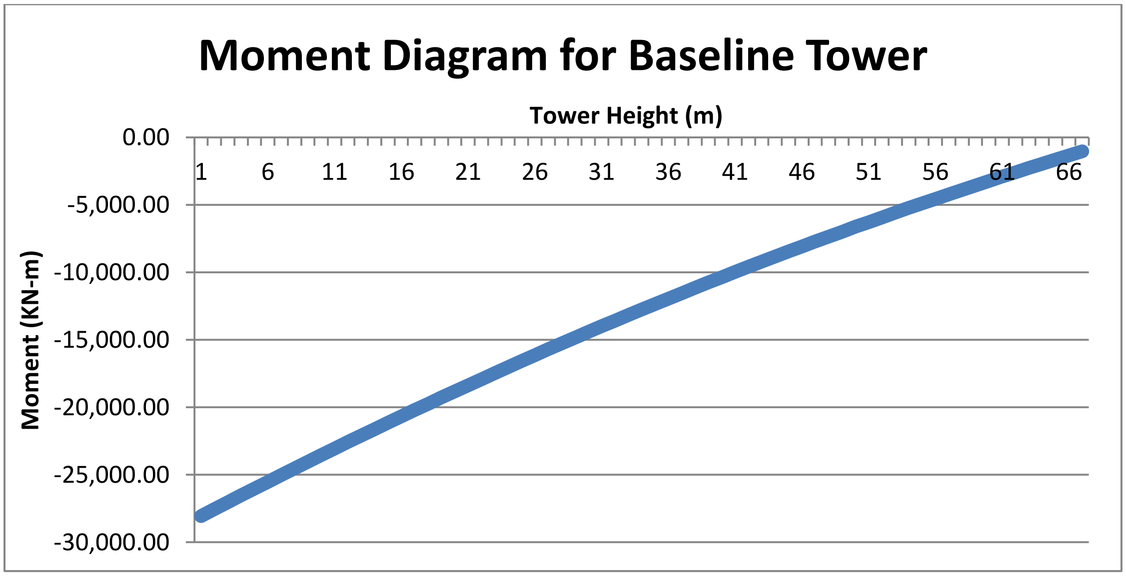


Figure 32: Moment Diagram for Baseline Tower.

The values for the moment diagram are observed as a linear trendline, even though the distribution of the wind profile is parabolic. As the moment calculation moved down the tower, additional sections were taken into consideration and therefore resulted in a greater moment value. Analysis showed that the range of wind forces acting on each one-meter section varied so slightly that it allowed for a linear increase of forces down the tower height.

The moment of inertia (*I*) and the perpendicular distance from the neutral axis to the farthest fiber of the cross section (c) were identified for each one-meter segment. The values for I and c accounted for the change of wall thickness and the taper angle of the tower.

The axial stress was calculated along the tower height using Equation (2), $\sigma_{axial} = \frac{P}{A}$. The dead load for the first one-meter section, at the top of the tower included the weight of the nacelle, weight of the rotor, and the self weight of the 1- meter section, which can be seen in Table 10. As sections were analyzed further down the tower, the dead load was successively increased to account for the weights of the additional tower sections.

Table 10: Dead Load Specifications

Dead Load	
Tower Section Weight	1,650 kg
Nacelle Weight	88,000 kg
Rotor Weight	32,000 kg
Total Tower Weight	110,400 kg

Figure 33 shows the combined stresses graphed as a function of the tower height. The combined stress includes the summation of the bending and axial stresses.

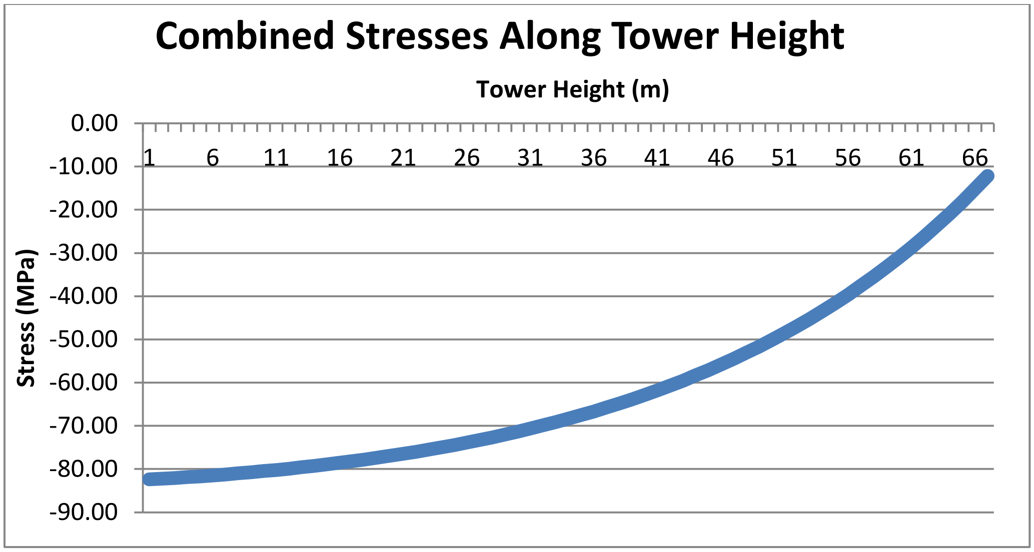


Figure 33: Axial and Bending Stresses along Turbine Tower.

The magnitude of the combined stress at the top of the tower was calculated to be 12 MPa. At the bottom of the tower, the maximum combined stress was determined to be 82 MPa. Although the tower's profile has a taper angle and its wall thickness varies with height, the axial stress ($\frac{P}{A}$) remained relatively consistent throughout the tower at approximately 0.20 MPa. Therefore the combined stress analysis was controlled primarily by the bending stresses.

4.2.4 Buckling Analysis

The buckling analysis consisted of investigating both column buckling and local buckling. The analysis for the Princeton wind turbine tower is presented below.

Column Buckling

The column buckling was investigated at the base of the tower using both the Timoshenko method for evaluating effective length factor, K, and the AISC method for calculating allowable compression stress as described in Section 2.2.2. Table 11 shows the allowable column buckling stress for the baseline tower. Once the *m* factor was determined using the Timoshenko method, the AISC method was used to calculated the allowable column buckling stress.

Table 11: Allowable Column Buckling Stress for Baseline Tower

Parameter	Value
I1/I2 ratio	0.4
***m* factor**	1.9
K	2.3
λ	436.6
σ_{cr} (MPa)	10.4
$\sigma_{allowable}$ (MPa)	6.2

Since the slenderness ratio is greater than 113, the tower is categorized as a long column, and the following equation was used to determine the critical stress:

$$\sigma_{cr} = .877 * Fy$$

Figure 34 presents the results for the allowable column buckling compared to the calculated stresses. The calculated stresses on the tower only considered axial stresses because when the tower is vertical, there are no bending stresses acting on the tower. The graph shows that the baseline tower will not fail due to column buckling because the allowable column buckling stress is larger than the calculated axial stress.

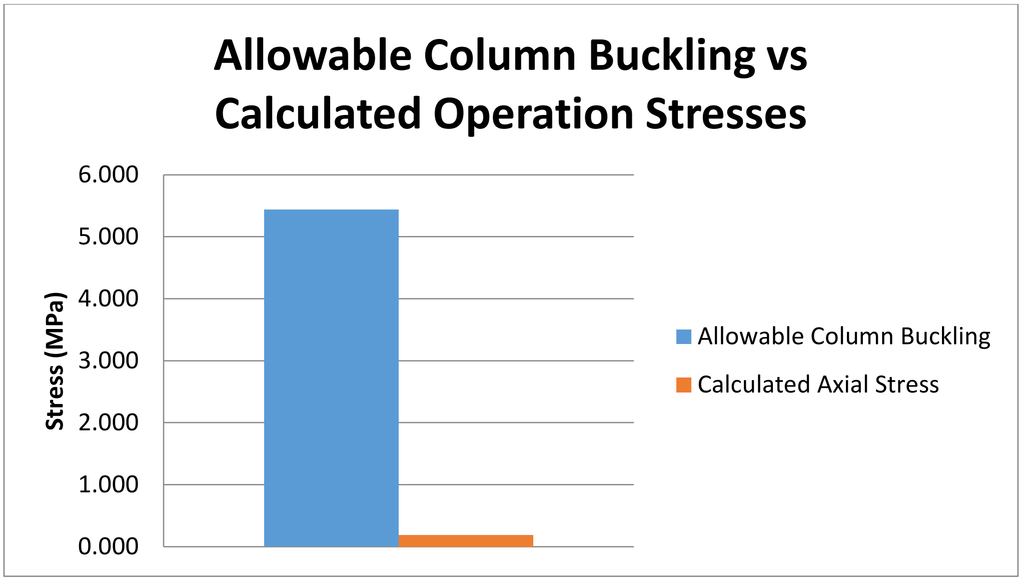


Figure 34: Allowable Column Buckling vs. Calculated Operational Stresses.

Local Buckling

Using both the Troitsky method and the Wind Energy Handbook method as previously described in Section 2.3.2, Table 12 presents the results for the local buckling calculations along the tower height. The local buckling capacity varied with changes in the radius and thickness of the tower's wall. Complete calculations can be seen in Appendix G.

Table 12: Local Buckling Stresses vs. Actual Stresses Results

Tower Length	Troitsky	Wind Energy Handbook	Combined Stress
1	170	125	82
2	170	125	82
3	170	125	82
4	170	125	82
5	169	125	82
6	169	125	81
7	169	125	81
8	169	125	81
9	169	125	81
10	169	124	80
11	169	124	80
12	169	124	80
13	169	124	80
14	169	124	79
15	169	124	79
16	169	124	79
17	169	124	78
18	169	123	78
19	169	123	77
20	169	123	77
21	169	123	76
22	169	123	76
23	169	123	75
24	168	123	75
25	168	123	74
26	168	123	74
27	168	123	73
28	168	123	73
29	168	123	72
30	168	123	71
31	168	123	71
32	168	123	70
33	168	123	69
34	168	123	68
35	168	123	68
36	168	123	67
37	168	123	66
38	168	123	65
39	167	123	64
40	167	123	63
41	167	123	62
42	167	123	61
43	167	123	60
44	167	122	58
45	167	122	57
46	167	122	56
47	167	122	54
48	167	122	53
49	167	122	52
50	167	122	50
51	167	122	49
52	166	122	47
53	166	122	45
54	166	122	43
55	166	122	42
56	166	122	40
57	166	122	38
58	166	122	36
59	166	122	33
60	166	122	31
61	166	122	29
62	166	122	26
63	165	122	24
64	165	122	21
65	165	122	18
66	165	122	15
67	165	122	12

The maximum calculated stress was observed at the base of the tower, and is found to be within the allowable stress boundaries for both local buckling methods. The figure below illustrates the local stress comparison at one-meter sections along the height of the tower (Figure 35).

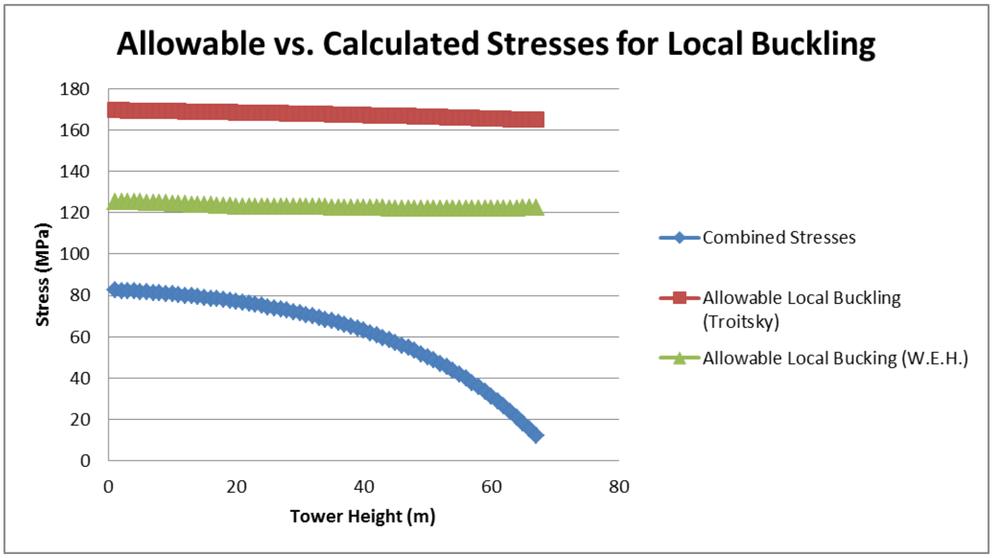


Figure 35: Comparison of Allowed Local Buckling Stress to Calculated Combined Stresses.

As demonstrated by the figure, the baseline tower will not fail due to local buckling. Going forward, this project uses the Troitsky local buckling theory for investigating the alternative towers because it is the most applicable.

4.3 Economic Analysis

The total cost of the Princeton Wind Turbine project was $7.1 million, roughly $2,367/kW. The project costs were broken down into turbine cost, foundation, site work, and turbine erection. Methuen Construction provided costs estimates for each of those project elements (Boyle, personal communication, 2013). About $5 million was allotted to the turbine cost which included the fabrication and delivery of the two 1.5MW turbines and towers. The foundation work, which included rock anchors and cast-in-place concrete, cost approximately $375,000. The site work for the project included clearing, road construction, rock blasting, drainage improvements, and loam and seed, and the total cost of these elements was about $675,000. The turbine erection included crane rental, crew wages, and other miscellaneous expenses totaling approximately $350,000. A summary table of the project costs can be seen in Table 13.

Table 13: Princeton Wind Turbine Project Costs

Project Element	Cost
Turbine Costs	$5,000,000
Foundation	$375,000
Site Work	$675,000
Turbine Erection	$350,000
Total Project	$7,150,000
Total Cost per kW	$2,367

Of the turbine erection costs, the total costs associated with the crane were $241,050. This price included the rental cost of the Manitowac crane and an additional attachment that is required for the erection of wind turbines. The price also included round trip transportation of the crane to and from the Princeton location and its transportation between the two wind turbines sites. The erection of the tower required a smaller crane in addition to the Manitowac crane; therefore, the crane rental breakdown also includes the costs for a 50-ton assist crane. The cost estimate also includes an assembly and disassembly cost. Finally, the rental costs include the price of the crane operators over the rental period. Table 14 presents the costs of each of the aforementioned crane rental elements.

Table 14: Crane Rental Costs

Crane Rental Element	Cost
Rental of Manitowac Crane and wind attachment	$95,000
Crane Operator for 6 days for turbine erection	$9,300
Assist crane for 6 days for turbine erection	$9,000
Roundtrip transportation	$50,000
Crane assembly and disassembly	$47,250
Crane operator for 10 days for crane erection	$15,550
Transport between turbines	$15,000
Total Crane Rental	$241,050

4.4 Tilt-Up Method Analysis

The tilt-up erection method was explored for the baseline tower to determine the feasibility of erecting the tower using this method. The calculations in Appendix D present hand calculations that verified formulas calculated in *Excel*. Table 15 provides a summary of the calculated values for the minimum required cable tension and maximum calculated stresses for each tilt-up analysis.

Table 15: Overview of Tilt-Up Cases with Varying Number of Guy Wires

# of Attachments	Attachment Location From Base of Tower (m)	Minimum Tension (N)	Maximum Stress (MPa)
1	27.75	31,000,000	60
2	27.75, 47.75	29,900,000	25
3	27.75, 40.75, 53.75	28,800,000	24

4.4.1 One-Point Attachment

The first case analyzed the tower with a single lifting cable attached at the center of gravity, located 27.75 meters from the base of the tower. Table 16 summarizes the minimum tension required to lift the tower from an initial incline with respect to the horizontal.

Table 16 Minimum Required Tension for Initial Lifting Conditions

Incline Angle	Minimum Tension Required (N)
0°	∞
1°	62,000,000
2°	31,000,000

Lifting the tower from the ground (0°) with guy wires pulling horizontally would result in dragging the tower along the ground rather than lifting it vertical. Lifting the tower at 2° required half of the tension of lifting the tower at 1°. Because of this immense difference, an assumption was made that an apparatus was placed below the tip of the tower to position the tower end approximately 2º (2.34 meters) off the ground (Figure 36). This positioning of the tower prior to lifting would still allow workers to reach the tower if necessary. For each of the following cases, the minimum required tension was calculated from a 2° initial incline above the ground to remain consistent.

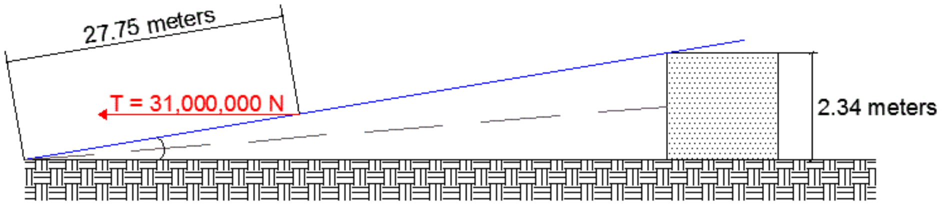


Figure 36: One-Point Attachment with Lifting Apparatus.

As the tower was lifted up, the bending stresses decreased and approached zero, while the axial stresses became the governing stress. This is because the stresses were changing from bending to axial stresses as the tower approached a vertical inclination. Figure 37 shows the calculated stress curve calculated at every analyzed angle (θ = 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80° and 90°). The blue curve at the top represents the stresses along the length of the tower as lifting just starts at 2° and the purple curve at the bottom represents the stresses when the tower is fully erected at 90°.

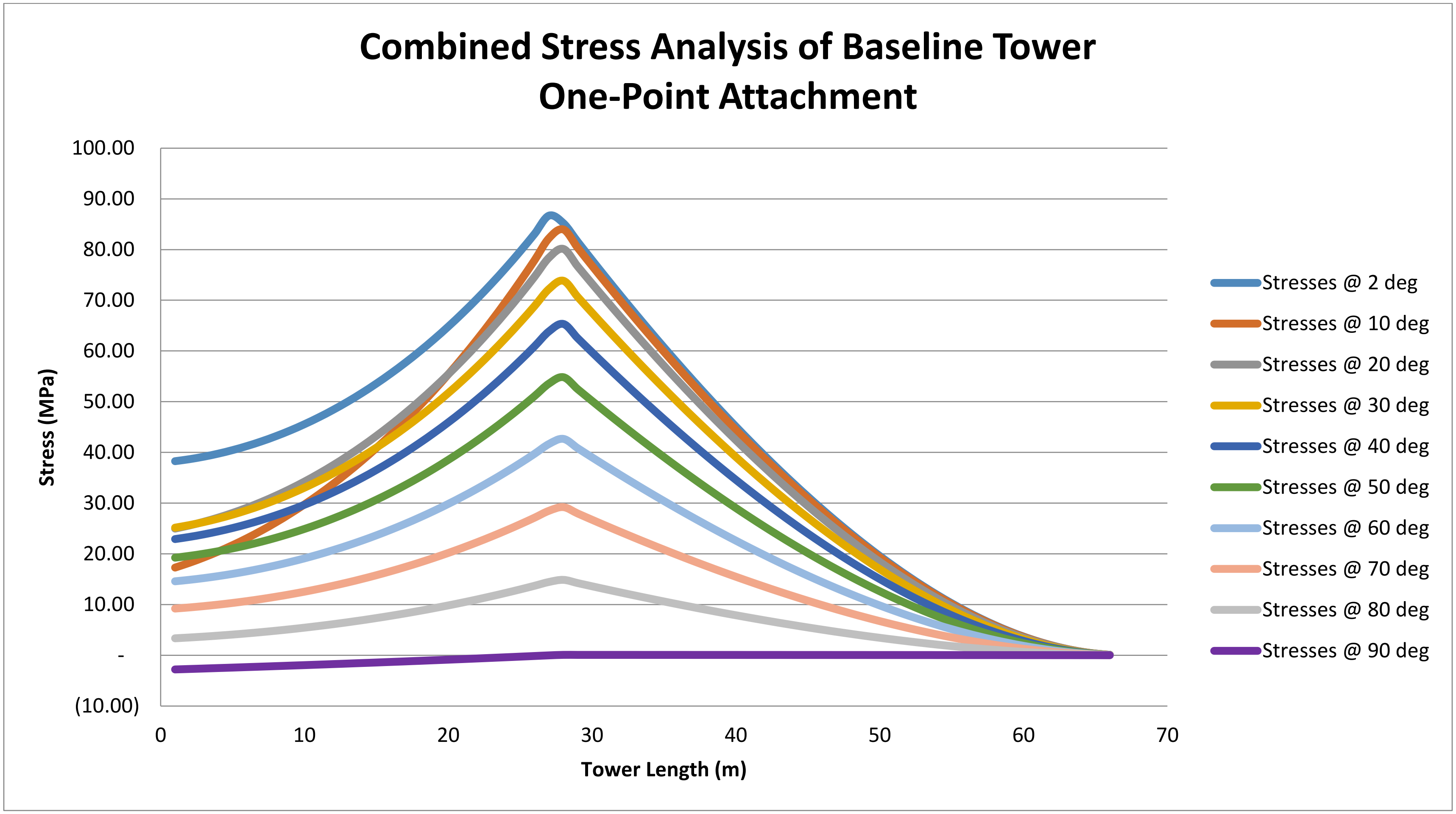


Figure 37: Combined Stress Analysis of Baseline Tower: One-Point Attachment.

Stresses along the height of the tower were calculated at 10° increments and the greatest stresses were found at 2°. Figure 38 depicts the stresses along the tower height for 2° where the maximum stress is located at 27.75 meters from the base, which corresponds to the guy wire attachment point. The maximum stress was about 83 MPa, which is below the allowable local buckling (red line) and the allowable bending stress for steel (purple line).

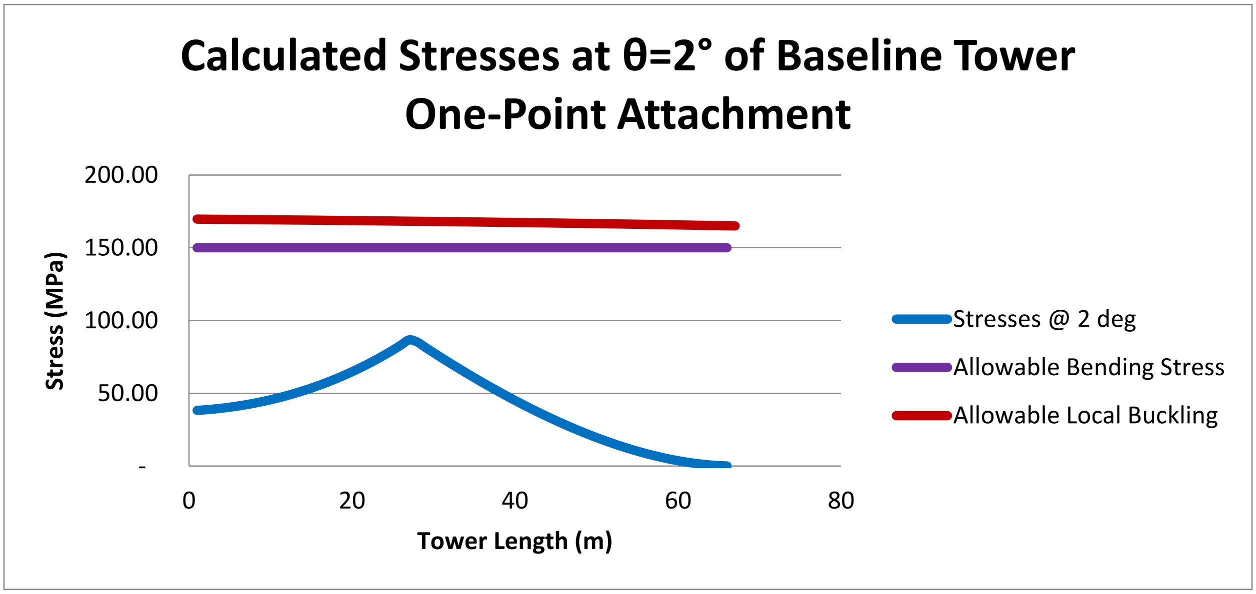


Figure 38: Calculated Stresses at 2° of Baseline Tower: One Point Attachment.

The combined stresses produced along the tower height are below the allowable bending stress for A-36 steel and can withstand local buckling stresses. This analysis suggested that lifting the tower with one guy wire was feasible in terms of the tower's capacity. However, the tension force required would be 3,485 tons. No crane has the ability to lift at this capacity, making this erection method impractical to implement for the baseline tower design.

4.4.2 Two-Point Attachment

The minimum tension required to lift the tower with two attachment points beginning at 2° was just under 30,000,000 N, or 3,372 tons. The calculated tension was the total tension required to lift the system and was divided between the two wires, thus each carries roughly 15,000,000 N, or 1,686 tons.

Similar to the one-point analysis, stresses along the tower decreased at each subsequent angle as the tower is lifted. The calculated stress curves for each angle can be seen in Figure 39. As the tower approaches 90°, the bending stresses converged to 0 MPa because they change to axial stresses.

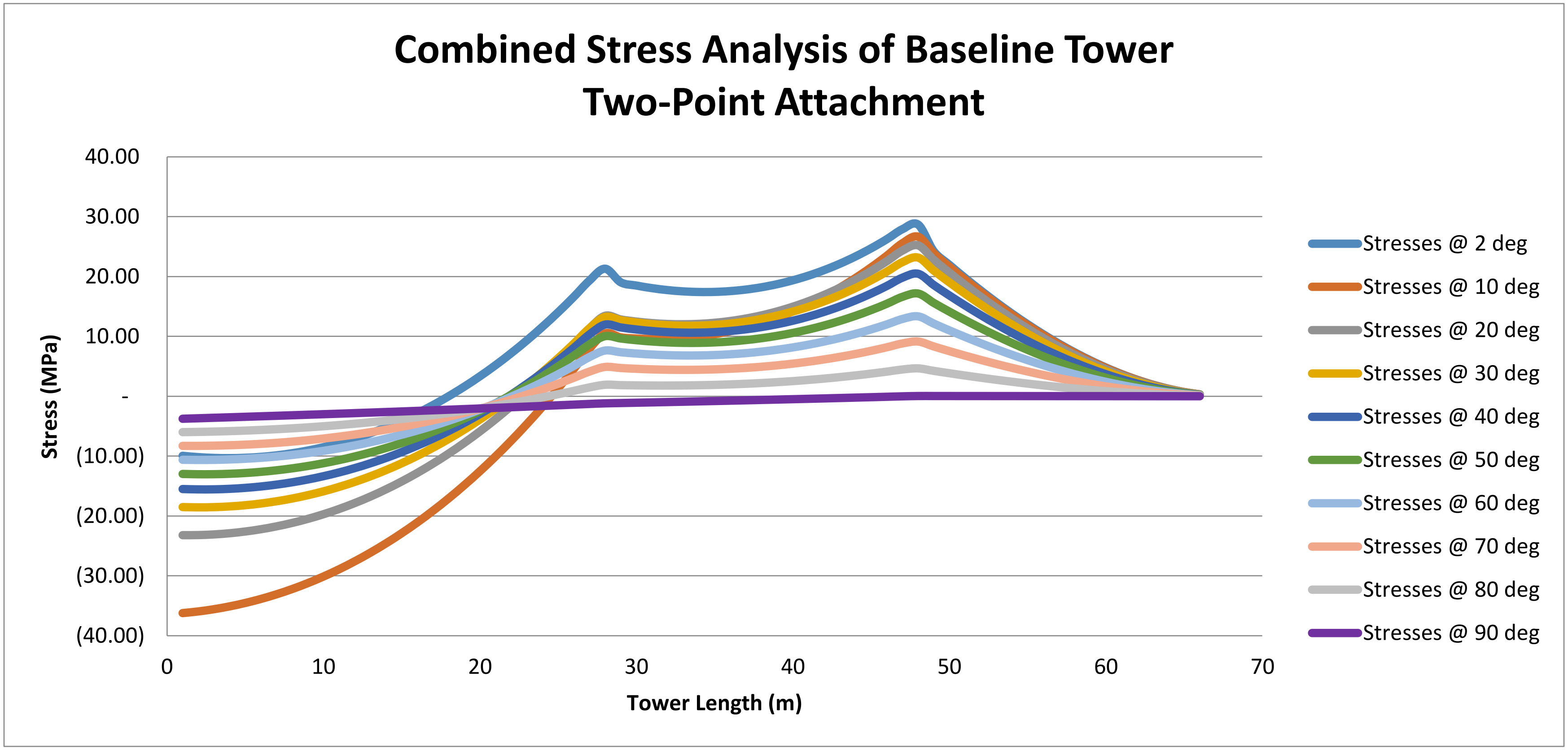


Figure 39: Combined Stress Analysis of Baseline Tower: Two Point Attachment.

As depicted in Figure 40, the stresses along the tower height at 2° of inclination are less than the allowable bending stress. It is important to note that the overall stresses have decreased when compared to the one-point attachment analysis. The maximum stress for the one-point attachment analysis was roughly 83 MPa, and the maximum stress for two lifting points was reduced to 28 MPa. The calculated stresses for the two-point analysis were also lower than the allowable local buckling (red line) and the allowable bending stress (purple line).

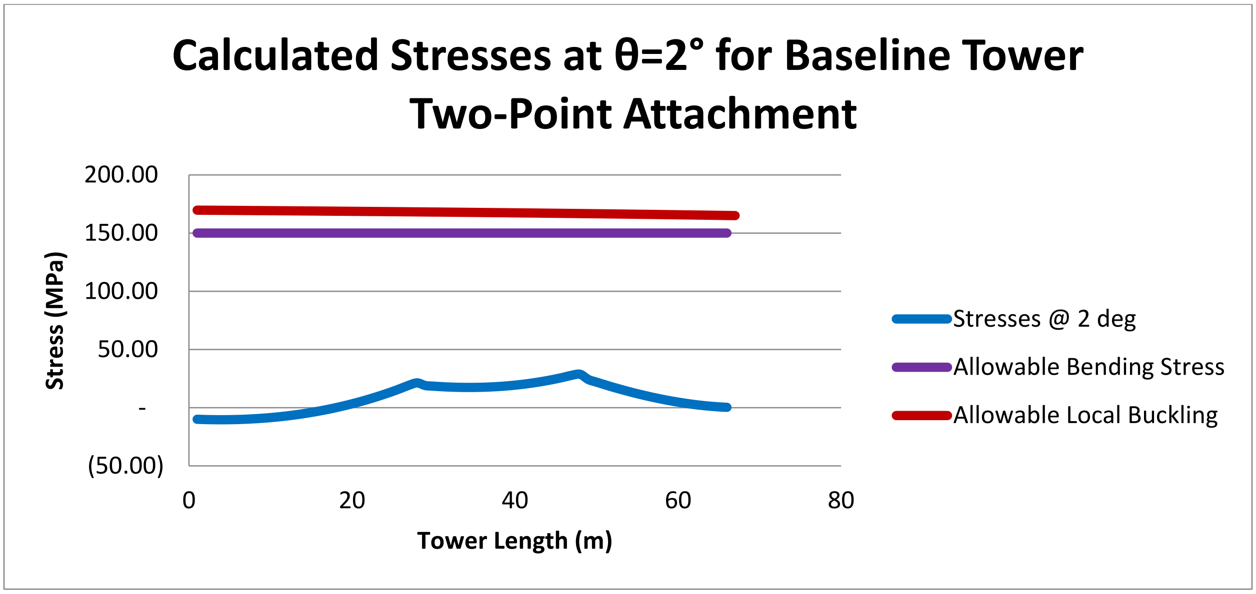


Figure 40: Calculated Stresses at 2° for Baseline Tower: Two Point Attachment.

This analysis suggests that lifting the tower with two guy wires is feasible in terms of the tower's capacity. The combined stresses produced along the tower height are below the allowable bending stress for A-36 steel and can withstand local buckling stresses. The calculations also determined that the overall stresses along the tower height are smaller than that of the one point attachment analysis, making the two point attachment tilt-up method a more effective approach. However, the tension force required would be 3,360 tons. No crane has the ability to lift at this capacity, making this erection method impractical.

4.4.3 Three-Point Attachment

The third case analyzed the tower using three guy wires, whose initial locations are demonstrated in Figure 41B. The minimum tension needed for these attachments is 33,500,000 N which is distributed equally to the three wires. The calculations for the initial placement of guy wires produced a larger tension moment than the one and two wire configurations. The wire configuration was therefore relocated higher on the tower to produce a smaller moment at the top of the tower as demonstrated in Figure 41A. Therefore, larger moments occur at the base of the tower, which reduced the required magnitude of the tension force. The moment due to the self-weight remains the same and must be overcome by the moment due to the tension forces. The new arrangement yielded a minimum tension of 28,800,000 N (3,237 tons); which was the smallest of all three configurations.

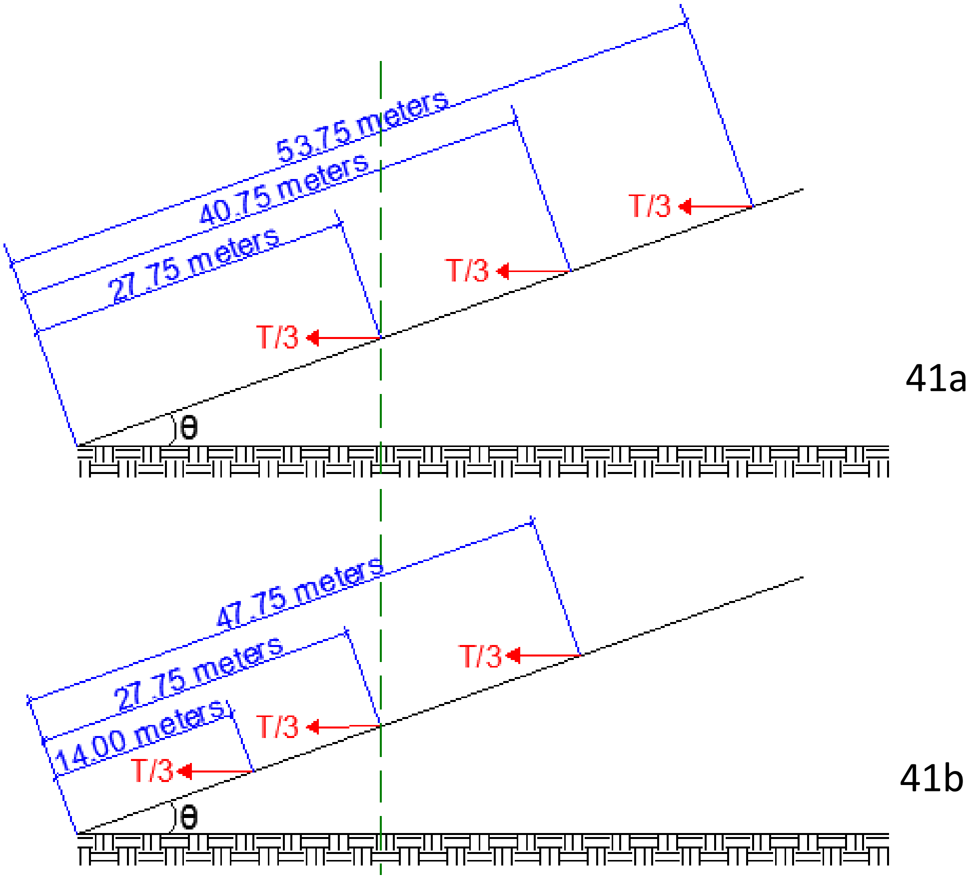


Figure 41: A-Final Placement of Guy Wires B- Initial Placement of Guy Wires.

Comparable to the one and two-point attachments, the stresses followed the same trend as the other configurations and decreased at each subsequent angle. The calculated stress curves for the initial 2° and each 10° increment in angle can be seen in Figure 42. As the tower approaches 90°, the bending stresses converge to 0 MPa as more forces contribute to the axial direction.

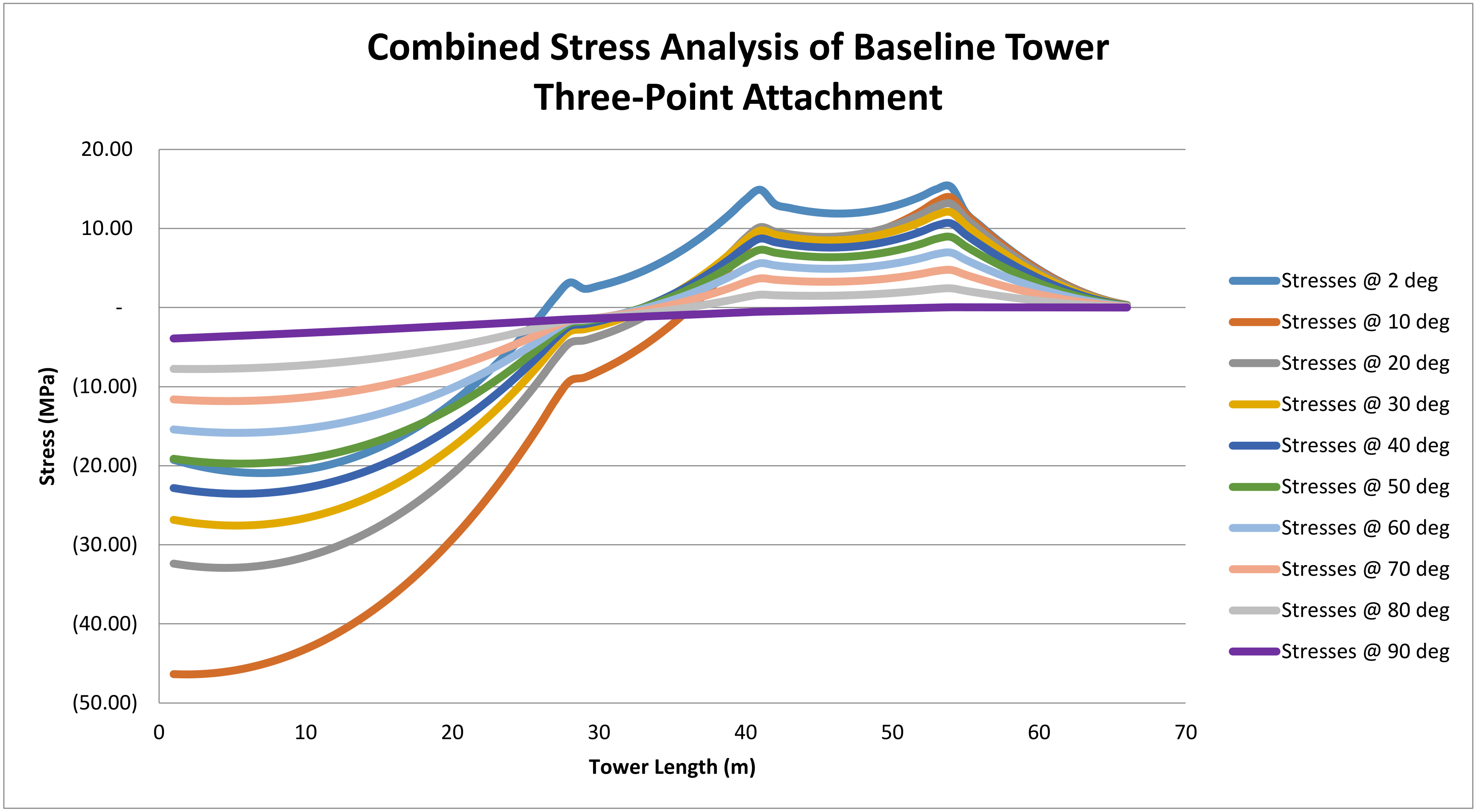


Figure 42: Combined Stress Analysis of Baseline Tower: Three Point Attachment.

As depicted in Figure 43, the stresses along the tower height at 2° are less than the allowable bending stress (purple line) and the allowable local buckling (red line). Unlike the results for the one and two-point analyses, the maximum stress for the three-point analysis was observed in the bottom portion of the tower; the maximum value was 19 MPa. The maximum stress experienced at an attachment point occurred at the third guy wire, with a stress of 14 MPa.

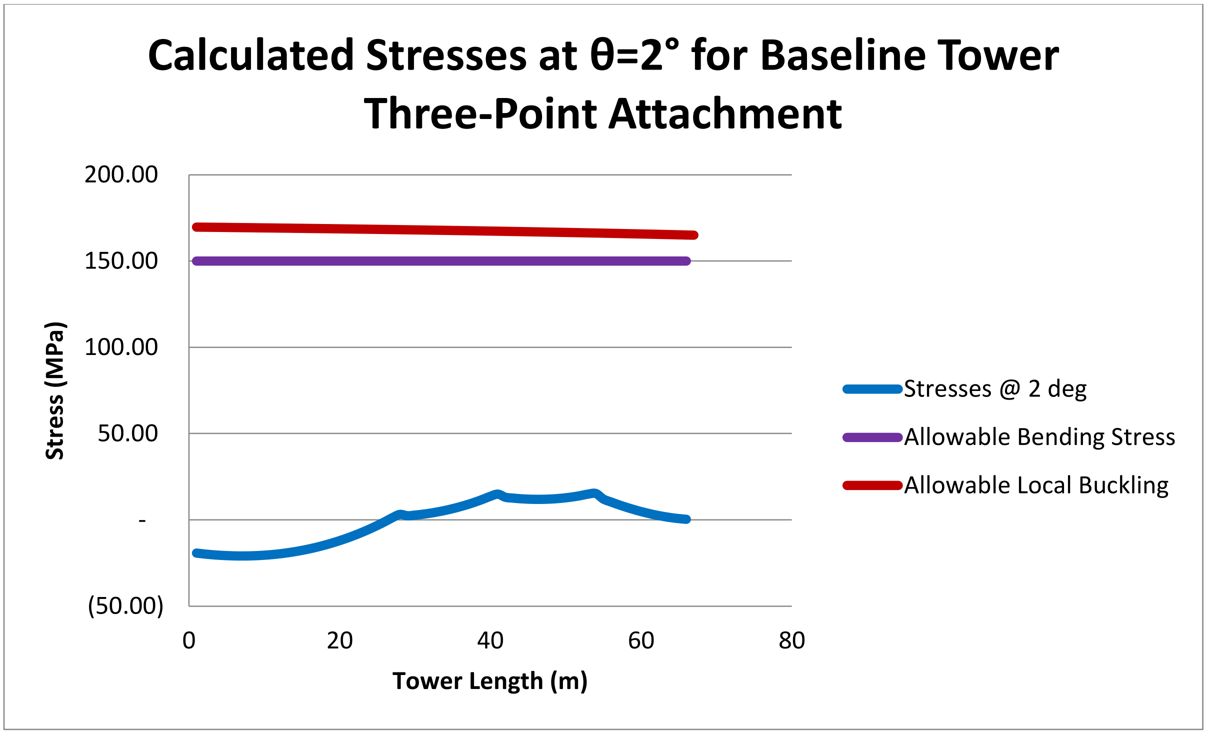


Figure 43: Calculated Stresses at 2° Angle for Baseline Tower: Three Point Attachment.

This analysis suggests that lifting the tower with three guy wires is feasible in terms of the tower's capacity. It was also the most effective tilt-up method because it yields the lowest overall stresses acting along the tower. Future analysis of the alternative tower designs using the tilt-up erection method will only consider three point guy wire arrangements. However, this case still requires 3,237 tons of force to pull the tower vertical. In the case of the Princeton wind turbines and towers of similar size, the tilt-up erection method was found to be impractical.

Yielding Results

The yielding check was performed at the base of the tower for the three-point attachment. The results suggested that the tower does not fail due to yielding because interaction equation was less than 1. This test was conducted at the first one-meter section of the baseline tower, which can be seen in Figure 44. By altering the calculated slenderness ratio values, yielding of the tower change accordingly. Further calculations for this yielding check along the remaining length of the tower can be found in Appendix K.

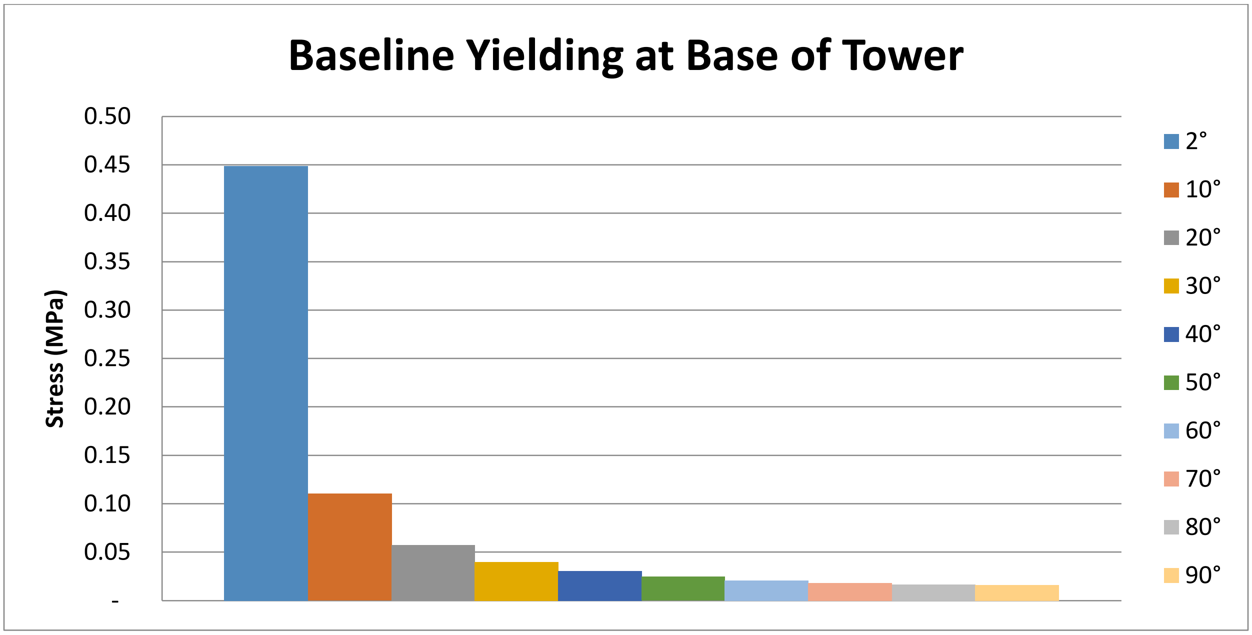


Figure 44: Yielding Results for Baseline Tower.

4.5 Summary

The wind turbine tower in Princeton, MA served as a baseline case study for stresses endured during operation. The analyses performed provided a framework for alternative tower designs moving forward with the study of the tilt-up erection method. A cost analysis was developed and served as a baseline to compare project costs for the alternative towers.

The baseline turbine tower was further analyzed using the tilt-up erection method to investigate whether the tower could have been erected using this alternative method. The results suggest that it is feasible in terms of the tower’s capacity to erect the tower via the tilt-up method with the three guy wire configuration. However, due to the large required tension forces for a tower size similar to Princeton’s, no such crane exists to erect the baseline tower design. The completion of the stress analyses for operations and tilt-up erection of the baseline tower provided a framework to develop the designs and analyses of the alternative turbine towers.

5.0 Decision Tool for Towers

Having completed a baseline analysis of the Princeton, MA wind turbine tower, a framework for future tower analyses was created using the developed spreadsheet. Figure 45 shows the steps taken to create the framework tool.

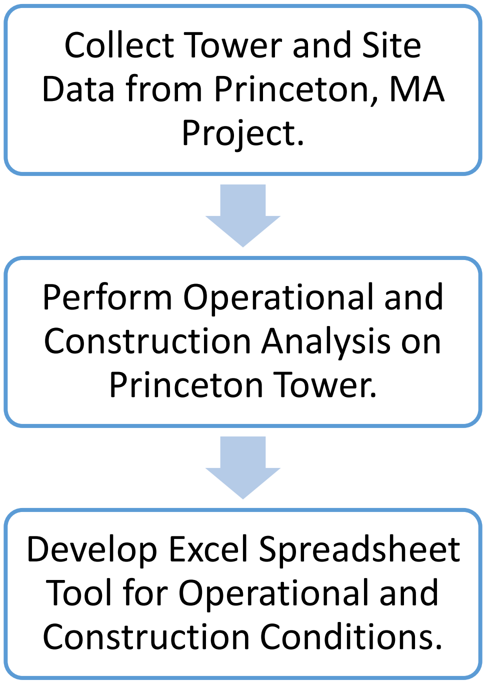


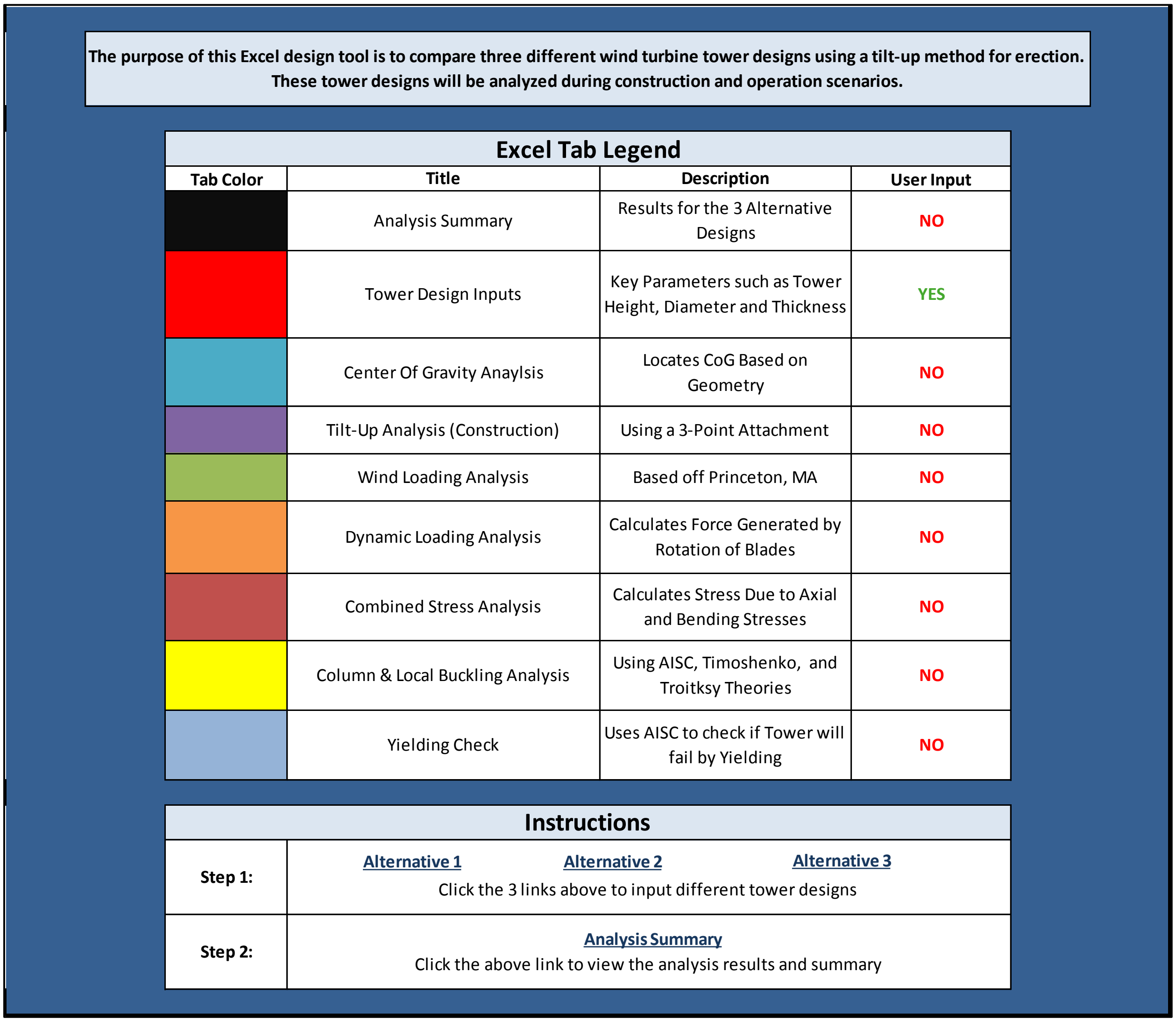
Figure 45: Processes Involved with *Excel* Spreadsheet

An *Excel* spreadsheet was created to aid in the investigation of the applied loads, internal forces and stresses that would act on a wind turbine tower during tilt-up construction as well as those experienced during operation. The analyses associated with construction and operation are summarized in Table 17.

Table 17: Stresses Associated with Construction and Operation of Turbine Tower

Tower Use	Analyses Performed
Construction	• Combined Stresses • Local Buckling • Minimum Tension Required
Operation	• Combined Stresses • Local and Column Buckling • Dynamic Thrust Force

The *Excel* spreadsheet was designed with a limited number of inputted design parameters to allow for a simple, easy to use tool for structural design and analysis. The first tab of the file includes instructions for using the tool, as seen in Figure 46.



The purpose of this Excel design tool is to compare three different wind turbine tower designs using a tilt-up method for erection. These tower designs will be analyzed during construction and operation scenarios.

Excel Tab Legend

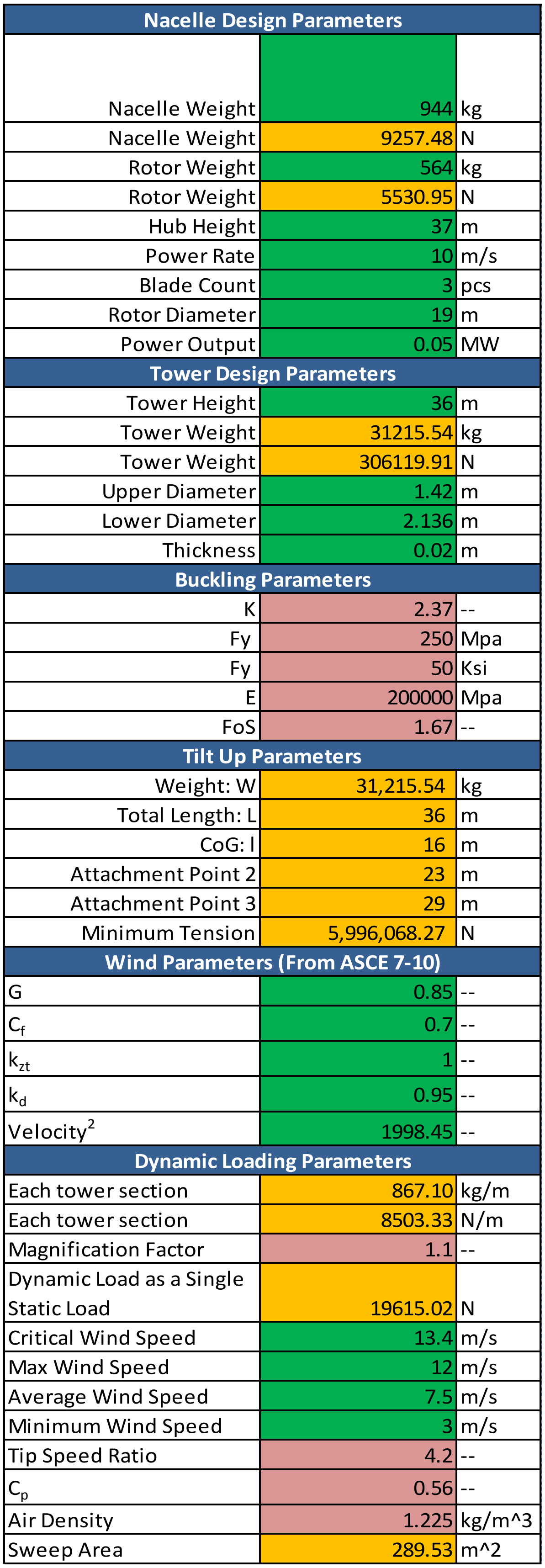
Tab Color	Title	Description	User Input
⬛	Analysis Summary	Results for the 3 Alternative Designs	NO
🟥	Tower Design Inputs	Key Parameters such as Tower Height, Diameter and Thickness	YES
🟦	Center Of Gravity Anaylsis	Locates CoG Based on Geometry	NO
🟪	Tilt-Up Analysis (Construction)	Using a 3-Point Attachment	NO
🟩	Wind Loading Analysis	Based off Princeton, MA	NO
🟧	Dynamic Loading Analysis	Calculates Force Generated by Rotation of Blades	NO
🟥	Combined Stress Analysis	Calculates Stress Due to Axial and Bending Stresses	NO
🟨	Column & Local Buckling Analysis	Using AISC, Timoshenko, and Troitksy Theories	NO
🟦	Yielding Check	Uses AISC to check if Tower will fail by Yielding	NO

Instructions

Step 1:	Alternative 1 Alternative 2 Alternative 3 Click the 3 links above to input different tower designs
Step 2:	Analysis Summary Click the above link to view the analysis results and summary

Figure 46: *Excel* Spreadsheet Instruction Tab.

The red tabs indicate alternative tower designs the user wishes to investigate. The user can input up to three different tower designs (labeled in red as “Alternative 1, “Alternative 2”, and “Alternative 3”) into the *Excel* sheet to provide a direct comparison of multiple towers. Figure 47 presents the cells into which the user will input the tower specifications. The green cells indicate areas for manual input, the yellow cells are populated based on the input of the green cells. The cells colored red contain values that are standard for all wind turbine tower structures and should not be changed.



Nacelle Design Parameters		
Nacelle Weight	944	kg
Nacelle Weight	9257.48	N
Rotor Weight	564	kg
Rotor Weight	5530.95	N
Hub Height	37	m
Power Rate	10	m/s
Blade Count	3	pcs
Rotor Diameter	19	m
Power Output	0.05	MW
Tower Design Parameters		
Tower Height	36	m
Tower Weight	31215.54	kg
Tower Weight	306119.91	N
Upper Diameter	1.42	m
Lower Diameter	2.136	m
Thickness	0.02	m
Buckling Parameters		
K	2.37	--
Fy	250	Mpa
Fy	50	Ksi
E	200000	Mpa
FoS	1.67	--
Tilt Up Parameters		
Weight: W	31,215.54	kg
Total Length: L	36	m
CoG: l	16	m
Attachment Point 2	23	m
Attachment Point 3	29	m
Minimum Tension	5,996,068.27	N
Wind Parameters (From ASCE 7-10)		
G	0.85	--
C_f	0.7	--
k_{zt}	1	--
k_d	0.95	--
Velocity^2	1998.45	--
Dynamic Loading Parameters		
Each tower section	867.10	kg/m
Each tower section	8503.33	N/m
Magnification Factor	1.1	--
Dynamic Load as a Single Static Load	19615.02	N
Critical Wind Speed	13.4	m/s
Max Wind Speed	12	m/s
Average Wind Speed	7.5	m/s
Minimum Wind Speed	3	m/s
Tip Speed Ratio	4.2	--
C_p	0.56	--
Air Density	1.225	kg/m^3
Sweep Area	289.53	m^2

Figure 47: Screenshot of Input and Calculated Values

5.1 Investigation of Construction of Wind Turbine Towers

The construction of wind turbine towers with the tilt-up erection method involved calculating the tension forces required to lift the tower using three guy wires and the combined stresses experienced by the tower. The spreadsheet automatically defaults to a three-point attachment scenario since it produces the smallest stresses on the tower. Once the tower specifications are entered into the input cells on the red alternative tabs, the *Excel* spreadsheet calculates the tension forces in the guy wires as the tower is lifted from an initial incline of 2° to the vertical position. Using these tension forces and other tower specifications, the *Excel* file also calculates stresses experienced by the tower during construction. The resulting calculations are the purple “Alternative 1, 2 and 3” tilt-up tabs (Figure 48). The purple tabs do not need to be altered, but instead provide the calculations if the user wishes to investigate the actual stresses at each meter along the length of the tower for every angle of inclination.

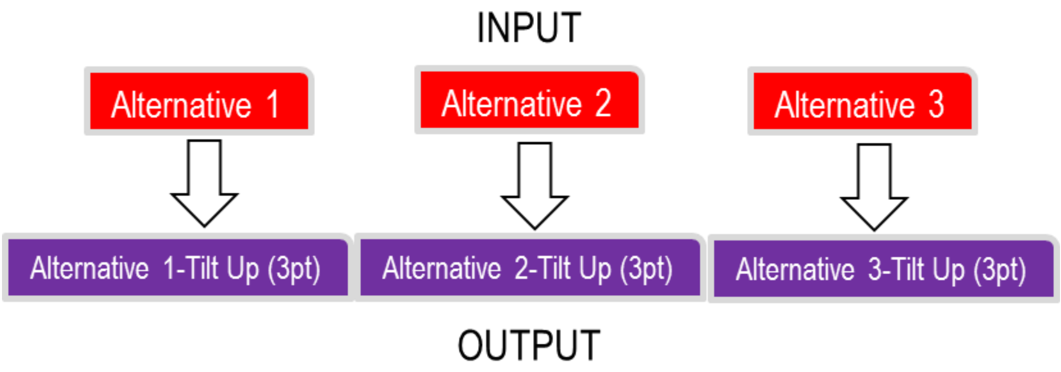
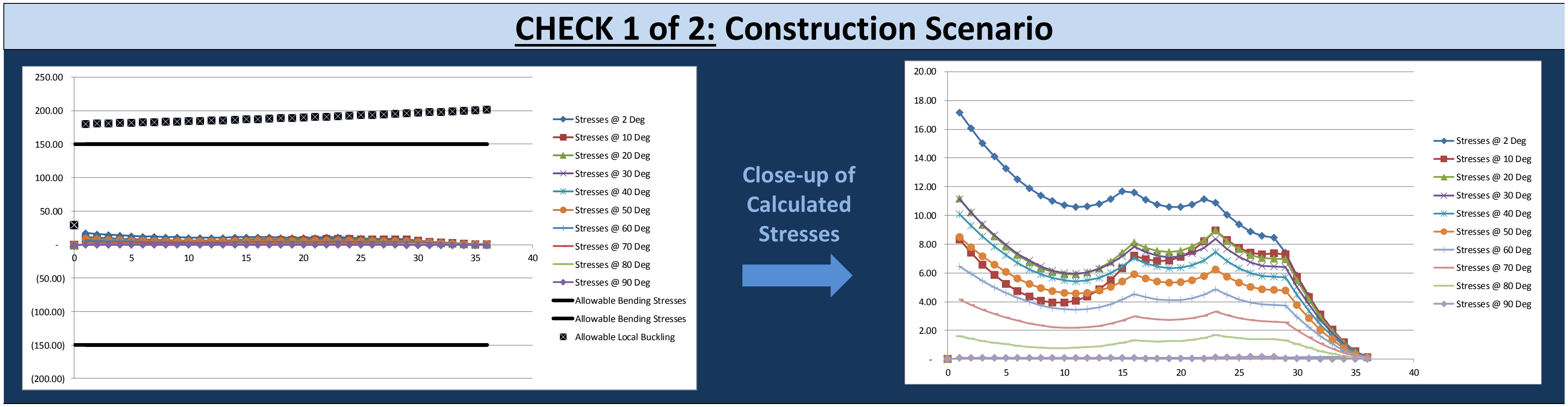


Figure 48: Flowchart of Construction Calculations

Once the data is entered and calculated, the user can view the “Analysis Summary” tab which displays graphs that demonstrate whether or not the tower will fail during construction and by which failure mode (Figure 49). The summary page also provides the values for the minimum tension required to lift the tower and the maximum stresses experienced. All three of the alternatives are presented on the same page to allow for an easy comparison. The purpose of the summary tab is to allow the user to find the essential information without searching through the calculation tabs. The calculation tabs for each of the alternatives were left viewable, but protected to provide the user the opportunity to further investigate calculations without changing the values inadvertently.

The *Excel* file was developed to calculate tower heights up to 90 meters and automatically generates zeroes for section heights taller than the actual tower height value. It is important to note that at tower sections greater than the tower height, the graph will display values that do not reflect the behavior of the analyzed tower. For example, if the tower is 35 meters tall, the remaining 55 meters of calculations will display a value of zero. Due to the limits of *Excel*, the graphs found on the summary page must present all the tower sections up to 90 meters. Therefore, the checks for the construction and operation of the tower only apply along the corresponding tower height.


CHECK 1 of 2: Construction Scenario

Close-up of Calculated Stresses

Figure 49: Screenshot of Check 1 of 2 on Summary Page.

If the actual stresses during construction (“Check 1 of 2” on the Analysis Summary Tab) are less than the limits of the allowable bending, local buckling and yielding stresses, then the tower will not fail while being erected. If the tower passes these checks, the design of the tower can be supported using the tilt-up method.

5.2 Investigation of Operational Wind Turbine Tower

The loading and stresses acting on the operating wind turbine tower include the dynamic thrust force from the wind, axial loading from the weight of the turbine and self-weight of the tower, and bending stresses from lateral load effects. Local and global buckling are the limit states that loads and stresses are compared to for evaluating the design. In the *Excel* spreadsheet, these parameter calculations can be found in their respective tabs (Figure 50).

Figure 50: Calculation Tabs for Tower While in Operation.

Each operational calculation tab is linked from the red alternative tabs and, therefore, are updated as the design parameters are changed. The flowchart (Figure 51) below demonstrates the relationship between all of the operational tabs and their calculated values. The final results are presented on the summary page for each alternative tower.

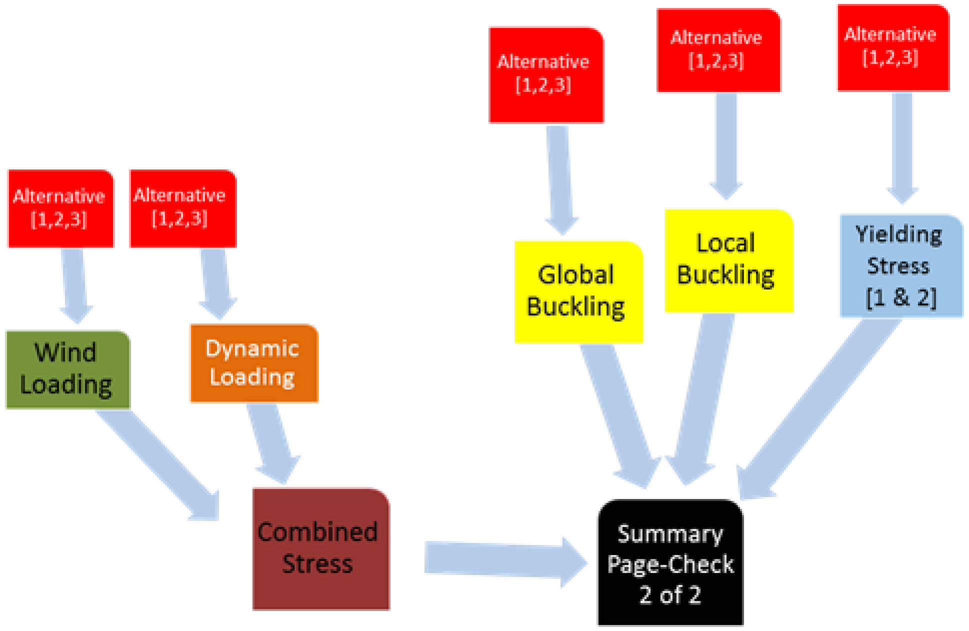
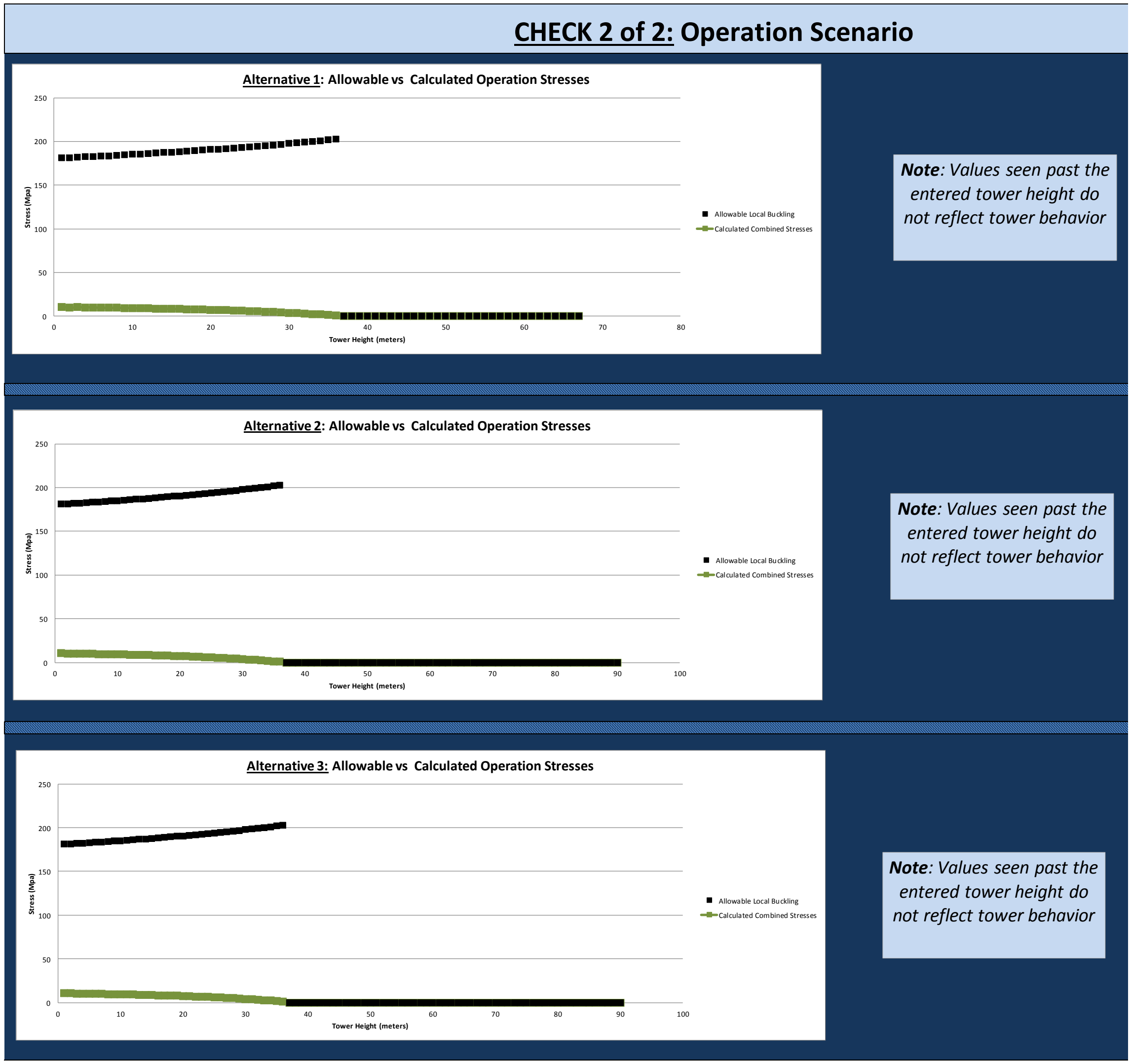


Figure 51: Flowchart of Operational Calculations.

If the calculated operational stresses (“Check 2 of 2” in the Analysis Summary tab) are less than the allowable values for local and column buckling, and yielding, the tower is operational (Figure 52). As previously mentioned, values presented for tower sections higher than the analyzed tower height do not reflect the actual tower behavior.



CHECK 2 of 2: Operation Scenario

Alternative 1: Allowable vs Calculated Operation Stresses

***Note**: Values seen past the entered tower height do not reflect tower behavior*

Alternative 2: Allowable vs Calculated Operation Stresses

***Note**: Values seen past the entered tower height do not reflect tower behavior*

Alternative 3: Allowable vs Calculated Operation Stresses

***Note**: Values seen past the entered tower height do not reflect tower behavior*

Figure 52: Screenshot of Summary Tab for Operational Stresses of Alternative Towers.

The purpose of creating the design framework tool was to enable users to input their own tower designs and verify that they would comply with the allowable stress requirements for both operating conditions and the tilt-up erection method. After performing the necessary analyses on the baseline, the framework tool was designed to follow similar methods when creating the user friendly tool. At the conclusion of the alternative tower analyses, if the tower alternatives passes all three checks on the summary page, then the tower designs are adequate to withstand the stresses occurring during construction and operation for the tilt-up erection method. The user can perform trial-and-error iterations for different tower parameters to determine towers designs that are adequate for operation and construction. It should be noted that this tool serves as a framework for comparing erection methods. Further site condition analyses for each individual project should be performed, and should include, but are not limited to, wind loading, soil profiles, and foundation design.

6.0 Alternative Tower Analysis Results

This chapter serves to give an overview of the results for the three alternative towers that were investigated using the *Excel* spreadsheet. All three alternative towers were analyzed using the same tilt-up methods as the baseline. The table below outlines the specifications for each tower.

Table 18: Alternative Tower Specifications

Specification	Alternative 1	Alternative 2	Alternative 3
Turbine Type	Endurance Wind Power-E-3120	Northern Power Systems 60-23	EWT DW52-900
Nacelle Weight (kg)	3,628	7,800 (combined with rotor weight)	9,072
Rotor Weight (kg)	564	---	5,757
Hub Height (m)	37	23.5	35
Power Rate (m/s)	9.5	14	14
Blade Count	3	3	3
Rotor Diameter (m)	19.2	21	51.5
Power Output (kW)	50	60	900
Tower Height (m)	36	23	35
Upper Diameter (m)	1.42	0.91	1.39
Lower Diameter (m)	2.14	1.36	2.08
Thickness (m)	0.012	0.01	0.01

6.1 Construction Analysis

The minimum required tension to lift each alternative tower was calculated and is summarized in Table 19. Additionally, the maximum stresses exerted on the tower are summarized in the table below.

Table 19: Minimum Required Tension for Alternative Towers

Alternative	Minimum Required Tension (MN)	Maximum Stress (MPa)
1-Endurance Wind	3,552 (400 tons)	17.02
2-Northern Power Systems	1,178 (132 tons)	12.89
3-EWT	2,882 (324 tons)	14.28

While each of the three towers had different design specifications, each displayed similar trends for the calculated stresses. All three alternatives experienced stress behaviors comparable to the three-point analysis of the baseline tower. The largest stresses were experienced at 2° of inclination. As the tower approached 90°, the bending stresses decreased to 0 MPa as the internal stresses changed to axial stresses.

The second alternative, the Northern Power Systems tower, was the smallest of the analyzed towers and thus required the smallest tension force for erection. Figure 53 displays the combined stresses at every angle for the second alternative. All three of the alternatives experienced combined stresses that were well below the allowable limits. Figure 54 displays the combined stresses experienced by the second alternative tower at 2° compared to the allowable stress values. The calculated combined stresses experienced during construction for the remaining two tower alternatives can be found in Appendix I.

The analyses of each alternative revealed that the towers would fail during construction due to yielding. While using three guy wires was a viable option to erect the towers in terms of the towers' capacities, the large resultant forces at the first one-meter section of the tower caused the towers to yield. The towers experienced yielding failure during the initial 2º of tilt-up but for each subsequent angle, the yielding stress decreased to be within the allowable limit. If the towers were designed to avoid yielding, then the tilt-up method would be feasible.

The analysis of the alternative towers determined that they required less than 400 tons of tension force, which existing cranes have the capacity to lift. The analyses revealed that the tilt-up construction method would be possible if design alterations were made to the base of the tower.

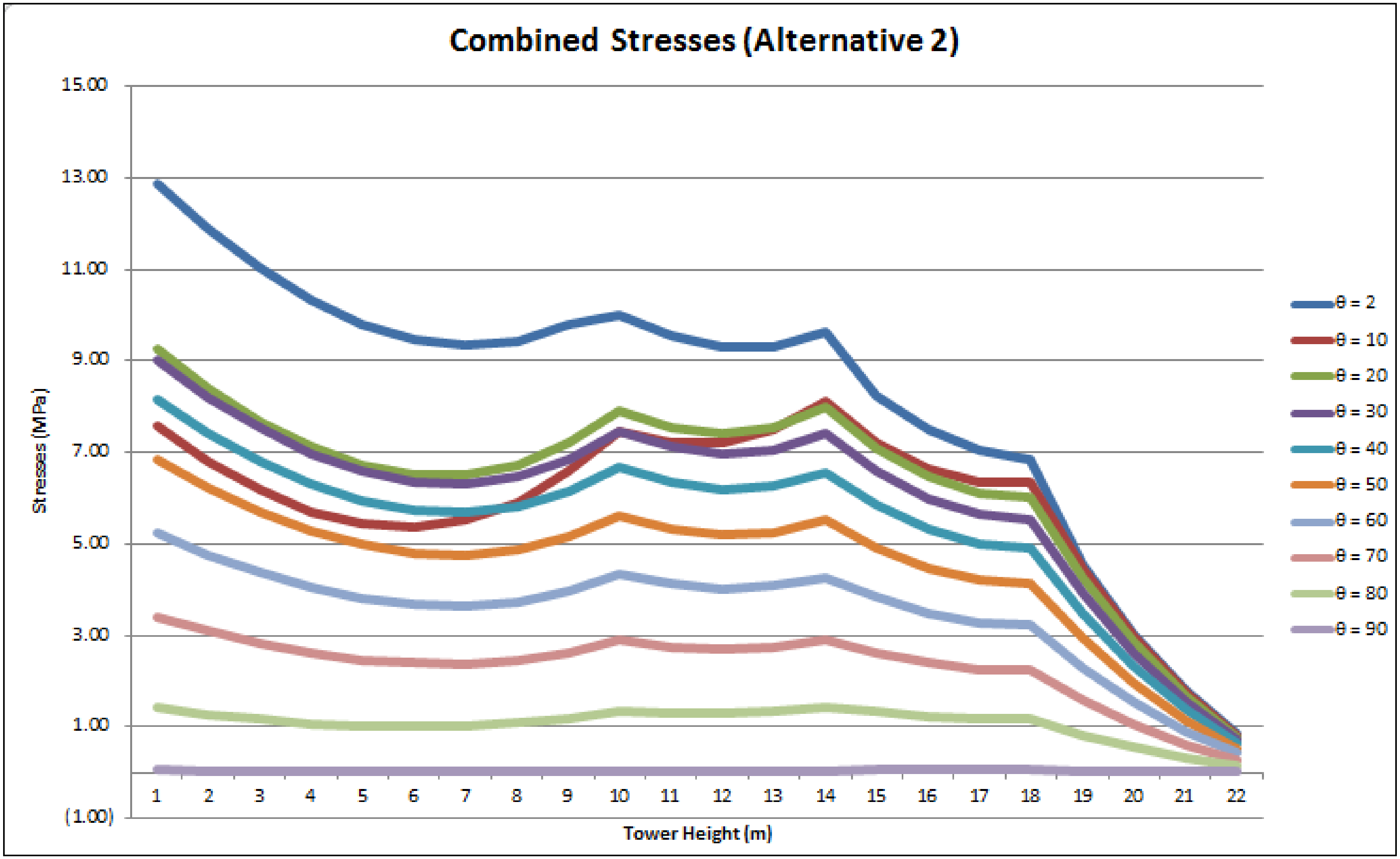


Figure 53: Combined Stresses for Alternative 2 at Each Analyzed Angle.

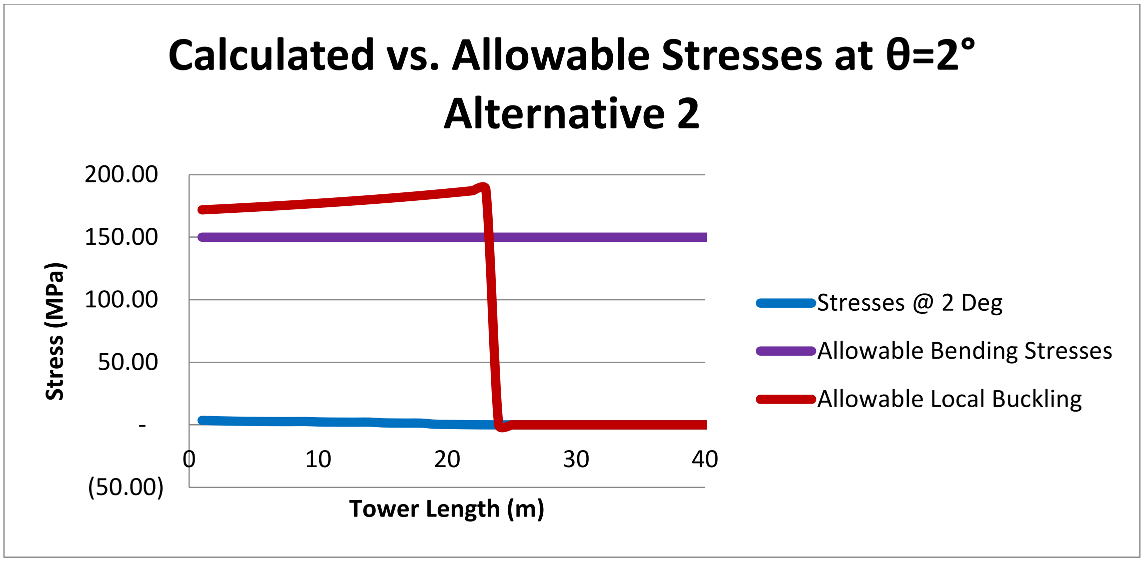


Figure 54: Calculated vs. Allowable Stresses at 2° for Alternative 2.

Similar to the baseline, the yielding check was performed on each of the three alternative designs. If the combination of both axial and bending moment is above 1, then the tower will fail due to yielding. Figure 55 presents the data for the yielding check for the second alternative. The yielding checks for Alternative 1 and Alternative 3 can be found in Appendix I.

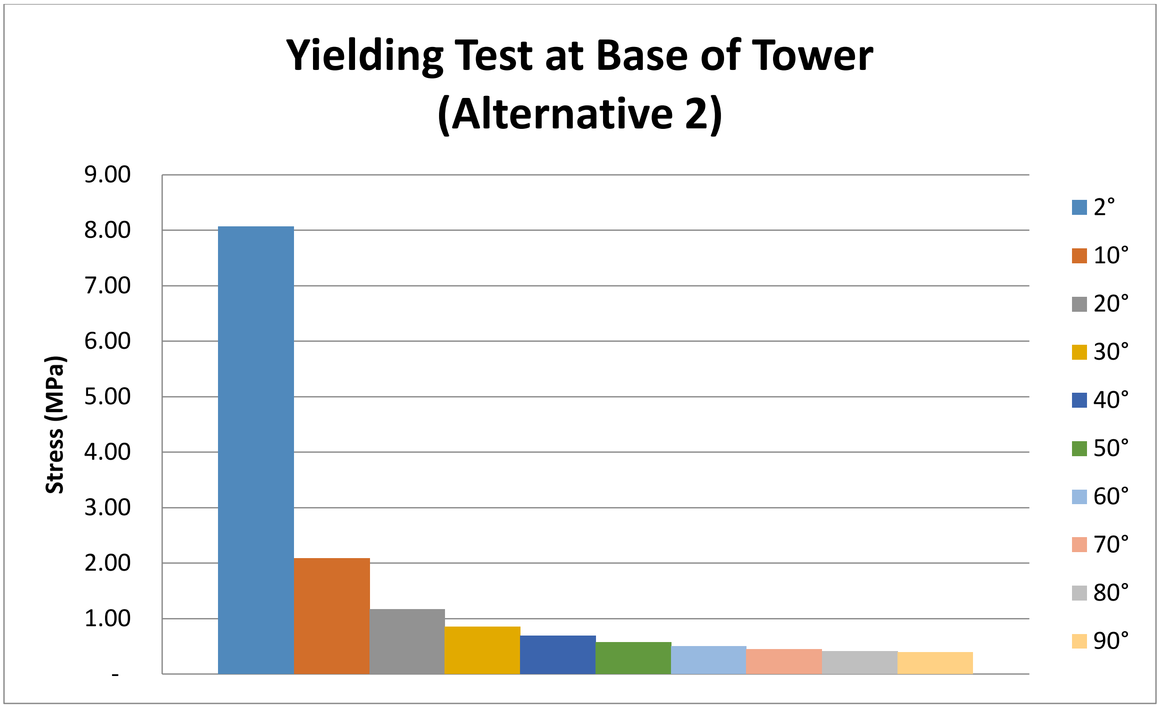


Figure 55: Yielding Test (Alternative 2).

The analyses of all three alternatives concluded that the towers would fail due to yielding because the combined axial and bending effects produce an interaction value well above 1;

approximately eight times the allowable limit. A detailed analysis for a yielding check along the length of the tower can be found in Appendix K.

6.2 Operational Analysis

Although the alternative towers designs failed during construction analysis, a structural analysis was still explored for operating conditions. The following sections outline the loading and stress results for the three alternative tower designs. The analysis considered the changing wind, dynamic and dead loading for each tower and the effects they had on combined stresses. These load cases and stresses were compared to the limiting values of column and local buckling, which also varied with each tower design.

The structural analysis for the alternative towers followed the same process as for the baseline tower. The *Excel* spreadsheet was set up for a user to input initial nacelle and tower design parameters, wind loading parameters and dynamic loading parameters to calculate the associated loading. Note that the alternative towers used the same wind loading parameters as the baseline tower. The combined stresses and column and local buckling were also determined.

Results for each alternative design include a table of loading conditions, the moment diagram calculated along the tower height and a comparison of combined stresses to the allowable local and column buckling stresses. The table includes: the wind profile along the height of the tower (calculated at the mid-height of each one-meter section), the dynamic load (the equivalent single static load due to the wind forces acting on the turbine blades), and the dead load. Analyses for Alternative 2 can be seen below (Table 20, Figure 56, Table 21 and Figure 57) while those for Alternative 1 and Alternative 3 can be found in Appendix J.

Table 20: Loading Conditions for Alternative 2

<table>
<tr><th colspan="6">Alternative Tower Design 2</th></tr>
<tr><th colspan="4">Lateral Wind Loading</th><th colspan="2">Dynamic Loading</th></tr>
<tr><td>Section</td><td>F (N)</td><td>Section</td><td>F (N)</td><td>Thrust Force</td><td>21,332 N</td></tr>
<tr><td>1</td><td>963.02</td><td>13</td><td>947.85</td><td>Magnification Factor</td><td>1.1</td></tr>
<tr><td>2</td><td>949.06</td><td>14</td><td>943.79</td><td>Equivalent Static Load</td><td>23,465 N</td></tr>
<tr><td>3</td><td>935.11</td><td>15</td><td>938.51</td><th colspan="2" rowspan="2">Dead Loading</th></tr>
<tr><td>4</td><td>921.16</td><td>16</td><td>932.20</td></tr>
<tr><td>5</td><td>907.20</td><td>17</td><td>924.94</td><td>Tower Section Weight</td><td>≅ 277 kg/m</td></tr>
<tr><td>6</td><td>922.63</td><td>18</td><td>916.83</td><td>Nacelle + Rotor Weight</td><td>7,800 kg</td></tr>
<tr><td>7</td><td>934.99</td><td>19</td><td>907.93</td><td>Total Turbine Weight</td><td>≅ 14,170 kg</td></tr>
<tr><td>8</td><td>943.33</td><td>20</td><td>898.32</td><td colspan="2" rowspan="5"></td></tr>
<tr><td>9</td><td>948.55</td><td>21</td><td>888.05</td></tr>
<tr><td>10</td><td>951.22</td><td>22</td><td>877.17</td></tr>
<tr><td>11</td><td>951.79</td><td>23</td><td>865.71</td></tr>
<tr><td>12</td><td>950.59</td><td colspan="2"></td></tr>
</table>

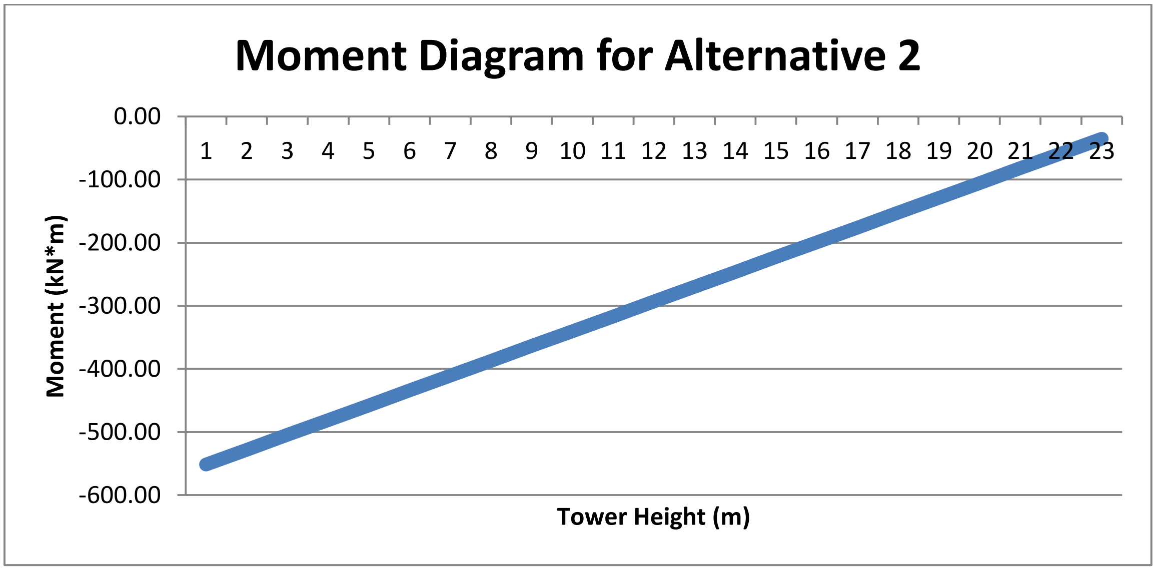


Figure 56: Moment Diagram (Alternative 2).

The table below displays the results for the column buckling check for Alternative 2. Similar to the baseline, the Timoshenko and AISC methods were used to calculate the allowable stress.

Table 21: Column Buckling Check for Alternative 2

Parameters	Alternative 2
$\frac{I_1}{I_2}$ ratio	0.7
“m” factor	2.2
K	2.1
λ	1142.7
σ_{cr} (MPa)	0.2
$\sigma_{allowable}$ (MPa)	0.1

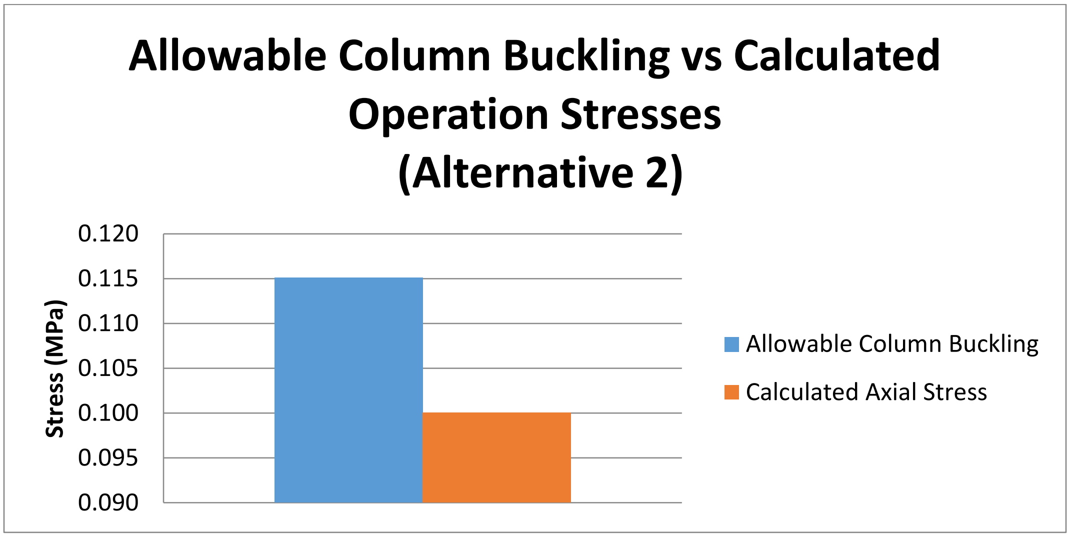


Figure 57: Allowable Column Buckling Stresses vs. Operational Stresses (Alternative 2).

For each of the alternatives the moment diagram followed the same trend line as that for the baseline tower. The maximum moment was observed at the base of the tower while the moment converged to 0 along the tower height. The combined stress (bending and axial) was compared to the allowable stress values for both column and local buckling. The results showed that all three of the alternative designs had the same *m* factor, and therefore the same allowable stress. The calculated stresses were lower than both buckling stresses, which determined that the tower will not fail under operating conditions.

It is important to observe that the overall stresses along the tower for Alternative 2 have increased compared to those for Alternative 1. Although Alternative 2 has a shorter tower height and experienced a smaller wind profile and dead load, the power output for this alternative is 10 kW larger and with a larger sweep area. The increase in the power output produced larger dynamic loading conditions which yielded larger stresses along the tower height.

Of the three alternative cases, Alternative 3 experienced the largest stresses and loadings along the tower height (see Appendix J for graphs). Additionally, it produced the largest power output and therefore the largest dynamic loading conditions at the top of the tower.

6.3 Economic Analysis

The economic analysis for the alternative tower designs was developed using the criteria given in the analysis of the baseline. This analysis assumed that the turbines would be hypothetically constructed on the same site as the baseline study in order to provide a cost comparison. The site work was assumed to be the same as for the baseline because access roads and site clearing are needed for all projects and these prices would not significantly vary between the baseline and alternative designs. The foundations for each tower were estimated at the industry average of $175,000 for every alternative tower design (Windustry, 2014). Cost estimates for each turbine and tower were obtained from the individual turbine manufacturers and included shipping (EWT, Northern Power Systems, Endurance, 2014). The crane required to erect each alternative was found by determining the lifting tension each tower required and identifying the corresponding crane with the required capacity. The crane rental costs were provided by a crane rental company, Bigge Crane and Rigging Company, and are for a one month rental (Biggie Crane and Rigging Co., 2013). Table 22 presents the cost estimates for each alternative tower design that was analyzed.

Table 22: Cost Estimate for Alternative Towers

Project Element	Alternative 1	Alternative 2	Alternative 3
Site Work	$675,000	$675,000	$675,000
Foundation	$175,000	$175,000	$175,000
Turbine Costs	$455,000	$400,000	$2,080,000
Turbine Erection	$80,000	$27,000	$69,000
Total Project Cost	$1,385,000	$1,277,000	$2,999,000
Power Output (kW)	50	60	900
Project Cost per kW	$27,700	$21,283	$3,332

The total project costs for the alternative tower designs per kilowatt range from $3,000 to $28,000, as opposed to the baseline tower, which cost about $2,367. This can be attributed to the fact that each alternative turbine generated a smaller power output than the baseline turbine. This suggested that it was more economical to erect a large turbine with greater power output rather than multiple smaller turbines in order to have the most cost effective project.

6.4 Summary

The *Excel* design tool showed that the three alternative towers passed all construction checks except for yielding. The results for the alternative tower designs revealed that the tower designs would fail during the erection process due to yielding. While the moment at the base of the tower did not cause a problem, the axial component caused the AISC yielding check (Equation 19) to exceed 1, and therefore fail. Due to the high tension forces caused by the guy wires, the hinge at the base of the tower had to exert large resultant forces to maintain equilibrium among the horizontal forces. Therefore, the axial component of the interaction equation, $\frac{P_r}{P_c}$, was well above the allowable limit. The alternative towers were tested in the design framework using a larger thickness. This resulted with an axial force and bending moment sum that was less than one and could pass the yielding check. Therefore, the towers could be erected without yielding failure.

Although the towers failed during the tilt-up erection, a structural analysis was still explored using the *Excel* design tool. The operational analysis suggested that the towers satisfied all of the allowable limits. The economic analysis of the alternative towers suggested that it would be more cost effective to erect two larger wind turbines as opposed to many smaller ones when a specific power output is desired.

7.0 Conclusion and Discussion

The goal of this project was to create a design framework for turbine towers as well as a means to investigate the use of the tilt-up erection method. This goal was achieved by creating a design tool from the baseline study which was then used to compare the traditional crane erection method with the tilt-up method. The Princeton tower served as a baseline case study to analyze stresses endured on the tower during operation and construction scenarios. By understanding the loading conditions and the resulting behaviors of the tower, the baseline provided a framework for the design and investigation of alternative towers.

The structural analysis for the baseline tower in operation considered the wind, dead and dynamic loadings on the tower, as well as the effects of column and local buckling and bending stresses. Further analyses determined the feasibility of the tilt-up method for the baseline tower which considered various guy wire placements to yield the most effective method. These analyses determined that placing three guy wires at and above the center of gravity of the tower yielded the smallest stresses endured by the tower. Because this arrangement produced the smallest required tension forces in the wires, it was used for alternative investigations of the tilt-up erection method. Results suggested that the baseline tower could be erected within the tower's capacity using the tilt-up method; however, it is not practical from a logistical standpoint. Currently, there are no cranes available that have the required lifting capacity for a tower of this size. Future analysis could investigate the use of more than three guy wires to decrease the required tension, as this project only looked into three due to time constraints.

A design framework was created from the baseline investigation via an *Excel* spreadsheet. Calculations used in the baseline case were verified and then replicated for the design and analysis of alternative towers. With the design tool, the user can input the geometry and material properties of the proposed tower, along with the turbine information, and obtain analyses for both operating and tilt-up erection conditions. The design calculations can accommodate tapered tower profiles and varying wall thicknesses. Design parameters for the alternative towers were determined from models currently available in the industry. A comparison of the alternative towers, and the baseline specifications and costs can be seen in Table 23.

Table 23: Comparison of Design Parameters Between Baseline and Alternative Towers

Design Parameter	Baseline: Princeton	Alternative 1: Endurance Wind Power E-3120	Alternative 2: Northern Power Systems 60-23	Alternative 3: EWT DW52-900Wind Power
Power Output (kW)	1,500	50	60	900
Tower Length (m)	67	36	23	35
Cost per kW ($)	2,367	27,700	21,283	3,332

The analysis of the alternative towers in the tilt-up erection method suggested that all of the towers failed due to yielding at the first one-meter section above the foundation. Methods to resist yielding failure include thickness tapering and adding stiffener rings to the base of the tower. After extensive research and trial-and-error using the design tool, a uniform thickness throughout the tower causes the tower to be highly susceptible to yielding failure. The baseline tower did not fail due to yielding because of a greater thickness at the base of the tower. As the tower height increases the thickness decreases. In order to avoid failure due to yielding, the alternatives should follow a similar design of the baseline tower, and include a larger thickness at the base. Increasing the thickness also increases the moment of inertia and radius of inertia. These increases resulted in a decrease in the slenderness ratio, which ultimately decreased the axial resultant force at the base of the tower. By doing so, the axial portion of the yielding check, $\frac{P_c}{P_r}$, will decrease, causing the sum of the axial and bending effects to be below 1.

One negative aspect to increasing the thickness is increasing the overall weight of the tower, resulting in increased material prices and crane capacities. Another potential solution to avoid yielding would be to add stiffeners to the base of the tower during tilt-up construction. From the three alternative tower results, all towers would fail due to yielding until the tower passes the 2° incline. After this angle, the axial forces and bending moments appear to be well below the allowable limit. The ring stiffeners could act as a binding collar around the base of the tower to help prevent yielding during the initial 2° incline. These stiffeners could be removed after the erection of the tower and reused. This would be a more economical solution compared to increasing the thickness because the failure mode is only a behavior of the initial erection process.

Large scale wind turbine projects generally cost less per kilowatt than smaller scale wind projects. Compared to the average costs for similar sized projects, the alternatives this project analyzed were found to cost less per kilowatt. A more in depth economic analysis should be performed to determine if these savings are significant enough to warrant using the alternative tilt-up erection method.

As part of the goal of this project, the feasibility of using the tilt-up erection method was explored to construct a standard 1.5MW commercial wind turbine. As the analysis revealed, the tilt-up erection method was not practical for wind turbines of this size. However, the analyzed alternatives found that using the tilt-up erection method would be practical if adjustments at the base of the tower are included in the tower design. Because the smaller tower alternatives do not have the capacity to support a single 1.5MW wind turbine, multiple turbines would be required to produce the same power output as a large scale commercial wind project. Alternative 1, 2, and 3 would require 30, 25, and 2 turbines, respectively. Even though Alternative 3 requires a crane to lift roughly 325 tons, the project is more economical because it requires 2 turbines rather than 30 or 25.

Based on the analysis of the baseline and alternative towers, the tilt-up method can be a viable option for erecting wind turbine towers. However, limits to consider should include the height of the tower, amount of open space to tilt-up the tower, and the number of turbines required to generate the desired power output. The tilt-up erection for a site involving multiple turbines poses a logistical challenge so that the towers that are erected first do not impact the erection process for subsequent towers. This is part of the concern with sufficient land area because there needs to be adequate space to erect each turbine tower individually. Larger, commercial towers would be best erected using the traditional crane method, but smaller, residential towers could investigate using the tilt-up method.

The limitations of the design tool should be considered. The design tool does not include the design of the tower foundation or the necessary connections between tower sections. Analyses that are completed in the design tool can also be expanded on or improved through additional studies. The *Excel* file serves as a basic analysis tool that can be used for preliminary investigations of the proposed tower.

Further research should be explored to optimize all erection processes of wind turbine towers. The results suggested that one major limiting factor was the weight of the tower. Thus, fabricating towers from a strong, lightweight material would require smaller lifting capacities. This research is already being conducted; for example, manufacturers are exploring the possibility of fabricating towers using composite materials. These lighter towers would allow for smaller costs of construction and erection.

This project found that the traditional method for erecting commercial wind turbine towers is the most practical. However, applying the tilt-up method to smaller, residential turbines could present lower costs when compared to the traditional erection methods. With lower project costs, more wind turbine projects could be built across the United States. This puts the United States one step closer to its goal of producing 20% wind powered electricity by 2030, and lowers the United States' dependence on energy sources produced from fossil fuels.

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Appendix A: Proposal

Framework for Erection of a Wind Turbine Tower

A Major Qualifying Project

Holly Ganser, Siena Mamayek, Melissa Samaroo, Dana Wolkiewicz

October 17, 2013

Abstract

This project analyzes the tower design implications and erection process of alternative methods of erecting wind turbines. Currently, the industry standard is the use of multiple cranes to install the tower. The alternatives would include an improved crane process, a tilt-up tower using a hydraulic jack, and a tilt-up tower using a system of pulleys. For each method, the stresses experienced by the tower, during both the erection and the lifetime of the tower, will be analyzed to determine a design that will maximize power output and height. The alternative methods are then economically analyzed in order to compare the alternatives against the standard crane process. The final outcome is a decision-making tool that recommends situations where each erection method should be utilized.

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1.0 Introduction

Over the last several years, wind power has been an increasingly popular renewable energy source. Generated by wind turbines, this energy serves as a clean, plentiful alternative to fossil fuels (Taylor, Unknown). Turbines range from small residential sizes to large commercial ones, and a single one-megawatt wind turbine has the capacity to produce enough energy to power as many as 400 households (GE Wind, 2009). Countries such as China and the United States are moving towards this new energy source because of its benefits previously mentioned (R. Wiser, M. Bolinger, 2008). In 2013, the annual wind power capacity of the United States reached an all-time high of roughly thirteen gigawatts (Figure 1)–almost double the amount from the previous year.

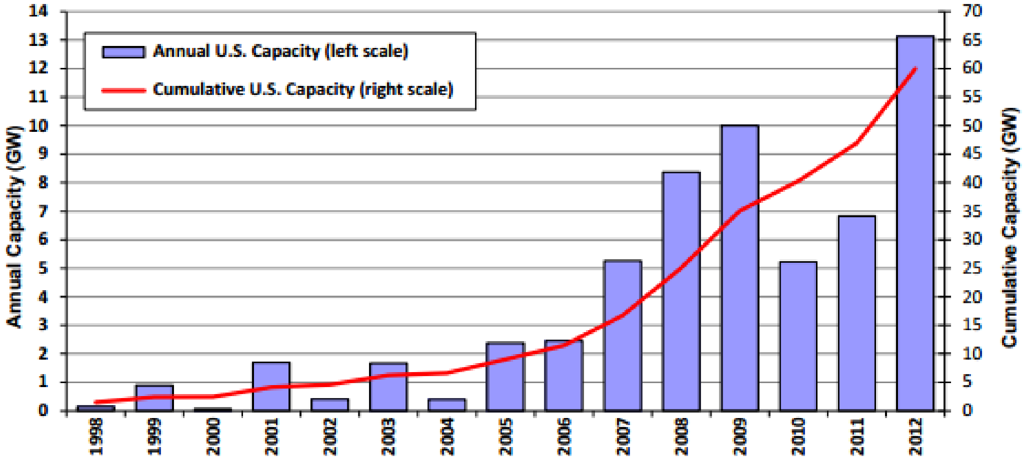


Figure 1: Annual and Cumulative Growth in U.S. Power Capacity. U.S. Dept. of Energy, 2008.

Although wind turbines have many benefits, there may be improvements to the erection process to make them more cost effective (S. Tegen, E. Lantz, M. Hand, B. Maples, A. Smith, and P. Schwabe, 2013). Construction companies are experiencing high construction costs due to the use of cranes in the tower installation process. Thus, the goal of this project is to provide recommendations for the optimization of wind turbine installation by exploring different tower erection processes. This project will investigate several tower erection methods to develop a set list of design criteria, schedule and cost of each method.

2.0 Background

2.1 Brief history

Wind is the result of the heating of the earth's surface. The sun heats up areas of land and the air above it. The warmer, fast-moving air particles exert more pressure and thus less air is needed to maintain a constant air pressure. The less dense air rises and the colder, more dense air rushes to fill in the empty spaces; creating wind (Layton, 2006). It is typically windier in the afternoon and early evening after the sun has warmed the air all day than it is in the morning when the sun has been down for several hours. The moving air particles contain energy and if something is placed in the path of wind, energy will be transferred and the objects will move.

The modern day wind turbine evolved from the early windmill used to process grain. The early designs generally had a set of four horizontal, rotating blades attached to a post. The post also held all of the milling equipment. The entire system could be rotated to face the blades in the correct wind orientation (Shepherd, 2008). In the 1880s, Denmark and the United States began experimenting with generating electricity using the windmill technology. By the 1930s, wind turbines were generating electricity for farms that were a long distance from the main power system. The development of electricity systems saw a decline in wind turbine use, but the fuel shortage scare in the 1970s caused Americans to seek out alternative energy sources (Layton, 2006). Today, there are over 29,440 megawatts of wind energy installed in the United States ("Wind Energy:Facts," 2013).

2.2 Anatomy of Wind Turbines

Wind turbines are designed to reach optimum wind speeds at a predetermined geographical location. A wind turbine consists of a rotor that typically has three blades attached at the hub. The hub is attached to the front of the nacelle, which holds the mechanical components that converts wind into kinetic energy. The nacelle sits atop a tower and foundation, which provides the structural stability for the turbine.

2.2.1 Foundation

The key design requirement for wind turbine foundations is the resistance to overturning forces. The foundation, typically a concrete footing, must provide adequate strength to resist extreme wind load conditions. Although there is no universal set of specified standards for the design of wind turbine foundations, certain design criteria must be addressed: stiffness, strength, stability, differential settlement, durability and the economic impact (Morgan, 2008).

2.2.2 Tower

Wind turbines are capable of reaching higher wind speeds with respect to the height of the tower. Typically the tower is made of tubular steel and is prefabricated in a factory and transported to the site. Tower heights range from upwards of 250 feet. The heights are mainly determined by surrounding geographical conditions such as soil type and terrain. From a design perspective, the cross-sectional dimensions and local buckling are essential design criteria. The tower must provide adequate stiffness as to not buckle from the loads above. A tower should not be built within a radial distance of the tower height plus a safety factor to avoid potential damage to existing structures (Gipe, 2004).

2.2.3 Turbine

The nacelle is the large casing that sits atop of the tower which holds all the mechanical components for converting wind into kinetic energy. The hub, attached to the front of the nacelle, is where the blades stem outwards. The blades can be upwards of 150 feet in length. As the wind turns the blades, the rotor hub turns the gearbox. The faster the gearbox is rotated, more electricity is produced by the generator. All structures below the nacelle are designed to withstand the dead loads and vibrations produced by the turbine.

Vertical Axis Wind Turbines

Vertical Axis Wind Turbines (VAWTs) are designed with a vertical shaft stemming upwards out of the ground with blades anchored to the top and bottom of the shaft (Figure 2). The greatest advantage of VAWTs is the mechanical component; the generator and gearbox can be installed at the base of the tower. The shaft structure does not have to account for the dead load of these components and are accessible for service and maintenance. A disadvantage to these systems is the lack of a stable tower structure. The system relies on guy wires for support and limits the elevation of the rotor. With a lower elevation, the rotor is unable to reach optimal wind speeds and hence operates at a lower efficiency. VAWTs are ideal for small scale application in areas where connection to power grids is unavailable (Jha, 2011).

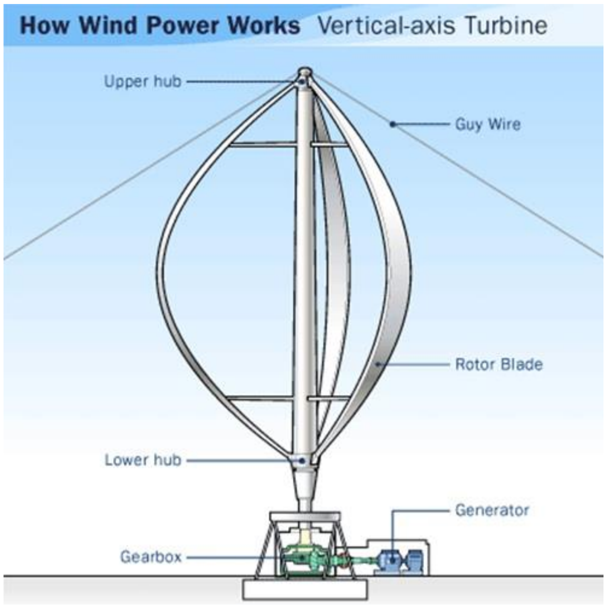


Figure 2: Vertical Axis Wind Turbine.

Horizontal Axis Wind Turbine

Horizontal Axis Wind Turbines (HAWTs) are the most commonly used design in the wind power industry (Figure 3). HAWTs are primarily designed upwind to allow wind to pass through the rotor blades at a 90 degree angle allowing the system to rotate to align with the wind. These systems are capable of reaching higher elevations and are directly proportional to the tower height. Larger turbines operate efficiently in winds around 33 mile per hour. The radius of the blades is directly proportional to the power output of the turbine. An upwind turbine model paired with a three blade system is the most common design in the market. The advantage of this design is that the system is capable of automatically adjusting to the wind direction (Jha, 2011).

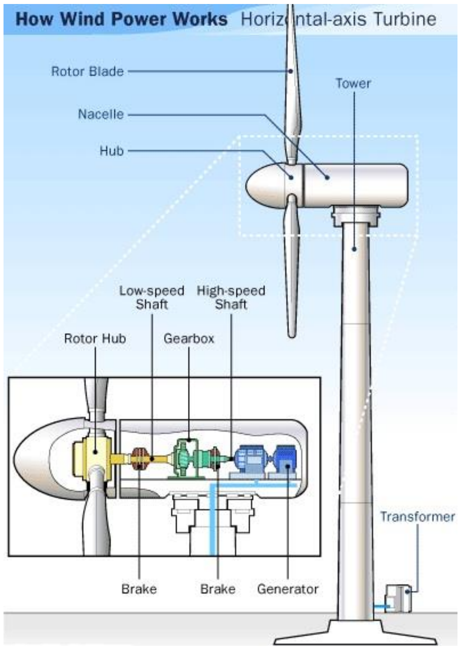


Figure 3: Horizontal Axis Wind Turbine.

2.2.4 Sizes

Wind turbine sizes range from small residential use to large commercial use, depending on desired power output. From the standard HAWT upwind three blade design class, a 1.5 to 2 megawatt system dominates the commercial industry. Heights range upwards of 300 feet with blades around 150 feet. Because wind speeds increase at higher elevations, there is more potential for harnessing wind power. Figure 4 below predicts future tower heights and their output capacity.

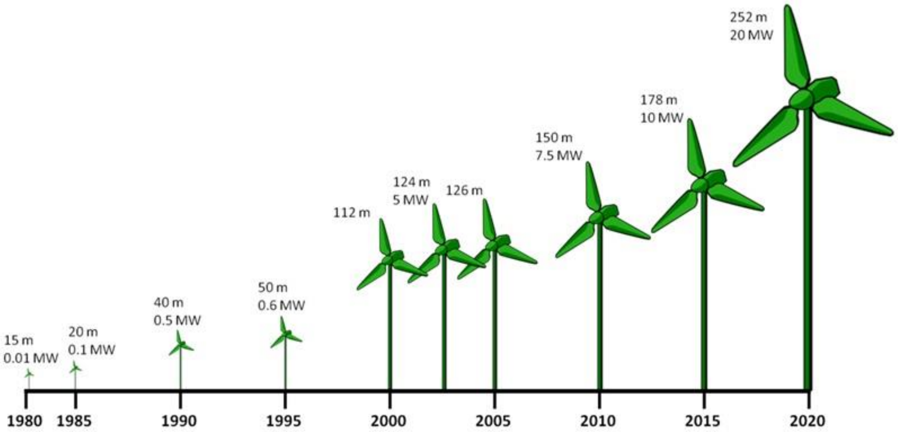


Figure 4: Predicted Tower Heights.

Small turbine designs, mainly for residential use, have much lower tower heights. Design requirements take into account surrounding obstacles to still maximize efficiencies. For example, if the desired blade length is 10 feet long, to meet the minimum clearance of 30 feet above the ground, the tower height must be at least 40 feet tall. Some residential-size wind turbines are mounted on rooftops to increase their elevation. Output capacities to generate enough electricity for a residential home ranges from 2-10 kilowatts (Gipe, 2004).

2.3 Tower Design Factors

The tower is the main support for the wind turbine. For this reason, it is important that the tower is structurally sound and will be able to support the adequate loads and stresses (Negm & Maalawi, 2000). The turbine should be made of a lightweight material for economic and construction reasons. The turbine should also have a high stiffness and a high stiffness to mass ratio to minimize the deflection at the top of the turbine. The turbine tower must also be designed to allow minimum vibrations for stability, increased fatigue life, and has minimal noise levels. To avoid large amplitudes, natural frequencies are separated from the existing ones. These amplitudes are caused by resonance, and can be minimized by measuring the performance index. Another way to reduce vibrations is by maximizing the natural frequencies of the system, since higher natural frequencies are favorable for reducing both of the steady-state and transient responses of the tower.

Optimization equations are used and basic assumptions are made about the tower during the design process. The first assumption is that the tower acts as a cantilever beam that is made up of sections which have different but uniform cross-sectional properties (Negm & Maalawi, 2000). The mass at the top of the tower (the nacelle/rotor unit) is assumed to be fixed. The cross section of the tower is a thin-walled and circular which is assumed to be linearly elastic, isotropic and homogenous. While deflections are taken into consideration, axial and shear deformations are negligible in this instance.

2.3.1 Loading

The factors involved with designing a wind turbine tower are numerous. According to the IEC, loads that shall be considered in the design calculations are: gravitational and intertial loads, aerodynamic loads, actuation loads and other loads such as wake loads, impact loads, ice loads, etc (Commission, 2008). These loads lend themselves to local buckling, bending and flexural stresses. The loads and stresses associated with the turbine tower are dynamic and must be dealt with as a combined loading problem (Savilonis, personal communication, 20 September 2013). This dynamic loading is a result of periodic loading from the turbine rotation and when the blades pass in front of the tower (Sørensen & Sørensen). The standards set in place explain that the design load cases shall be calculated by combining:

- Normal design situations and appropriate normal or extreme external conditions;
- Fault design situations and appropriate external conditions;
- Transportation, installation and maintenance design situations and appropriate external conditions.

These design load cases are examined to verify the structural integrity of the wind turbine by designing loads for worst case scenarios.

In addition to these load cases, the following factors are also taken into account where they are relevant:

- Wind field perturbations due to the wind turbine itself (wake induced velocities, tower shadow, etc.);
- The influence of three dimensional flow on the blade aerodynamic characteristics;
- Structural dynamics and the coupling of vibration modes;
- Aero elastic effects;
- The behavior of the control and protection system of the wind turbine.

Using dynamic simulations with a structural dynamics model are usually used to calculate wind turbine loads. The IEC dictates parameters for these simulations in order to ensure the structure is reliable.

2.3.2 Local Buckling

Common areas of failure criteria are buckling failure due to extreme loading and fatigue failure (Sørensen & Sørensen). With wind turbine towers, it is ideal to make the cylinder thickness as thin as possible; however, this may lead to local instability. The critical buckling stress equation, given below, assumes perfect geometry for an axially loaded tubular tower.

$$\sigma_{cr} = 0.605 * C * E * \frac{t}{r}$$

Where:

C = coefficient due to length of the shell

E = E-modulus

t = wall thickness

r = radius of cylinder.

2.3.3 Power Output

There are many important components that comprise a wind turbine however not all of them are directly responsible for harnessing the wind energy. Although the tower height is capable of reaching higher wind speeds and the generator is responsible for converting wind into kinetic energy; it is the rotor diameter that relates to power output and ultimately the size of the turbine (Gipe, 2004).

The power output of wind turbines is calculated with the Swept Area Method. This method determines the mass flow of air through the area of the rotor disk.

$$P = \frac{1}{2}\rho U^3 A$$

Where:

P = available wind power

ρ = air density

U = air velocity

A = rotor area.

It is important to note that for standard conditions, the density of air is 1.225 kg/m^3. Also that power is proportional to the area swept by the rotor. In such cases for a conventional wind turbine, the formula for sweep area is that of a circle (Manwell, 2002). Since wind passes through the rotor blades, the turbine does not capture 100% of the energy. The maximum amount of wind captured by the rotor is 59.3% as the defined by the Betz Limit (Gipe, 2004).

2.4 Tower Erection Methods

Depending on varying site conditions, tower height and desired power output, there are several methods for erecting the wind turbine tower. The following section outlines five methods for tower erection, along with the advantages and disadvantages of each.

2.4.1 Crane

One of the most common methods of erecting a wind turbine is with the use of two cranes: a crawler crane and a tower crane (Biggie Crane and Rigging Co., 2013). The combination of these cranes lifts each segment of the tower in suspension and slowly places them in correct location. The tower crane is the main piece of equipment used during the erection of a wind turbine tower. These cranes can reach up to 550 feet high, and can carry loads as heavy as 4,000 short tons. The crawler crane (reaching up to four hundred feet and having a lifting capacity of approximately 3,500 short tons) supplements the tower crane and acts as a balancing support for suspended tower segments.

The combinations of these two cranes have advantages and disadvantages. Tower cranes give the best combination of height and lifting capacities, especially for projects such as wind turbines (Khaleej Times, 2009). However, these cranes can be quite costly, and are not mobile once they are on-site. The main advantages of crawler cranes are their ability to mobilize (with or without a load) around the construction site and to perform lifts with little setup needed (Biggie Crane and Rigging Co., 2013). Some disadvantages include its heavy weight, and the inability to easily and cheaply relocate from one site to another.

2.4.2 Tilt-Up Method with Self-Supporting Frame

Similar to the process of offshore tower installation, the tilt-up method is one alternative to using cranes. This turbine tower has a self-supporting frame and is fully assembled on the ground. The tower is then hooked to several anchors and guy wires and the tower pivots around a base as the guy wires pull the fully assembled up into the standing position (Figure 5).

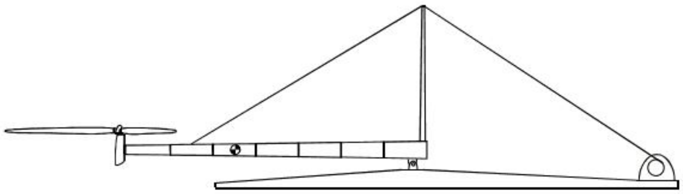


Figure 5: Tilt-Up Method with Self-Supporting Frame.

When using this method of tower erection, there are some limitations that the contractor might face. In order for this method to successfully work, the tower cannot exceed a specific height and weight because of the bending moment of the tower. In addition, special equipment may be needed in order to assemble to tower before tilting up, such as a platform or small crane. Therefore, only small scale wind turbines could be erected by using the tilt up method. However, there are some benefits to this method; because this method includes a self-supporting frame, a tower crane would not be needed to lift the segments on top of each other, thus potentially reducing the cost.

2.4.3 Jack-Up with Offshore Platform Towers for Lifting

The erection methods for offshore drilling platforms could be used for the erection of wind turbines. Legs that are anchored to the ocean floor support the offshore oil-drilling platforms. The platforms are mounted on the legs which allow them to move up and down. This would relate to a wind turbine because the turbine would be assembled while it is on its side. Then, two lifting towers (which are much like the support legs for the offshore oil-drilling platforms) are erected along with two towers on each side of the wind turbine. The frame connected to the turbine tower is raised up the lifting towers using a rack-and-pinion mechanism. A final frame would guide the bottom of the tower as well. In this way, the entire wind turbine tower could be erected simultaneously. Figure 6 illustrates this concept.

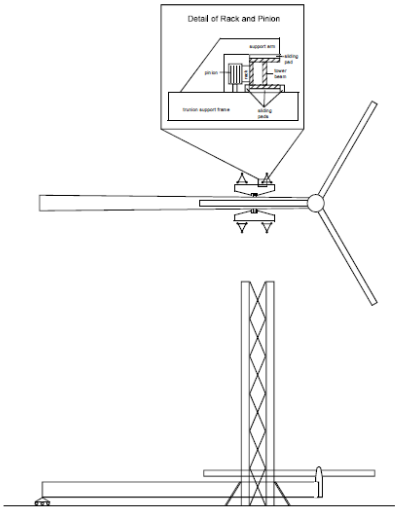


Figure 6: Jack-Up with Offshore Platform Towers.

The advantages to this self-erection method is that the time to assemble and erect the wind turbine would decrease significantly because it could all be done at once as opposed to as in stages. However, site conditions will be a driving factor for this method because in order for the entire turbine to be assembled on its side, there needs to be a lot of open space. Furthermore, the frame that helps guide the turbine up the two lifting towers would have to be built into the tower and would also have to be taken into consideration for the design and fabrication of the tower.

2.4.4 Slip-Form Approach

The slip-form design involves erecting the tower from the top down. The top tower section is placed into a frame with a bearing that creates a horizontal couple that prevents the tower from tipping(Global Energy Concepts, 2008). An illustration of this method can be found below in Figure 7. This method has been implemented in oil rigs, but studies claim that the use of the frame would allow for the erection of a 5MW turbine. The use of this method eliminates the need for a crane and allows for construction in a location where land area is limited. There is one major disadvantage to this method. In order for the frame to maintain a constant cross-sectional bearing on the tower section, the tower cannot be tapered.

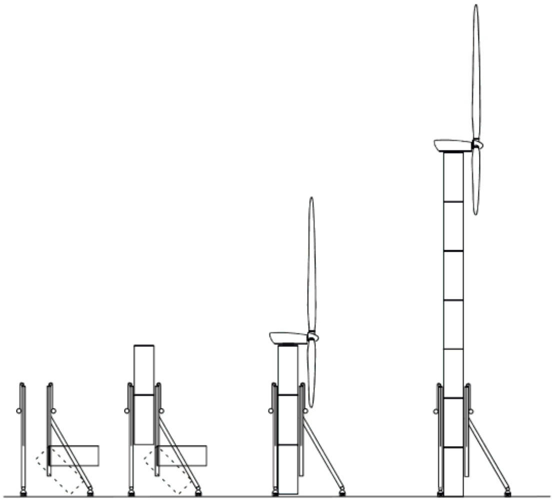


Figure 7: Slip Form Erection Method.

2.4.5 Telescoping Tower

One alternative method for self-erecting a tower would be through telescoping. Multiple tower sections would be pre-fabricated to fit inside one another and eventually extruded upwards. The tallest tower section, which would also be the innermost section, would require a greater length as to install the nacelle on top of the tower while at a relatively low elevation. This elevation must also be predetermined as to not allow the blades to touch the ground. To finalize the installation of the wind turbine, a lifting mechanism would raise the tower to its full height. Figure 8 gives illustrates this process. Challenges with this method include, what type of lifting mechanism would be feasible and how each connection point of the individual tower parts would be designed.

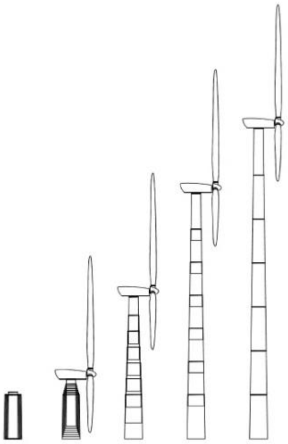


Figure 8: Telescoping Tower.

3.0 Scope of Work

The scope of work will be broken out into several stages. The first will consist of background research to understand both the design of wind turbines and the current construction process used in the industry. The second stage will include a baseline investigation of a wind turbine located in Princeton, Massachusetts. This investigation will include a structural analysis of the turbine tower as well as determine the driving factors of construction. The third stage will explore alternative methods for optimizing the tower erection process by redesigning the tower for the proposed method. In addition, a schedule and cost estimate for construction will be developed. Each case will be assessed based on site conditions, transportation constraints and safety regulations.

In order to determine a framework for the optimal erection method of a wind turbine, we must complete the following objectives:

1. Understand the design and construction process for wind turbines;
2. Perform structural analysis of a wind turbine tower;
3. Identify factors that impact time and cost of erection;
4. Determine alternative tower design and construction method;
5. Create a decision making tool to determine the feasibility of each method.

4.0 Capstone Design Statement

The Accreditation Board for Engineering and Technology (ABET) has set standards that each engineering student must reach to be prepared for engineering practice. Students demonstrate this through a Capstone Design Experience. The Capstone Design Experience must include a majority of the following considerations: economic, environmental, sustainability, manufacturability, ethical, health and safety, social and political. This Major Qualifying Project will fulfill the ABET standards by including the considerations listed below.

4.1 Economic

A cost analysis of tower designs and construction methods will determine the feasibility of each of the different methods. The cost analysis will examine factors such as price of materials and manufacturing, shipping costs, construction costs, and time to construct. The final conclusion of the project will depend heavily on this economic analysis.

4.2 Environmental

Wind turbines are increasing in popularity because of their low environmental impact when compared to traditional fossil fuels. This project will explore using different tower erection processes and will take into consideration building and permitting codes. Following these building and permitting codes will ensure that the lowest environmental impact is made when the towers are constructed.

4.3 Sustainability

The use of wind turbines for electricity reduces dependence on fossil fuels which are limited resources. Wind is a naturally occurring and renewable resource that can be converted into electricity. This project will seek to find a cheaper method to erect a wind turbine tower. If a cheaper method is found, it is possible to construct more wind turbines and lessen the dependence on fossil fuels.

4.4 Manufacturability

The major focus of this project will be the erection process of wind turbine towers. A tower will be designed for each erection method for maximum power output. At the completion of this project there will be a set of recommendations that describe the best conditions to use each erection method tested.

4.5 Ethical

This project will follow the code of ethics for engineers in order to ensure that the designs are held to the highest degree of honesty and integrity. Safety and reliability for the construction of the turbine tower will not be compromised at the expense of an optimized erection method.

4.6 Health and Safety

Each tower will be designed to withstand the maximum wind speeds with a factor of safety. The tower will be taken through a series of checks to ensure the tower can withstand the stresses exerted on it without falling. The erection methods will also be analyzed to ensure that proper safety precautions are taken as specified by OSHA.

4.7 Social

Renewable energy, specifically from wind turbines, is becoming a more socially acceptable source of power. However, some cases experience a low return on investment. Slow payback rates discourage the community because they are not reaping the benefits as quickly as anticipated. By optimizing the construction process, this project aims to lower startup costs which would allow for a faster payback period.

5.0 Methods

In order to determine a framework for the optimal erection method of a wind, five objectives were created to outline the methodology:

1. Understand the design and construction process for wind turbines;
2. Perform structural analysis of a wind turbine tower;
3. Identify factors that impact time and cost of erection;
4. Determine alternative tower design and construction method;
5. Create a decision making tool to determine the feasibility of each method.

The flowchart in Figure 9 illustrates how our baseline case will lead to an investigation of alternative designs and construction methods. The criteria for which cases will be compared are broken down and discussed in sections 3.1 -3.3 below.

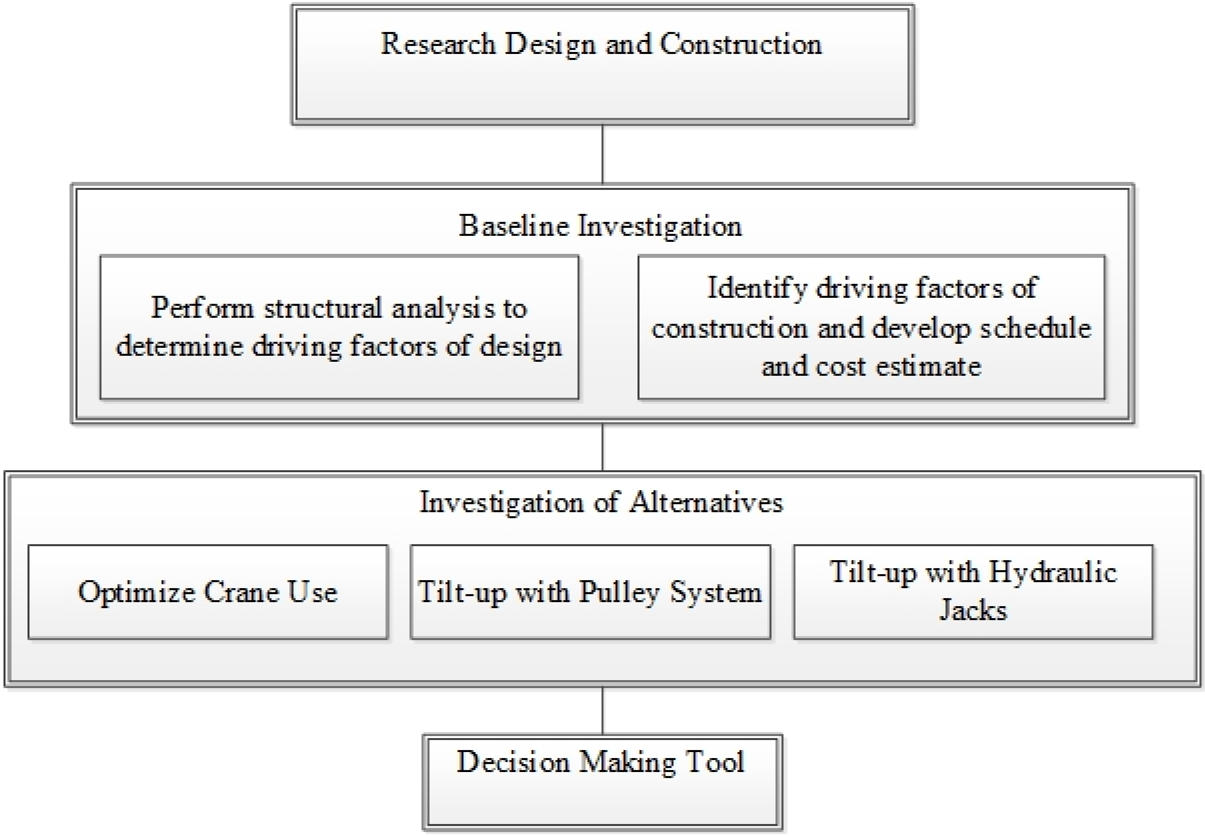


Figure 9: Objective Flowchart.

5.1 Understand the Design and Construction Process

In order to thoroughly understand the design and construction aspects of a wind turbine, we will perform extensive research. This will include exploring existing design standards for wind turbines and similar structures as specified by the International Electrotechnical Commission (IEC), the American Institute of Steel Construction (AISC) and the American Society of Civil Engineers (ASCE-7).

In order to better understand the erection process and challenges that may arise, a visit to an existing wind turbine site in Princeton, Massachusetts will serve as the baseline investigation. Wind data and environmental conditions will be gathered from this site to serve as constants throughout the project.

5.2 Perform Structural Analysis on a Wind Turbine Tower

Structural analysis of a wind turbine tower is necessary to understand the critical loading and stresses applied to the tower. To accomplish this, we will use an analysis tool to determine the maximum loads and stresses that our turbine tower can withstand. Completing a structural analysis of a wind turbine tower was necessary to understand the critical loading and stresses applied to the tower during operation. The factors that will be subject to change and will be analyzed are outlined in Objective 2 and can be seen in Table 1.

Table 1: Criteria for Baseline and Alternative Cases

TURBINE	
Power Output	1.5-2 MW
Number of Blades	3
Design Type	Upwind
TOWER	
Material	Tubular Steel
Thickness	Uniform (approximately 40 mm)
ENVIRONMENTAL FACTORS	
Wind Speeds	*Will be determined from Princeton visit
Location	Princeton

5.3 Identify Factors that Impact Time and Cost of Erection

The driving factors of the erection process will be identified with regard to time and cost of construction. Background research and interviews will be conducted to develop a cost analysis of the crane erection method. Factors that will be included in the cost analysis are outlined in Objective 3 of **Error! Reference source not found.**. Once the driving factors are determined, they will serve as part of our baseline to compare with the alternative cases.

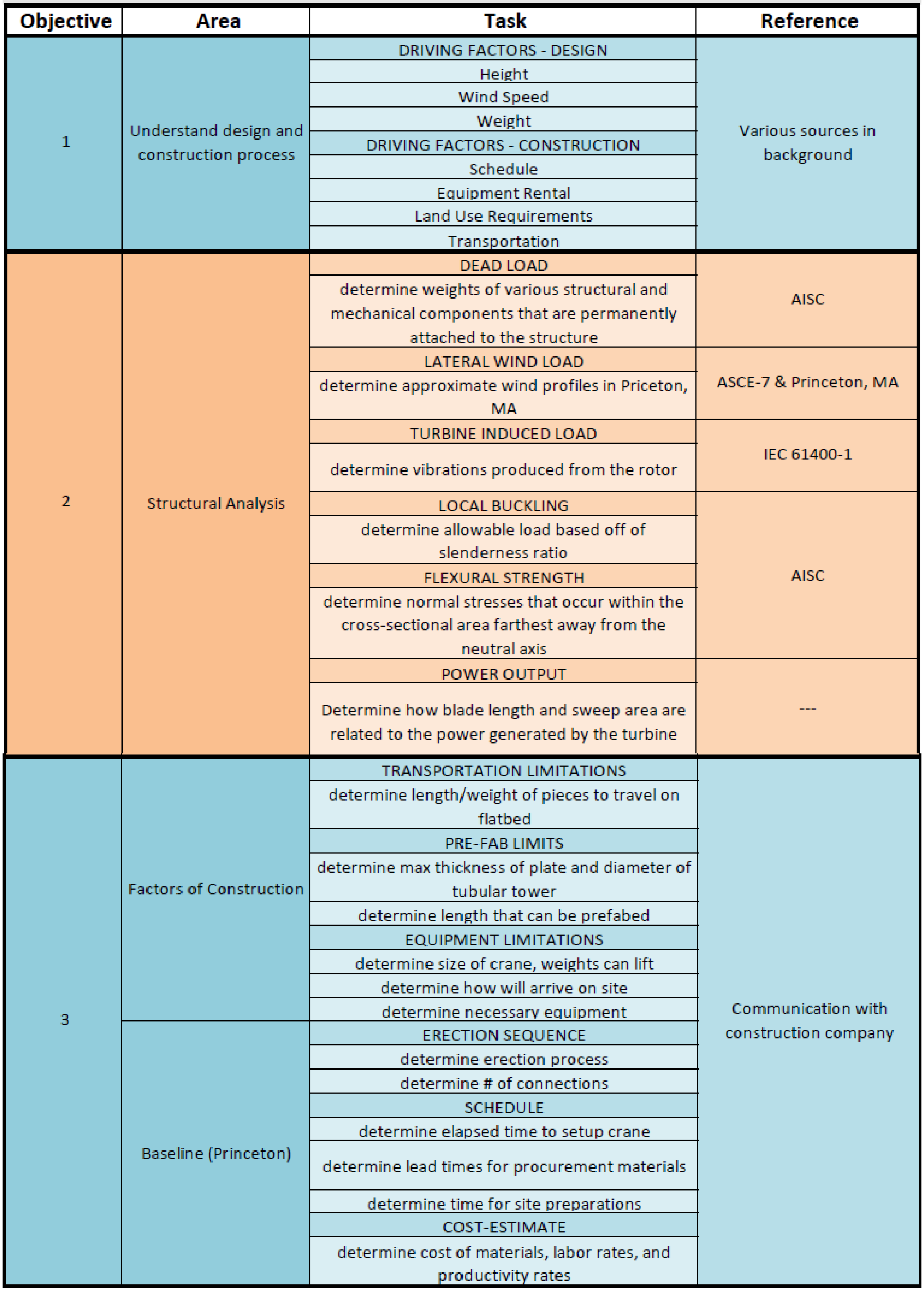
5.4 Determine Alternative Tower Designs and Erection Methods

Identifying alternative methods for more efficient installation of wind turbines will be based on the driving factors found for design and erection. Alternative methods that will be considered include: optimization of current crane applications, a tilt-up tower by pulley system and a tilt-up tower by hydraulic jacks. After analyzing each erection method, a tower redesign will be created to accommodate the particular erection method while maintaining the criteria specified in and yielding limits for A-36 steel. Completing a structural analysis of a wind turbine tower was necessary to understand the critical loading and stresses applied to the tower during operation.

. Additional analysis will include a schedule and cost estimate for construction. Aspects for each tower design and erection method are outlined in Objective 4 of **Error! Reference source not found.**.

5.5 Discuss Implications of Each Alternative Application

Limiting factors including existing site conditions and safety regulations will be identified to discuss the implications of each alternative. These factors combined with the previous analyses of design, cost and schedule, will complete the case study for each scenario. Objective 5 of Figure 10 outlines the process we will use to create a decision making tool.



Objective	Area	Task	Reference
1	Understand design and construction process	DRIVING FACTORS - DESIGN	Various sources in background
		Height	
		Wind Speed	
		Weight	
		DRIVING FACTORS - CONSTRUCTION	
		Schedule	
		Equipment Rental	
		Land Use Requirements	
		Transportation	
2	Structural Analysis	DEAD LOAD	AISC
		determine weights of various structural and mechanical components that are permanently attached to the structure	
		LATERAL WIND LOAD	ASCE-7 & Princeton, MA
		determine approximate wind profiles in Priceton, MA	
		TURBINE INDUCED LOAD	IEC 61400-1
		determine vibrations produced from the rotor	
		LOCAL BUCKLING	AISC
		determine allowable load based off of slenderness ratio	
		FLEXURAL STRENGTH	
		determine normal stresses that occur within the cross-sectional area farthest away from the neutral axis	
		POWER OUTPUT	---
		Determine how blade length and sweep area are related to the power generated by the turbine	
3	Factors of Construction	TRANSPORTATION LIMITATIONS	Communication with construction company
		determine length/weight of pieces to travel on flatbed	
		PRE-FAB LIMITS	
		determine max thickness of plate and diameter of tubular tower	
		determine length that can be prefabed	
		EQUIPMENT LIMITATIONS	
		determine size of crane, weights can lift	
		determine how will arrive on site	
		determine necessary equipment	
	Baseline (Princeton)	ERECTION SEQUENCE	
		determine erection process	
		determine # of connections	
		SCHEDULE	
		determine elapsed time to setup crane	
		determine lead times for procurement materials	
		determine time for site preparations	
		COST-ESTIMATE	
		determine cost of materials, labor rates, and productivity rates	

4	Alternative Design: Crane Alteration	DESIGN FACTORS	Team analysis
		determine max height	
		determine max wind speed (for turbinbe output of power)	
		CHECK STRUCTURAL STABILITY	
		dead load, wind loads, turbine induced loads, local buckling and flexural strength	
		ERECTION SEQUENCE	
		determine erection process	
		determine # of connections	
		SCHEDULE	Team Analysis - Refer to knowledge from Objective 2
		determine elapsed time to setup crane	
		determine lead times of materials	
		determine time for site preparations	
		COST-ESTIMATE	
		determine cost of materials, labor rates, and productivity rates	
4	Alternate Design: Tilt up Method	DESIGN FACTORS	Team Analysis
		determine max height	
		determine max wind speed (for turbinbe output of power)	
		CHECK STRUCTURAL STABILITY	
		dead load, wind loads, turbine induced loads, local buckling and flexural strength	
		CONSTRUCTED	Team Analysis - Refer to knowledge from Objective 2
		determine erection process	
		determine # of connections	
		SCHEDULE	
		determine elapsed time to setup crane	
		determine lead times of materials	
		determine time for site preparations	
		COST-ESTIMATE	
		determine cost of materials, labor rates, and productivity rates	
4	Alternate Design: TBD	DESIGN FACTORS	Team Analysis
		determine max height	
		determine max wind speed (for turbinbe output of power)	
		CHECK STRUCTURAL STABILITY	
		dead load, wind loads, turbine induced loads, local buckling and flexural strength	
		ERECTION SEQUENCE	Team Analysis - Refer to knowledge from Objective 2
		determine erection process	
		determine # of connections	
		SCHEDULE	
		determine elapsed time to setup crane	
		determine lead times of materials	
		determine time for site preparations	
		COST-ESTIMATE	
		determine cost of materials, labor rates, and productivity rates	
5	Develop Desicion Making Tool	SITE LIMITATIONS	Team Analysis - Refer to AISC Wind Profiles
		determine availability of access roads	
		geographical location	
		SAFETY LIMITATIONS	OSHA
		determine regulations	
		DRIVING FACTORS	Team Analysis - Refer to knowledge from Objective 2
		Tower Height	
		Adjust constraints	

Figure 10: Objective Task Chart.

6.0 Deliverables

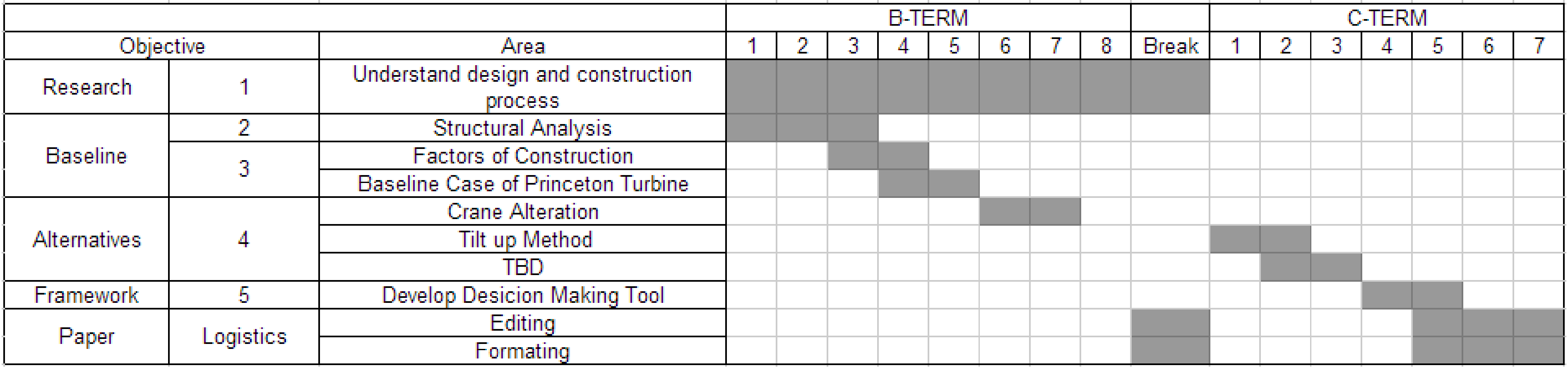
This project will focus on determining the best way to erect a wind turbine tower, as well as considering alternative options that may help save time and money depending on the site conditions. The final outcome of this project is to create a decision making tool to help determine the best possible erection method based on varying factors of the wind turbine tower.

7.0 Conclusion

Wind turbines are quickly becoming one of the most popular alternative energy sources. They provide energy without emitting harmful gases into the environment and without depleting any of the Earth's resources. However, wind turbines are expensive to install and the slow return on investment may deter groups from installing turbines where otherwise feasible. The goal of this project is to examine alternative tower erection methods in attempt to lower construction costs. In lowering the overall installation costs, the potential of installing more wind turbines in more locations becomes greater; providing clean, renewable energy to a greater population.

8.0 Schedule

Our proposed schedule is outlined below to highlight the major tasks of each objective.



			B-TERM									C-TERM						
Objective		Area	1	2	3	4	5	6	7	8	Break	1	2	3	4	5	6	7
Research	1	Understand design and construction process	■	■	■	■	■	■	■	■	■							
Baseline	2	Structural Analysis	■	■	■													
	3	Factors of Construction			■	■												
		Baseline Case of Princeton Turbine				■	■											
Alternatives	4	Crane Alteration						■	■									
		Tilt up Method										■	■					
		TBD											■	■				
Framework	5	Develop Desicion Making Tool													■	■		
Paper	Logistics	Editing									■					■	■	■
		Formating									■					■	■	■

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Appendix B: Field Notes and Photos from Princeton, MA Wind Turbine

- Field Notes from Site Visit (10/22/2013) in Princeton, MA
- Ed and Chris were linemen who work on the maintenance of the Princeton turbines
- Turbines installed in 2009
- Blades begin turning at wind speeds of 3 m/s
- Stops wind speeds at 20/25 m/s
- Can survive 59.5/52 m/s wind speeds
- Tower has 3 sections
- Need maintenance every 6 months in the gear box
- Wa Wa Wachusett Wind is Youtube video of construction
- General Contractor was Lumus Construction
- Crane was done by Hallamore (Baldwin crane lost the bid)
- Depending on the site, special cranes may be needed
- Caterpillar crane is roughly $28,000/day so way too expensive
- 3-4 cranes are needed on site 24/7
- 50 tractor trailers and a week of assembly for the crane
- Hallamore is known for telescoping crane (it was used on the Kingston, RI turbine)
- The company that used to own the Princeton ones were “Fuhrlander Wind” (German company)
- Big in Europe and China
- ARE (Canada) bought out Fuhrlander wind because they were going under in the US
- Then ARE went under, and now the turbines are owned by the municipality (PLMD)
- The Princeton turbines are FL1500
- Company “Wind Tech” makes their parts in Austria and sends them over. They make the turbines, etc.
- Every 6 month, new advancements are coming out and the already existing wind turbines become “outdated” even if they are only 9 months old
- It’s about $11,000 for a crane per day
- If it is too windy, you can’t use crane, and it’s a wasted day of $11,000
- To assemble crane it took 1.5 days
- Wind Turbines need an energy source to run..need grid power
- Aeronautical is a maintenance company that sucks
- The Princeton turbines are currently at about $80,000 in the red
- Late fall/early winter generates most power because of the temperatures change
- It was $7.5 million for the project for Princeton
- Took out a loan for it and had 10 years to pay it off
- Paying back $75-80,000 a month
- There is about a $800,000 loss because it’s older and needs more maintenance
- It’s expensive for the people because they are trying to pay back the loan
- If it was a private company, it could be paid off faster, but this is owned by the municipality, so the people have to pay it off
- Wind Turbines were great until Shale gas became popular and brought the cost of electricity down
- The blades are 130 feet long and move about 200 mph (fastest)
- 2 kinds of stops: emergency stop (super quick and bad for the gears) and slow stop (rolling stop)

- Wind turbines say “PMLD” (Princeton Municipal Light District) and are named “North” and “South”
- About $30/mW hour
- About $900/mW hour in summer when it’s humid
- Fuhrlander FL 1500 1.5 MW
- Installed in 2009
  Hub Heights for model= 61.5/65/100/114.5 m/s tubular tower
- The blades begin turning at wind speeds of 3 m/s
- low wind speed turbine
- stop wind speeds at 25/20 m/s
- can survive 59.5/52 m/s wind speeds
- maintenance requires crane + crane to assemble the crane
- $11,000/day
- maintenance every 6 months
- torquing required annually after heaviest loading (typically in winter)
- tower=3 sections bolts @ every section
- there is no standardization across wind turbines because they are changing so frequently
- project is a 7.5 million dollar project with a project 10 yr pay off
- high maintenance cost = $800,000 loss per year
- raising the electrical rates help to “stop the bleeding”
- Princeton has 2nd highest electrical rates in MA
- Site previously home of 12 90ft 50 kW turbines
- need to consider breaking stresses on tower (huge tower swinging can be observed)

The following pictures were taken during the site visit to the turbines in Princeton, MA. They include a visual of the full tower, looking up inside the tower, the access door, the bolts and a safety notice inside the tower.


6600 PSI
143 bolts
Torqued 3.28.13
white marker
D.P. E.R.


ZOTH
Energie- und
Automatisierungstechnik
CAUTION
PLEASE OBSERVE
ALL SAFETY PRECAUTIONS
PMLD

Appendix C: Interview Transcripts

Methuen Construction

MQP Team: Brief introduction to our project, description of what we are doing.

MQP Team: What role did Methuen play in the Princeton, MA turbine project?
Brian: Methuen was approached by the Municipal Light Department in 2007. They were in the process of procuring two 1.5MW turbines. PMLD put out a design-build type contract, where you would build access roads, foundations and construction of the turbines on the existing wind farm sites. Princeton had six original lattice-type wind turbines that were there in the 1980s and the early 90s and right up to 2007 which was when they started taking them down because maintenance was too much which was when they decided to put up the wind turbines.
Methuen won the bid and started construction in 2007. Teamed up with Lumus Construction who did the electrical work on the project and they supported the erection process. The Light Dept. bought the turbines directly from Fuhrländer.

MQP Team: Can you give us the general timeline from the start to end of construction?
Brian: We started construction in July 2007 and finished in October 2009. Big delays there because of the long lead items with the embedment rings that go into the foundation and getting the turbines fabricated and delivered to the site. The time of start to finish of construction should have been 6-7 months, but it was over 2 years because of delays and the fabrication process on Fuhrländer's side.
To install the towers it takes about a month, including set up of the crane. But with the crane already installed, probably takes about 3-4 days to put up the turbines.
The access road is the longest part of construction.
We installed the blades on the ground and then hoisted the rotor and three blades together.
The crane cost about $250,000 for 2.5 weeks to a month's worth of work.
It takes a week and a half to get the crane erected because it takes about 20 truckloads to get all of the components and pieces of it to the site.

MQP Team: Any information regarding the tilt up method?
Brian: We have done small tilt up construction wind turbines. We did a project for a small private company down the cape—where we fabricated and built the turbine. It was larger than a residential turbine, but not as big as a commercial one.
Basically, we had a pin at the bottom of the tower and we assembled the nacelle and the blades on the ground and used the counterweight to pick it up and swing it up. We did the design for this project as well.

MQP Team: Why isn't the tilt up used as often as the crane erection method?
Brian: The nacelles weigh a lot, about 75 tons, and the tower sections are very heavy as well. In order to do a tilt up construction, you would have to have a hydraulic jack or a pretty big fulcrum to do that.
They do have different types of cranes that they use in Europe that are track mounted that they use. They seem to be a little more efficient if you have a large wind farm.

MQP Team: Thoughts on the feasibility of a pulley system for tower erection?
Brian: You would to consider that there is a lot of weight. You would have to have a pretty big tower and a pulley system plus you would have to have a pulley truck or a system on track. And the time and cost to set that up probably would not be cost-effective.
The cranes you see being used are the most cost-effective. Especially on large wind farms where you can move on from one tower to the next tower

MQP Team: Major problems with construction? Or improvements that could be done?
Brian: It’s a pretty efficient process as is, the biggest challenge that you have building a wind turbine project is space and logistics. You have to get the crane set and bring in all of these parts and pieces on trucks and normally these turbines are on tops of hills so you have to get these pieces on top of these mountains or hills and that becomes very challenging.
We ended up bringing the nacelles to the bottom of the hill and bringing them up with a hydraulic 20 wheel machine that walks it up the hill for us on a tractor. One of the challenges with this is that the trucks sometimes can’t get up the hill. And you have to time everything so that the crane isn’t waiting around for you to get everything in place before you can use it.

MQP Team: What wind speeds cause the wind turbines to shut down?
Brian: Rule of thumb that around 25-30mph the turbines shut down. It isn’t the gusts that determine this, it’s the consistency of the wind at these speeds that is the issue.

MQP Team: Thank you very much for your time!

Atlantic Designs

Dana: We picked our project on wind turbines, specifically the construction process, so we were wondering if we could ask you a few questions about the general process.

Simon: We're an engineering company, involved with initial assessment, design, permitting, construction and structural review. And because I'm a partner in operating a turbine, I know the other end as well.

Dana: As for construction, can you elaborate on what your role is? Do you subcontract out? Do you do the construction yourself?

Simon: It depends on the relationship of the parties of the project. On most projects in Massachusetts, they have a process called control construction affidavit, it basically means on behalf of the building department you have to review, asses and certify aspects of construction. We will review and assess the civil component of that construction. There is an electrical and structural aspect as well which is done by the electrical engineer and the structural engineer. Construction management tends to be out of state so we will bring in a local inspector for the review.

Dana: Work on Gloucester Project? Could you elaborate on this?

Simon: Yes, we worked on two projects in Gloucester. We did the two 2.0MW wind turbines Gloucester engineering; those ones we did pretty much the construction engineering plans as part of the construction team.

We were more involved on the Gloucester Varian Semiconductor which is the biggest one in Massachusetts. It's a 2.5MW wind turbine—a Kenersys from Germany.

Dana: A lot of the focus of our project is about the construction and the use of cranes and trying to look at alternative methods to the erection process. Did you use cranes to install it?

Simon: Absolutely. The crane becomes a very sophisticated and involved process on each project. The two projects where we were the most involved in—one was for the Narragansett Bay Commission, down in Field Point in Providence. We installed three Goldwin, 70 meter high, 1.5MW turbines with 82 meter rotor diameters. We installed them in an actual wastewater treatment plant with very tough design requirements. I think we had about 25 plan sheets or so for the design—ranging from where the foundations were, where drainage space was, etc. Everything was very complicated in terms of setting up the crane, literally what you were doing in the erection process—making sure that the foundation is in place, you have the anchor bolts set and certified—in other words we survey and make sure everything is an approximate template before we put the tower up. It goes very quickly, literally, you normally set your base section in one day, because you have to lock the foundation in 25 hours, and the other two to three sections depending on turbine, go up very quickly the next day. The whole process, with a team of about 15 people coordinating through radio took maybe 3-5 minutes.

The toughest one was the one in Gloucester—not only was it the tallest turbine, it was also graded in a parking lot. We were next to a hill and we had to do a low-end lift because we couldn't work up the ridge from the other side. As I recall, we had to use a special crane for that one and here are only 6 or 10 of them in the country that will work—that was pretty neat as well.

Dana: Do you have the name of that crane company?

Simon: The one in Gloucester was done by Baldwin Crane. There are two contacts there—Mark Baldwin and Ernie Baldwin. They are very good to work with. We've worked with them on a bunch of projects, such as the Mount Wachusett Community College, the Gardiner North Correctional, a project of my own in Plymouth, Mass, which was a Goldwin project and they were our crane company. Another company is Barnhardt—they are national, they were our NBC project in Providence.

Dana: We are looking through the different construction processes and how cranes are used. From what we have gathered, when people use the traditional crane method, it's the tower crane and then a smaller, mobile crane that helps assemble it—is this correct?

Simon: What you do is you have two cranes. You can only lift up in about 20mph winds, need extreme precision to line up the bolts and each connection point.

Dana: We were looking at the different challenges associated with the use of cranes—a lot of them were with being out of money if you cannot assemble the tower or turbine on a specific day or within the timeframe.

Simon: On all of our bids we build in a couple of bad weather days. Usually about 5 days is adequate. I think the one in Newburyport we had about 2 or 3 weeks where we got hit by storm after storm and that can get very expensive. Some of the earlier projects, didn't build in those protections and they ended up with very significant change orders for the contractors.

Then you can get situations where we work for the contractors and the first two GEs that were on the base, they mobilized the cranes and they didn't set the anchor bolts properly (it was a new contractor on the foundations) and didn't have the engineer like us check the template before they went to erect and they had to manually grout out and reset the anchor bolts, get GE sign off in a 6-8 week period and mobilize the crane—this was a very expensive mistake.

Dana: Do you see any improvements that can be made to the erection process?

Simon: The earlier projects we did, the cranes were more of an issue. I remember the initial installation of Portsmouth, RI—they had some bad (defective) anchor bolts and they were shearing on the install when we were doing the blade lifts (?). Our preference is not to do a single blade lift, our preference is to attach hub, rotor, plan it out and do it in a single lift. On my end, for the crane part, if you do it right, it goes very quickly and smoothly and you're done. The logistics are much more involved with the utility company interface, figuring out how you're going to interconnect is probably one of the biggest challenges and getting your foundation right. There is way more work and attention for us on the foundation and construction. For example, with the Camelot turbine, we went with a spread footing design versus …?

Dana: Among all of the wind turbine projects you have done in the past, is there a certain percentage of construction costs is attributed to the erection process?

Simon: I'll give you a breakdown for some projects in eastern, MA: for a 1.5MW turbine, the turbine procurement comes in at about $2 million and you can usually add about $300,000 or more for delivery. The site graded contract and excavation and foundation contract, the crane contract, the mechanical completion contract, the electrical construction contract to do the interconnect came in about $1.3 million. So that gives you a total budget of about $3.6 million and that's on a project that's all planned and pretty much went according to plan, so there were no change orders. Typically, you can very easily end up with $200,000 or more of change orders.

Dana: Are we able to access your bids if they are public?
Simon: For most of the projects—we are involved with two types of projects; one is publicly owned and sponsored projects. We were the engineers for projects at UMass Dartmouth, the Mount Wachusett Community College turbines—you can probably access these bids online.
For private projects, owners tend to not want to share that information.

Dana: Total costs of transportation, erection—are we able to get this information?
Simon: Yes, I can get you the numbers. For example, the NBC project, the three turbine project, the total bid on that was $12.85 million. They had big problems with national grid so I know they had a lot of charges on the electrical side, but I don't recall what the crane budget is. I know for example, for our Camelot project, our crane budget was $350,000—the crane company doesn't just install the turbine on that one particular day. They also do the mechanical completion, which is a lot of work. It's about 3-4 weeks of making sure everything is properly connected, stabilized and works. Which is a big aspect of the crane dollar—that mechanical completion aspect.

Dana: Can you rent the crane on your own and have someone who is certified operate the crane, or does the crane company have someone they send out to do this work?
Simon: Yes, you could and in some of the earlier ones they did it. I would highly recommend not doing that, you really want an A-team. A big part is you have to comply with OSHA and those are all of the things that those guys do.

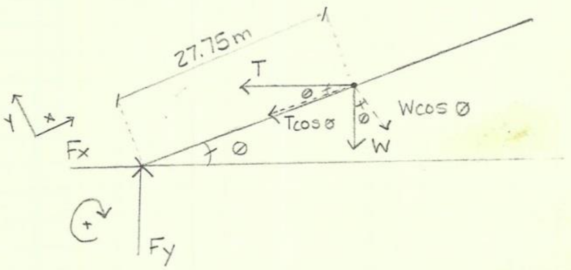
Dana: That's about all of the questions we had for you, thank you very much for taking the time to help us out.
Simon: Alright, good luck with it, gang!

Appendix D: Baseline Hand Calculations

One Point Analysis

BASELINE - 1 POINT ANALYSIS

Tower height = 67m
Cog = 27.75 m
Tower Section Weight = 16160 N



* For 1 pt analysis
W = Total Tower Weight
= 1082650 N

- Determine Critical T for given $\varnothing$

$$T(27.75 \sin \varnothing) > W \cos \varnothing (27.75)$$

$$T > \frac{W \cos \varnothing (27.75)}{27.75 \sin \varnothing}$$

@ $\varnothing = 1°$ $T = 62{,}024{,}976.96$ N
@ $\varnothing = 2°$ $T = 31{,}003{,}039.62$ N
@ $\varnothing = 3°$ $T = 20{,}658{,}192.63$ N

★ decreases by 50% $1° \rightarrow 2°$

- Determine Resultant Forces Fx, Fy

$+\uparrow \quad \Sigma F_y = 0 \qquad F_y = W \cos \varnothing$

$\xrightarrow{+} \quad \Sigma F_x = 0 \qquad F_x = T \cos \varnothing$

@ $\varnothing = 1°$ $F_y = 1082650 \cos(1) = 1{,}082{,}485.107$ N
$F_x = 62{,}024976.96 \cos(1) = 62{,}015{,}530.26$ N

@ $\theta = 2°$ $F_y = 1{,}081{,}990.48$

$F_x = 30{,}984{,}153.40$

@ $\theta = 3°$ $F_y = 1{,}081{,}166.27$

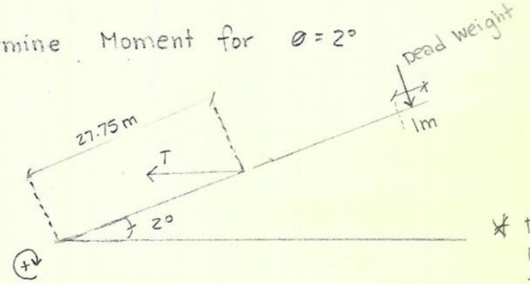
$F_x = 20{,}629{,}881.30$

- Calculate Combined Stresses

$$\frac{Mc}{I} + \frac{P}{A} = \sigma$$

* will Show process for $\theta = 2°$

- Determine Moment for $\theta = 2°$



* calculated at every 1m Section from top of tower

* Dead weight is a Uniform load and takes the resultant for each section

Top section (67)

M_{67} = Dead Weight of Section (Multiply Factor)(Moment Arm)(cos θ)

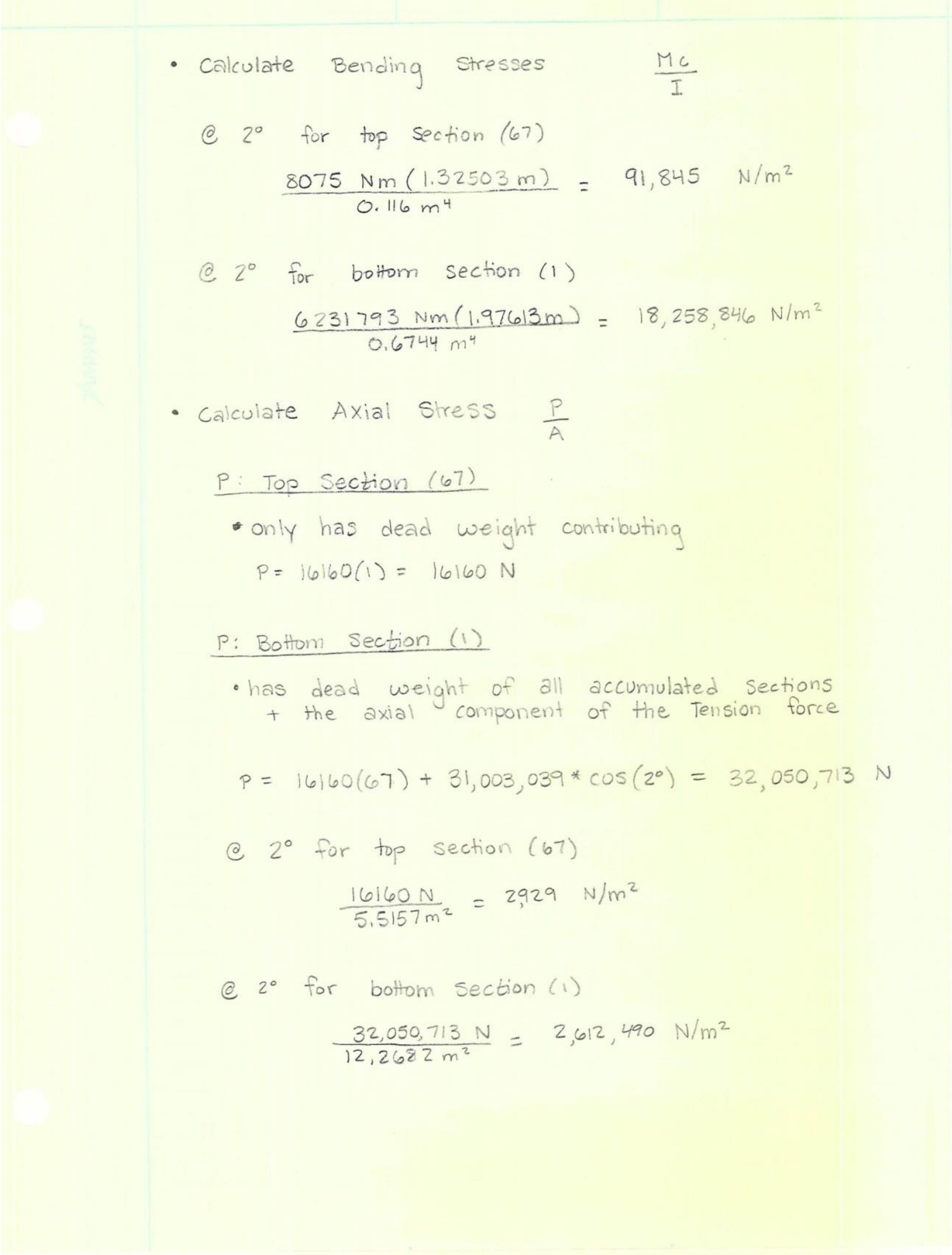
$M_{67} = 16160\ \text{N}(1)(0.5\text{m})(\cos(2°)) = \underline{\underline{8075\ \text{N}\cdot\text{m}}}$

Bottom Section (1)

M_1 = Dead Weight (Multiply Factor)(Moment Arm)(cos θ) − T (Moment Arm) sin θ

$M_1 = 16160(67)(33.5)(\cos(2°)) - 31{,}003{,}039.62(26.75)(\sin(2°))$

$= \underline{\underline{6{,}231{,}793.95\ \text{N}\cdot\text{m}}}$



- Calculate Bending Stresses $\frac{Mc}{I}$

@ 2° for top section (67)

$$\frac{8075\ Nm\,(1.32503\ m)}{0.116\ m^4} = 91{,}845\ N/m^2$$

@ 2° for bottom section (1)

$$\frac{6231793\ Nm\,(1.97613\ m)}{0.6744\ m^4} = 18{,}258{,}846\ N/m^2$$

- Calculate Axial Stress $\frac{P}{A}$

P: Top Section (67)

- only has dead weight contributing

$P = 16160(1) = 16160\ N$

P: Bottom Section (1)

- has dead weight of all accumulated sections + the axial component of the Tension force

$P = 16160(67) + 31{,}003{,}039 * \cos(2°) = 32{,}050{,}713\ N$

@ 2° for top section (67)

$$\frac{16160\ N}{5.5157\ m^2} = 2{,}929\ N/m^2$$

@ 2° for bottom section (1)

$$\frac{32{,}050{,}713\ N}{12{,}2682\ m^2} = 2{,}612{,}490\ N/m^2$$

- Combine Stress

$$\frac{Mc}{I} + \frac{P}{A}$$

@ 2° top Section (67)

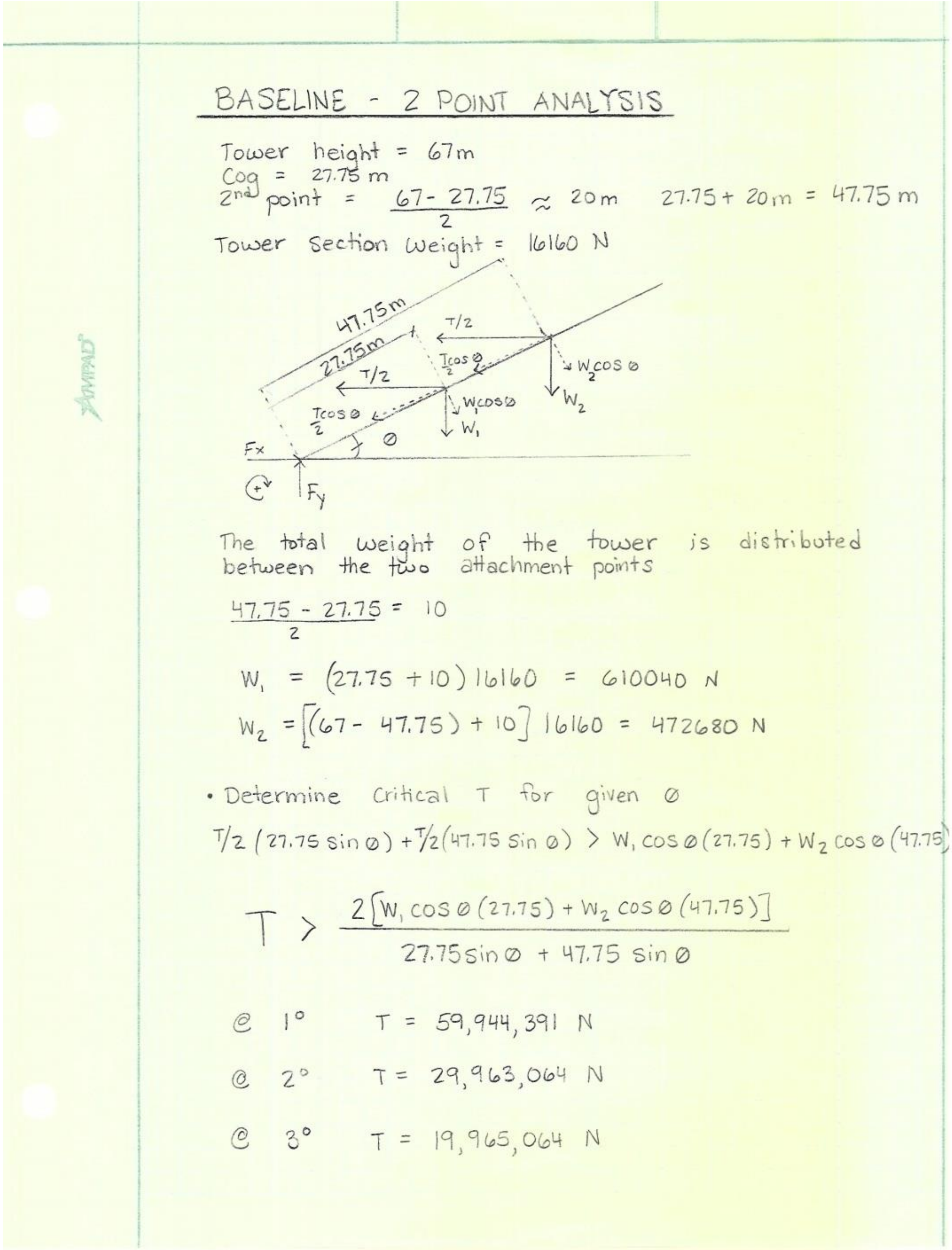
$$89{,}482 + 2{,}886 = \underline{\underline{0.09\ \text{MPa}}}$$

@ 2° bottom Section (1)

$$18{,}258{,}846 + 2{,}612{,}490 = \underline{\underline{20.87\ \text{MPa}}}$$

* Stresses were calculated for every m-section along the tower height and for every ($\emptyset$ = 2°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, 90°) using excel

Two Point Analysis



BASELINE - 2 POINT ANALYSIS

Tower height = 67m

Cog = 27.75 m

2^{nd} point = $\frac{67 - 27.75}{2} \approx 20\,m$ $\quad 27.75 + 20\,m = 47.75\,m$

Tower Section Weight = 16160 N

The total weight of the tower is distributed between the two attachment points

$$\frac{47.75 - 27.75}{2} = 10$$

$$W_1 = (27.75 + 10)\,16160 = 610040\ N$$

$$W_2 = [(67 - 47.75) + 10]\,16160 = 472680\ N$$

- Determine Critical T for given ϕ

$$T/2\,(27.75 \sin\phi) + T/2\,(47.75 \sin\phi) > W_1 \cos\phi\,(27.75) + W_2 \cos\phi\,(47.75)$$

$$T > \frac{2[W_1 \cos\phi\,(27.75) + W_2 \cos\phi\,(47.75)]}{27.75 \sin\phi + 47.75 \sin\phi}$$

@ 1° T = 59,944,391 N

@ 2° T = 29,963,064 N

@ 3° T = 19,965,064 N

- Determine Resultant Forces F_x , F_y

$+\uparrow \ \Sigma F_y = 0 \qquad F_y = W_1 \cos(\phi) + W_2 \cos(\phi)$

$\xrightarrow{+} \ \Sigma F_x = 0 \qquad F_x = T/2 \cos(\phi) + T/2 \cos(\phi)$

$\qquad\qquad = T \cos(\phi)$

@ $\phi = 1°$ $\qquad F_y = 1{,}082{,}555$ N

$\qquad\qquad F_x = 59{,}935{,}261$ N

@ $\phi = 2°$ $\qquad F_y = 1{,}082{,}060$ N

$\qquad\qquad F_x = 29{,}944{,}811$ N

@ $\phi = 3°$ $\qquad F_y = 1{,}081{,}236$ N

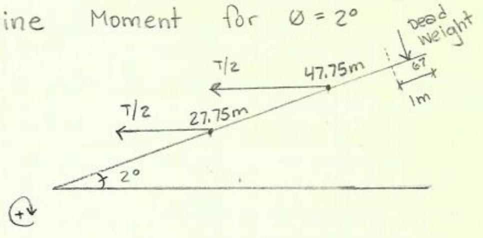
$\qquad\qquad F_x = 19{,}937{,}866$ N

- Calculate Combine Stresses

$$\frac{Mc}{I} + \frac{P}{A} = \sigma$$

* will calculate for $\phi = 2°$

- Determine Moment for $\phi = 2°$



Dead Weight is now a uniform load and takes the resultant for each Section

Top Section (67)

M_{67} = Dead Weight (Multiply factor)(Moment Arm) $\cos\phi$

$M_{67} = 16160(1)(.5)\cos(2°) = 8075$ N·m

Bottom Section (1)

$$M_1 = \text{Dead Weight}\,(\text{M. factor})\begin{pmatrix}\text{Moment}\\\text{Arm}\end{pmatrix}\cos\theta - \frac{T}{2}\begin{pmatrix}\text{Moment}\\\text{Arm}\end{pmatrix}\sin\theta - \frac{T}{2}\begin{pmatrix}\text{Moment}\\\text{Arm}\end{pmatrix} * \sin\theta$$

$$M_1 = 16160(67)(33.5)\cos(2°) - \frac{29963064}{2}(26.75)\sin(2°)$$

$$- \frac{29963064}{2}(46.75)\sin(2°) = -2{,}180{,}297 \text{ N}\cdot\text{m}$$

- Calculate Bending Stress $\sigma = \frac{Mc}{I}$

  @ 2° for top section (67)

  $$\frac{8075(1.32503)}{0.116} = 91{,}845 \text{ N/m}^2$$

  @ 2° for bottom section (1)

  $$\frac{-2{,}180{,}297(1.97613)}{0.6744} = -6{,}388{,}163$$

- Calculate Axial Stress $\sigma = \frac{P}{A}$

  P: Top Section (67)

  - only has dead weight contributing

    $P = 16160(1) = 16160$ N

  P: Bottom Section (1)

  - has dead weight of all accumulated sections + the axial component of the tension force

    1st tension contributes at Section 48

    2nd tension contributes at Section 28

  $$P = 16160(67) + \frac{29{,}963{,}064}{2}\cos(2°) + \frac{29{,}963{,}064}{2}\cos(2°)$$

  $$= 31{,}027{,}531 \text{ N}$$

@ 2° for top section (67)

$$\frac{16160\ N}{5.5157\ m^2} = 2929\ N/m^2$$

@ 2° for bottom section (1)

$$\frac{31{,}027{,}531\ N}{12.2682\ m^2} = 2{,}529{,}089\ N/m^2$$

- Combine Stress $\frac{Mc}{I} + \frac{P}{A} = \sigma$

@ 2° top section (67)

$91{,}845 + 2929 = \underline{\underline{0.09\ MPa}}$

@ 2° bottom section (1)

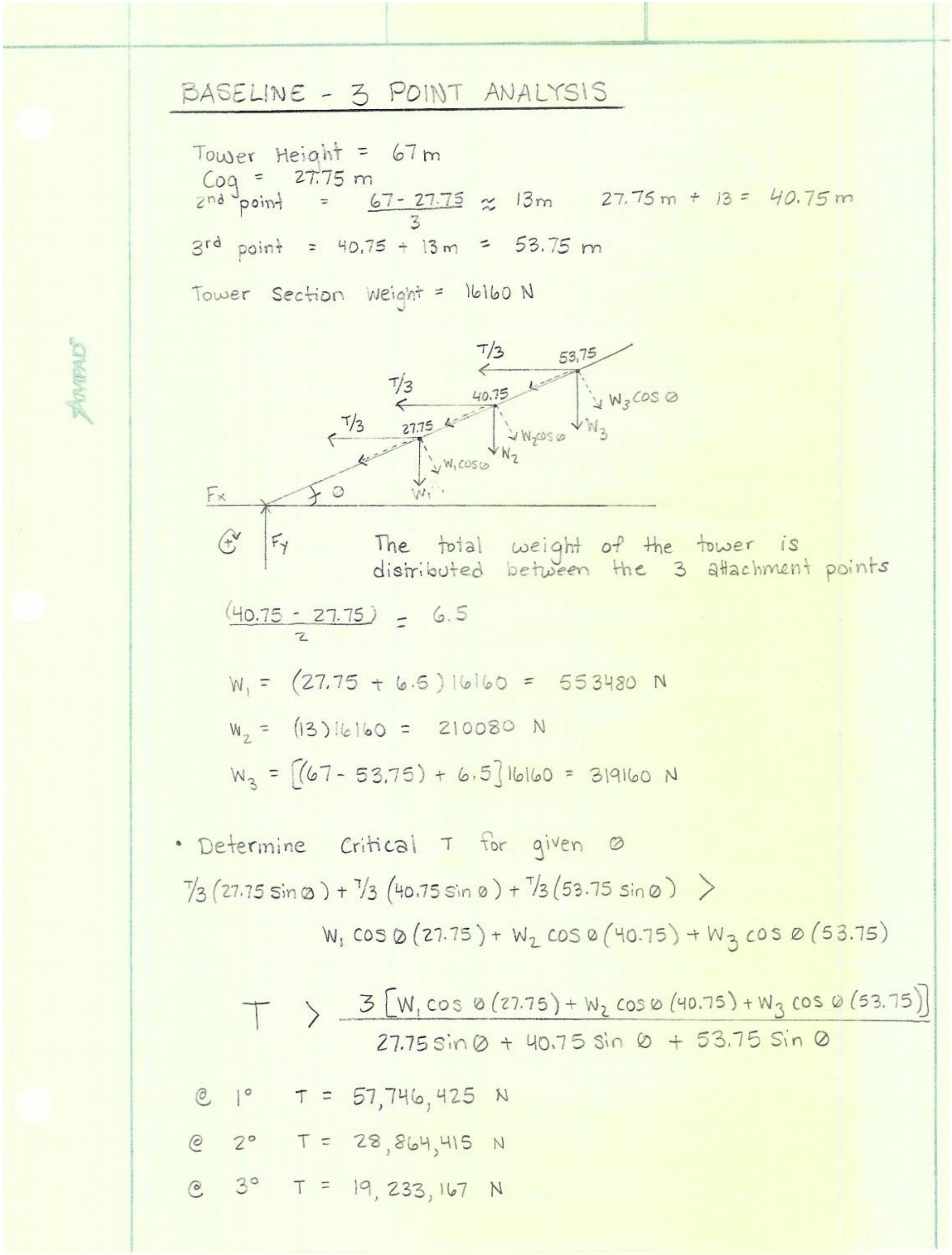
$-6{,}388{,}163 + 2{,}529{,}089 = \underline{\underline{3.86\ MPa}}$

* Stresses were calculated for every m- Section along the tower height and for every

(ϕ = 2°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, 90°)

Using excel

Three Point Analysis



BASELINE - 3 POINT ANALYSIS

Tower Height = 67 m

Cog = 27.75 m

2^{nd} point $= \frac{67 - 27.75}{3} \approx 13\text{m}$ $\quad 27.75\text{ m} + 13 = 40.75\text{ m}$

3^{rd} point $= 40.75 + 13\text{ m} = 53.75\text{ m}$

Tower Section Weight = 16160 N

The total weight of the tower is distributed between the 3 attachment points

$$\frac{(40.75 - 27.75)}{2} = 6.5$$

$W_1 = (27.75 + 6.5)\,16160 = 553480$ N

$W_2 = (13)\,16160 = 210080$ N

$W_3 = [(67 - 53.75) + 6.5]\,16160 = 319160$ N

- Determine Critical T for given θ

$$T/3\,(27.75 \sin\theta) + T/3\,(40.75 \sin\theta) + T/3\,(53.75 \sin\theta) > W_1 \cos\theta\,(27.75) + W_2 \cos\theta\,(40.75) + W_3 \cos\theta\,(53.75)$$

$$T > \frac{3\,[W_1 \cos\theta\,(27.75) + W_2 \cos\theta\,(40.75) + W_3 \cos\theta\,(53.75)]}{27.75 \sin\theta + 40.75 \sin\theta + 53.75 \sin\theta}$$

@ 1° T = 57,746,425 N

@ 2° T = 28,864,415 N

@ 3° T = 19,233,167 N

- Determine Resultant Forces Fx , Fy

$+\uparrow \ \Sigma F_y = 0 \qquad F_y = W_1 \cos\theta + W_2 \cos\theta + W_3 \cos\theta$

$\xrightarrow{+} \ \Sigma F_x = 0 \qquad F_x = T/3 \cos\theta + T/3 \cos\theta + T/3 \cos\theta$

$= T \cos(\theta)$

@ $\theta = 1^\circ$ $\quad F_y = 1,082,555$ N

$F_x = 57,737,630$ N

@ $\theta = 2^\circ$ $\quad F_y = 1,082,060$ N

$F_x = 28,846,832$ N

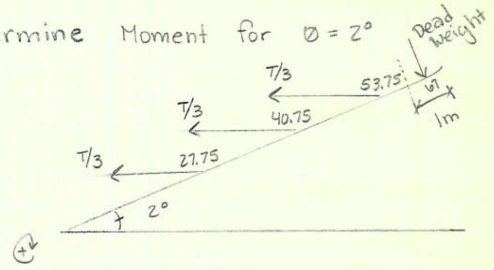
@ $\theta = 3^\circ$ $\quad F_y = 1,081,236$ N

$F_x = 19,206,809$ N

- Calculate Stresses

$$\sigma = \frac{Mc}{I} + \frac{P}{A}$$

- Determine Moment for $\theta = 2^\circ$



Dead weight is
now a uniform
load and takes
the resultant
for each section

Top Section (67)

M_{67} = Dead Weight (Multiply factor) (Moment Arm) cos θ

$M_{67} = 16160(1)(.5)\cos(2^\circ) = 8075$ N·m

Bottom Section (1)

$$M_1 = \text{Dead Weight}\,(\text{M. factor})\left(\text{Moment Arm}\right)\cos\theta - T/3\left(\text{Moment Arm}\right)\sin\theta$$

$$- T/3\left(\text{Moment Arm}\right)\sin\theta - T/3\left(\text{Moment Arm}\right)\sin\theta$$

$$M_1 = 16160(67)(33.5)\cos(2^\circ) - \frac{28{,}864{,}415}{3}(26.75)\sin(2^\circ)$$

$$- \frac{28{,}864{,}415}{3}(39.75)\sin(2^\circ) - \frac{28{,}864{,}415}{3}(52.75)\sin(2^\circ)$$

$$= -3{,}793{,}280 \text{ N·m}$$

- Calculate Bending Stress $\sigma = \frac{Mc}{I}$

@ 2° for top section (67)

$$\frac{8075\,(1.32503)}{0.116} = 91{,}845 \text{ N/m}^2$$

@ 2° for bottom section (1)

$$\frac{-3{,}793{,}280\,(1.97613)}{0.6744} = -11{,}114{,}122 \text{ N/m}^2$$

- Calculate Axial Stress $\sigma = \frac{P}{A}$

P: Top Section (67)

- only has dead weight contributing

$$P = 16160(1) = 16160 \text{ N}$$

P: Bottom section (1)

- has dead weight of all accumulated sections + the axial component of the tension force

1st tension contributes at Section 54

2nd tension contributes at Section 41

3rd tension contributes at Section 28

$$P = 16160\,(67) + \frac{28{,}864{,}415}{3}\cos(2°) + \frac{28{,}864{,}415}{3}\cos(2°)$$

$$+ \frac{28{,}864{,}415}{3}\cos(2°) = 29{,}929{,}552\ \text{N}$$

@ 2° for top section (67)

$$\frac{16160\ \text{N}}{5.5157\ m^2} = 2929\ \text{N}/m^2$$

@ 2° for bottom section (1)

$$\frac{29{,}929{,}552\ \text{N}}{12.2682\ m^2} = 2{,}439{,}591\ \text{N}/m^2$$

- Combine Stress $\frac{Mc}{I} + \frac{P}{A} = \sigma$

@ 2° top section (67)

$$91{,}845 + 2929 = \underline{\underline{0.09\ \text{MPa}}}$$

@ 2° bottom section (1)

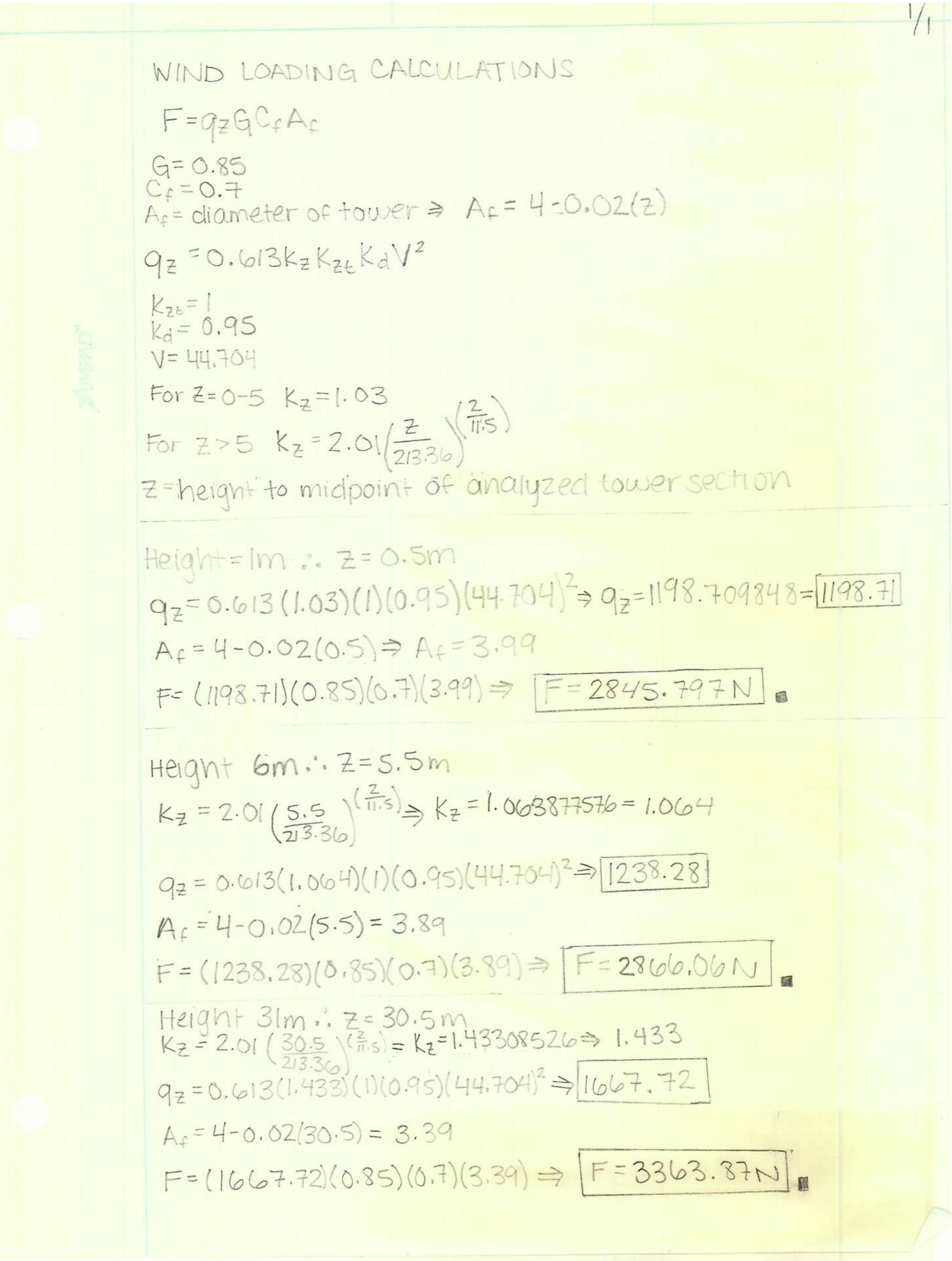
$$-11{,}114{,}122 + 2{,}439{,}591 = \underline{\underline{-8.67\ \text{MPa}}}$$

* Stresses were calculated for every m-section along the tower height and for every

(θ = 2°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, 90°)

using excel

Appendix E: Wind Loading Hand Calculations



1/1

WIND LOADING CALCULATIONS

$F = q_z G C_f A_f$

$G = 0.85$

$C_f = 0.7$

A_f = diameter of tower ⇒ $A_f = 4 - 0.02(z)$

$q_z = 0.613 K_z K_{zt} K_d V^2$

$K_{zt} = 1$

$K_d = 0.95$

$V = 44.704$

For $z = 0-5$ $K_z = 1.03$

For $z > 5$ $K_z = 2.01\left(\frac{z}{213.36}\right)^{\left(\frac{2}{11.5}\right)}$

z = height to midpoint of analyzed tower section

Height = 1m ∴ z = 0.5m

$q_z = 0.613(1.03)(1)(0.95)(44.704)^2 \Rightarrow q_z = 1198.709848 = \boxed{1198.71}$

$A_f = 4 - 0.02(0.5) \Rightarrow A_f = 3.99$

$F = (1198.71)(0.85)(0.7)(3.99) \Rightarrow \boxed{F = 2845.797\,N}$ ■

Height 6m ∴ z = 5.5m

$K_z = 2.01\left(\frac{5.5}{213.36}\right)^{\left(\frac{2}{11.5}\right)} \Rightarrow K_z = 1.063877576 = 1.064$

$q_z = 0.613(1.064)(1)(0.95)(44.704)^2 \Rightarrow \boxed{1238.28}$

$A_f = 4 - 0.02(5.5) = 3.89$

$F = (1238.28)(0.85)(0.7)(3.89) \Rightarrow \boxed{F = 2866.06\,N}$ ■

Height 31m ∴ z = 30.5m

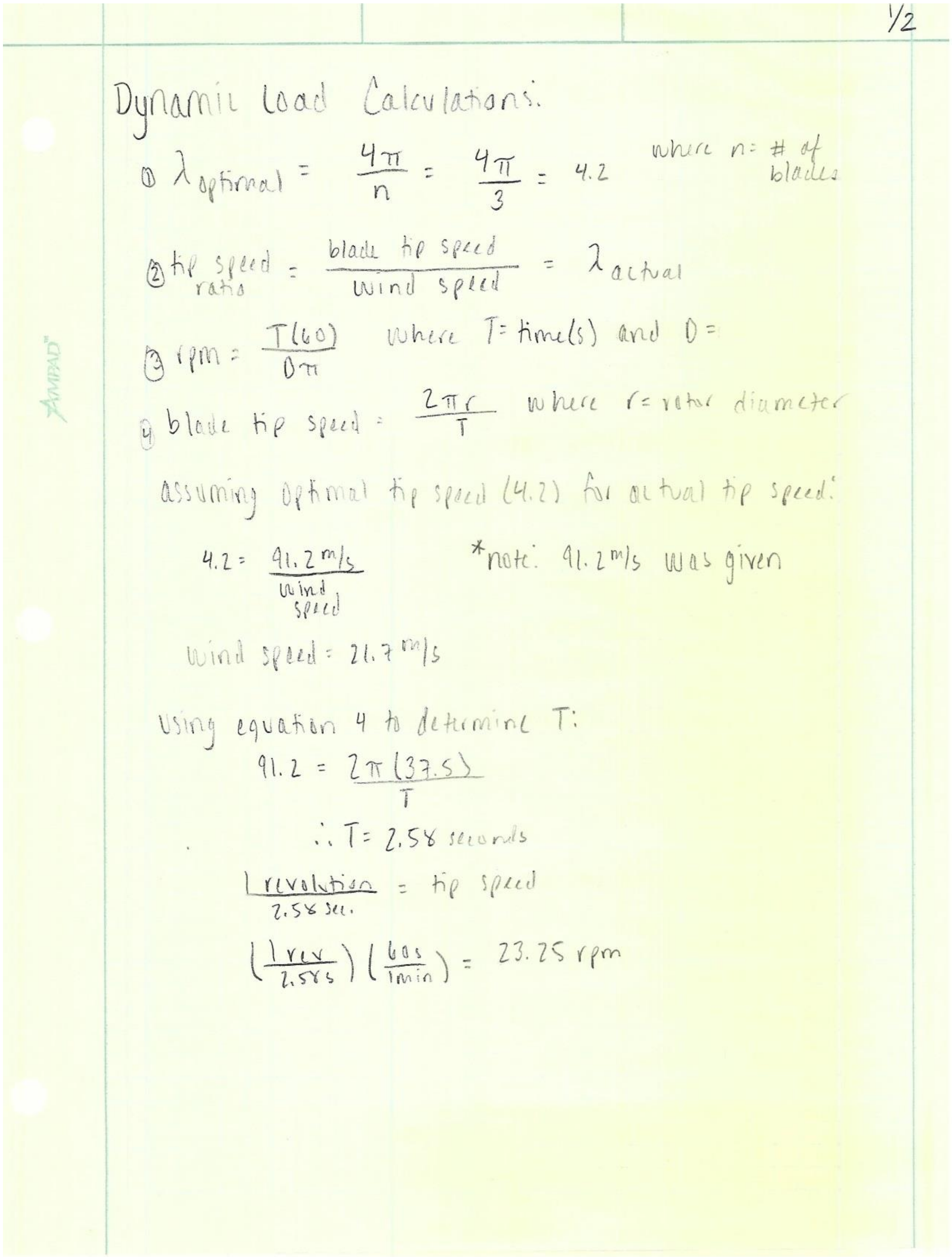
$K_z = 2.01\left(\frac{30.5}{213.36}\right)^{\left(\frac{2}{11.5}\right)} = K_z = 1.43308526 \Rightarrow 1.433$

$q_z = 0.613(1.433)(1)(0.95)(44.704)^2 \Rightarrow \boxed{1667.72}$

$A_f = 4 - 0.02(30.5) = 3.39$

$F = (1667.72)(0.85)(0.7)(3.39) \Rightarrow \boxed{F = 3363.87\,N}$ ■

Appendix F: Dynamic Load and Dynamic Magnification Factor Hand Calculations



1/2

Dynamic Load Calculations:

① $\lambda_{optimal} = \frac{4\pi}{n} = \frac{4\pi}{3} = 4.2$ where n = # of blades

② $\text{tip speed}_{ratio} = \frac{\text{blade tip speed}}{\text{wind speed}} = \lambda_{actual}$

③ $rpm = \frac{T(60)}{D\pi}$ where T = time(s) and D =

④ $\text{blade tip speed} = \frac{2\pi r}{T}$ where r = rotor diameter

assuming optimal tip speed (4.2) for actual tip speed:

$4.2 = \frac{91.2\,m/s}{\text{wind speed}}$ *note: 91.2 m/s was given

wind speed = 21.7 m/s

Using equation 4 to determine T:

$91.2 = \frac{2\pi(37.5)}{T}$

$\therefore T = 2.58$ seconds

$\frac{1\text{ revolution}}{2.58\text{ sec.}} = \text{tip speed}$

$\left(\frac{1\text{ rev}}{2.58\text{ s}}\right)\left(\frac{60\text{ s}}{1\text{ min}}\right) = 23.25\text{ rpm}$

Dynamic Force Calculations:

$P = \frac{1}{2} \rho V^3 A C_p$ where: $\rho =$, A = area,
V = wind velocity, C_p = power coefficient

assuming $\lambda_{(optimal)} = 4.2$:
linearly interpolate C_p from graph:

$$d = d_1 + \frac{g - g_1}{g_2 - g_1}(d_2 - d_1)$$

$$d = 0.541 + \left(\frac{4.2 - 4.0}{4.5 - 4.0}\right)(0.544 - 0.541)$$

$$d = 0.5422$$

find power:

$P = \frac{1}{2}(1.225\ \mathrm{kg/m^3})(13.4\ \mathrm{m/s})^3(4417\ \mathrm{m^2})(0.5422)$

$P = 19656.12\ \mathrm{N}$

*note: ρ is a constant and v was given

DYNAMIC MAGNIFICATION FACTOR

* Using Troitsky Text

Natural Frequency of tapered stack

$$F_n = \frac{3.52\ D_e}{48\ H_e^2}\sqrt{\frac{Eg}{2\ W_s}}$$

where based from Figure 5.1, option c for uniform taper

$$H_e = H\sqrt{\frac{2D_e}{D_e + D_b}} \qquad \text{where} \qquad D_e = \frac{D + D_b}{2}$$

CHECK FOR PRINCETON BASELINE TOWER

$D = 2.666$ m $= 8.7467$ ft $\qquad H = 67\text{m} = 220$ ft

$D_B = 4$ m $= 13.12336$ ft

$$D_e = \frac{8.7467 + 12.28084}{2} = 10.51 \text{ ft}$$

$$H_e = 220\sqrt{\frac{2(10.51)}{10.51 + 13.12336}} = 211.28 \text{ ft}$$

$$F_n = \frac{3.52\ (10.51)}{48(211.28)^2}\sqrt{\frac{(29000000)(386)}{2(0.283)}} = \underline{\underline{2.428}}$$

Compared to given information from Princeton (PMLD) department

$$F_n = 1.09$$

Frequency Ratio

Frequency of the force
= 0.2388

* from previous dynamic loading calculations

$$= \frac{\text{Frequency of the force}}{\text{Frequency of Structure}}$$

Based on above Calculations:

$$\frac{0.2388}{2.428} = .0983 \approx .1$$

Based on given:

$$\frac{0.2388}{1.09} = 0.21 \approx .2$$

Looking at CHART → Response of Single-Degree-of-freedom System to Harmonic Loading

Ratio of .1 & .2 yield 1.1 Magnification Factor

Therefore, for approximating a range, we will use the same magnification factor

IF

$$0.1 < \frac{\text{Frequency of the force}}{\text{Frequency of Structure}} < 0.3$$

THEN

Dynamic Magnification Factor = 1.1

If values are to fall below 0.1 for smaller tower design, 1.1 will still be used and yield a conservative value for the single static load

FOR ALTERNATIVES

		Alter. 1	Alter. 2	Alter. 3
D (upper ⌀)	=	1.42 m	0.91 m	1.39 m
D_b (lower ⌀)	=	2.136 m	1.36 m	2.08 m
H (height)	=	36 m	23 m	35 m
F_n (Frequency of Structure)	=	4.7466	7.4128	4.8947

* thrust force calculated in dynamic loading excel spreedsheet

		Alter. 1	Alter. 2	Alter. 3
Frequency Ratio	=	0.196	0.115	0.071

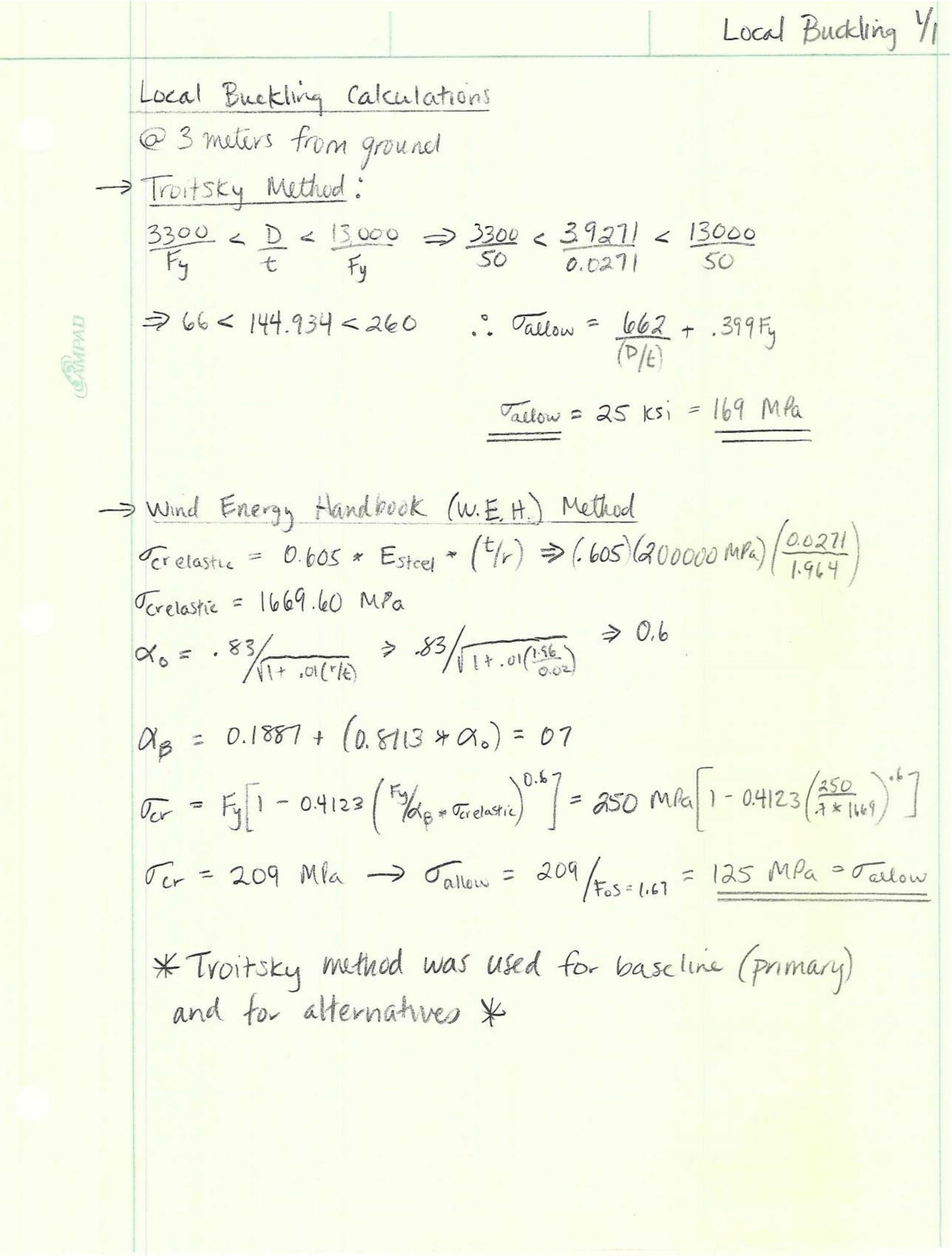
Alter. 1 → within range ✓

Alter. 2 → within range ✓

Alter. 3 → barely out of range

∴ will yield conservative values

Appendix G: Local Buckling, Column Buckling and Yielding Check Hand Calculations



Local Buckling 1/1

Local Buckling Calculations

@ 3 meters from ground

→ Troitsky Method:

$$\frac{3300}{F_y} < \frac{D}{t} < \frac{13{,}000}{F_y} \Rightarrow \frac{3300}{50} < \frac{3.9271}{0.0271} < \frac{13000}{50}$$

$$\Rightarrow 66 < 144.934 < 260 \qquad \therefore\ \sigma_{allow} = \frac{662}{(D/t)} + .399F_y$$

$$\underline{\underline{\sigma_{allow}}} = 25\text{ ksi} = \underline{\underline{169\text{ MPa}}}$$

→ Wind Energy Handbook (W.E.H.) Method

$$\sigma_{cr\,elastic} = 0.605 * E_{steel} * (t/r) \Rightarrow (.605)(200000\text{ MPa})\left(\frac{0.0271}{1.964}\right)$$

$$\sigma_{cr\,elastic} = 1669.60\text{ MPa}$$

$$\alpha_0 = .83/\sqrt{1 + .01(r/t)} \Rightarrow .83/\sqrt{1 + .01\left(\frac{1.96}{0.02}\right)} \Rightarrow 0.6$$

$$\alpha_\beta = 0.1887 + (0.8113 * \alpha_0) = 07$$

$$\sigma_{cr} = F_y\left[1 - 0.4123\left(F_y/\alpha_\beta * \sigma_{cr\,elastic}\right)^{0.6}\right] = 250\text{ MPa}\left[1 - 0.4123\left(\frac{250}{.7 * 1669}\right)^{.6}\right]$$

$$\sigma_{cr} = 209\text{ MPa} \rightarrow \sigma_{allow} = 209/_{FoS = 1.67} = \underline{\underline{125\text{ MPa} = \sigma_{allow}}}$$

* Troitsky method was used for baseline (primary) and for alternatives *

Column Buckling Calculations

I_1 = moment of inertia @ top of tower

I_2 = moment of inertia @ base of tower

$I_1/I_2 = .1/.3 \cong .4$

$\therefore$ from table, $m = 1.904$

$$K = \sqrt{\frac{\pi^2}{\quad}} = \sqrt{\frac{\pi^2}{1.593}} = 2.277$$

Column slenderness $= \lambda = \dfrac{K \cdot L}{r_2} = \dfrac{(2.3)(67 \text{ meters})}{(.3)} = 436.6$

where:

$K = 2.3$ (calculated)

L = length of tower

r_2 = radius of gyration @ base of tower

$$\sigma_e = \frac{\pi^2 E}{\lambda^2} = 10.356 \text{ MPa}$$

$\sigma_{cr} = (.877)(\sigma_e) = 9.082$ MPa ← for long columns

$\sigma_{calculated} = 0.1846 \leq \sigma_{cr} = 9.082$ ✓

Yielding check calculations

performed at the base of the tower (1-meter from bottom)

@ 2 degrees incline during tiltup:

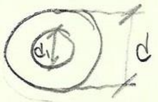
$$\left.\frac{P_r}{P_c} + \frac{M_r}{M_c} \le 1.0 \right\} \text{main check}$$

$$\frac{P_r}{P_c} = \frac{(\text{axial load} = 29.93\ \text{MPa})}{(P_c = \text{Area} \times \sigma_{\text{allowable}})} = .45$$

$$\sigma_{\text{allowable}} = \frac{\sigma_{cr}}{\Omega = 1.67}$$

$$\frac{M_r}{M_c} = \frac{(\text{bending moment} = -3.79)}{\left(\frac{F_y \cdot Z}{1.67}\right)} = 0.00$$

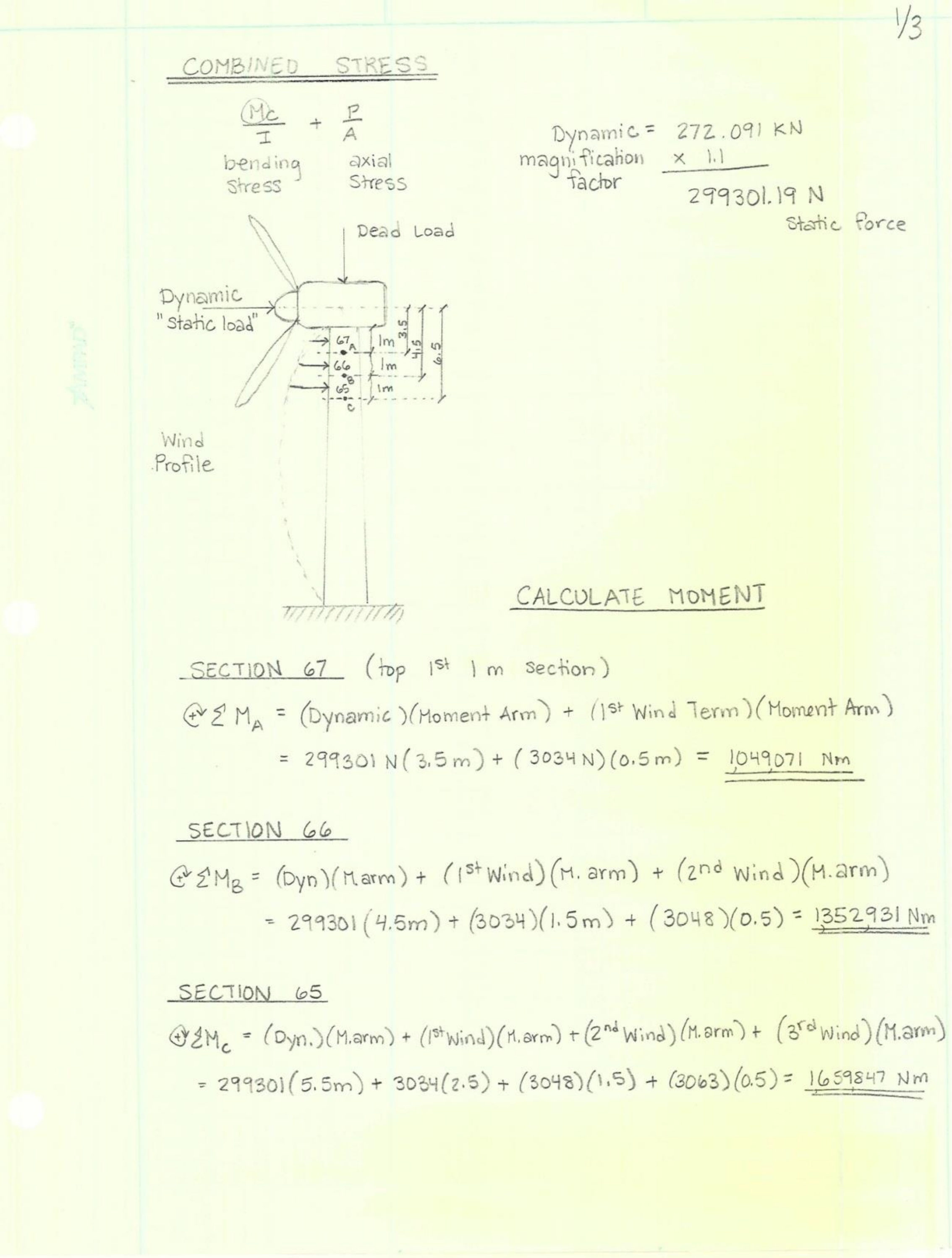
$$Z = \frac{1}{6}\left(d^3 - d_1^3\right)$$



$$\therefore \quad \frac{P_r}{P_c} + \frac{M_r}{M_c} \rightarrow .45 + 0.00 = .45$$

$\underline{.45 \le 1.0}$ ✓ passes yielding @ 2° incline

Appendix H: Combined Stress Hand Calculations



1/3

COMBINED STRESS

$$\frac{Mc}{I} + \frac{P}{A}$$

bending stress   axial stress

Dynamic magnification factor

$$\begin{array}{r} 272.091 \text{ KN} \\ \times\ 1.1 \\ \hline 299301.19 \text{ N} \end{array}$$

Static Force

CALCULATE MOMENT

SECTION 67 (top 1st 1 m section)

$\circlearrowright + \ \Sigma M_A$ = (Dynamic)(Moment Arm) + (1st Wind Term)(Moment Arm)

= 299301 N(3.5 m) + (3034 N)(0.5 m) = 1,049,071 Nm

SECTION 66

$\circlearrowright + \ \Sigma M_B$ = (Dyn)(M.arm) + (1st Wind)(M. arm) + (2nd Wind)(M.arm)

= 299301(4.5m) + (3034)(1.5m) + (3048)(0.5) = 1,352,931 Nm

SECTION 65

$\circlearrowright + \ \Sigma M_C$ = (Dyn.)(M.arm) + (1st Wind)(M.arm) + (2nd Wind)(M.arm) + (3rd Wind)(M.arm)

= 299301(5.5m) + 3034(2.5) + (3048)(1.5) + (3063)(0.5) = 1,659,847 Nm

SECTION PROPERTIES - from previous calculations

	c (m)	I (m^4)
67	1.33	0.122
66	1.34	0.119
65	1.35	0.116

* hand calculations are approx. Excel is more accurate

BENDING STRESS $= \frac{Mc}{I}$

Section 67

$$\frac{1049071(1.33)}{(0.122)} = 11.4 \text{ MPa}$$

Section 66

$$\frac{1352931(1.34)}{0.119} = 14.8 \text{ MPa}$$

Section 65

$$\frac{1659847(1.35)}{0.116} = 19.3 \text{ MPa}$$

Nacelle Weight = 862990 N
Rotor Weight = 318720 N
$\frac{\text{Tower Weight}}{\text{\# of Sections}}$ $\frac{1082650}{67} = 16158$ N

AXIAL STRESS $= \frac{P}{A} = \frac{\text{dead load}}{\text{X-section area}}$

Section 67

$$\frac{862990 + 318720 + 16158(67)}{\pi\left(\frac{1.33+1.32}{2}\right)^2} = 0.21 \text{ MPa}$$

Section 66

$$\frac{862990 + 318720 + 16158(66)}{\pi\left(\frac{1.34+1.33}{2}\right)^2} = 0.21 \text{ MPa}$$

Section 65

$$\frac{862990 + 318720 + 16158(65)}{\pi\left(\frac{1.35+1.34}{2}\right)^2} = 0.21 \text{ MPa}$$

3/3

COMBINED STRESS

Bending Stress + Axial Stress = Combined Stress

$$\frac{Mc}{I} + \frac{P}{A} = \sigma$$

Section 67

11.4 + 0.21 = 11.6 MPa

Section 66

14.8 + 0.21 = 15.01 MPa

Section 65

19.3 + 0.21 = 19.51 MPa

* again = hand calculations are approximations
Excel values are more accurate
with less rounding

Appendix I: Construction Stresses for Alternative Tower Designs

This appendix contains the calculated stresses for alternative 1 and 3 tower designs that were analyzed.

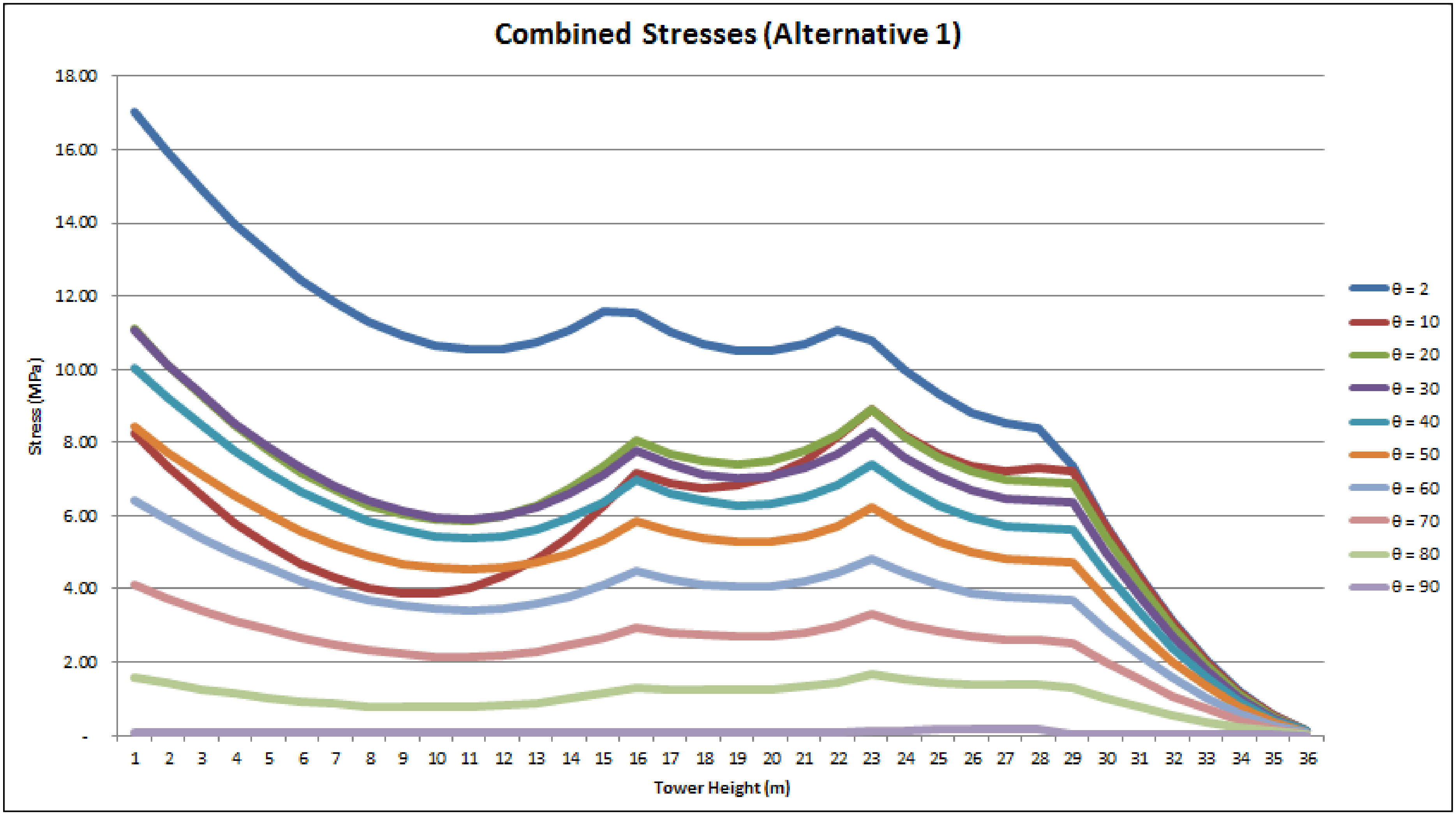


Figure 58: Combined Stresses for Alternative 1 at Each Analyzed Angle.

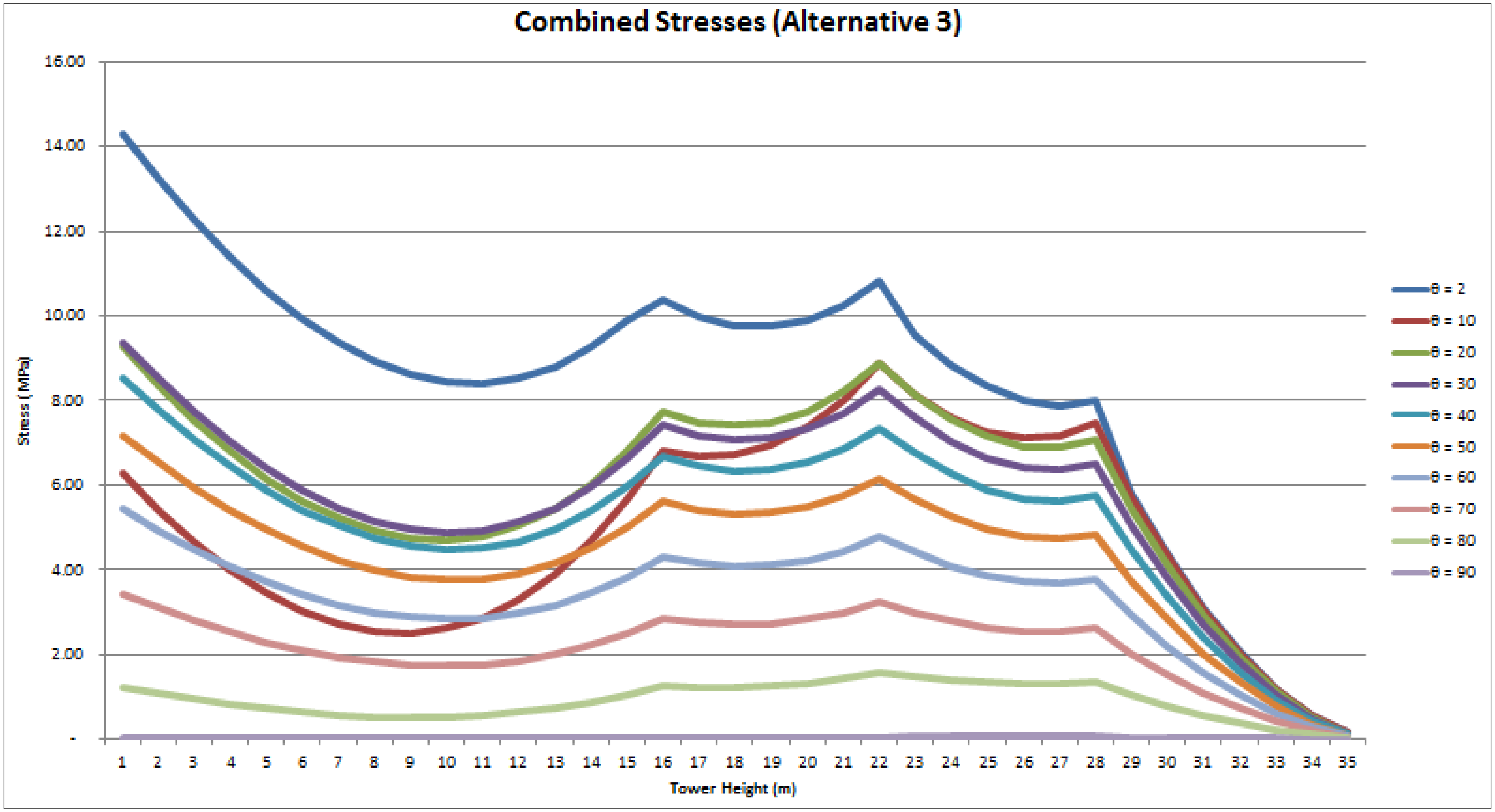


Figure 59: Combined Stresses for Alternative 3 at Each Analyzed Angle.

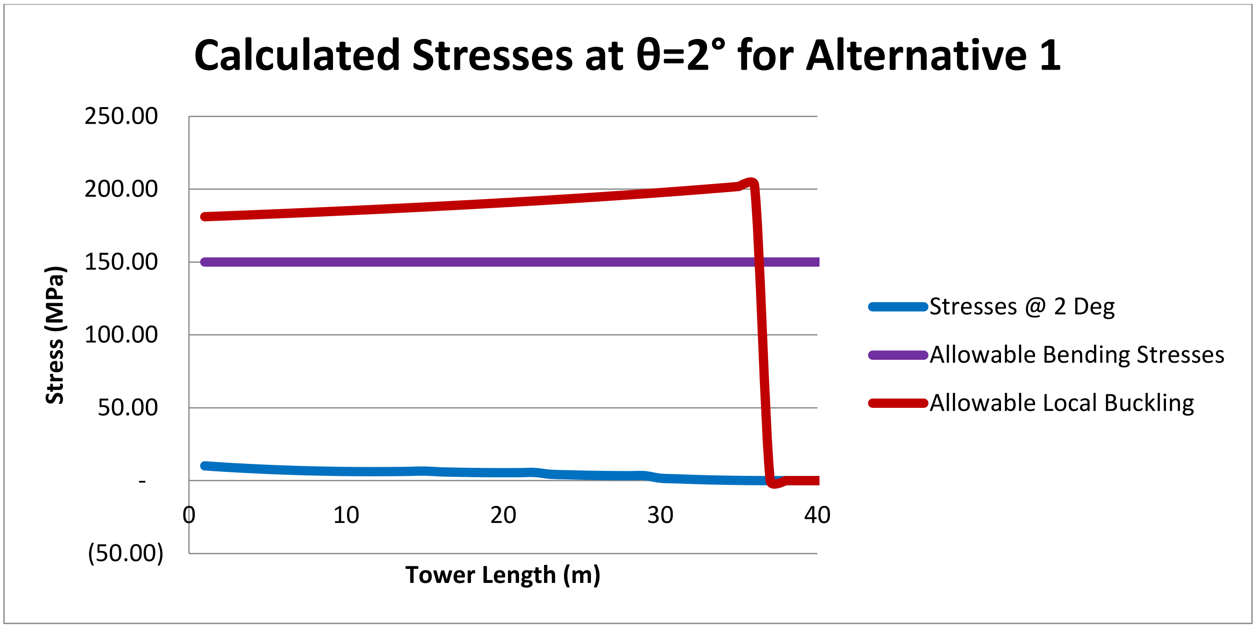


Figure 60: Calculated vs. Allowable Stresses at 2° for Alternative 1.

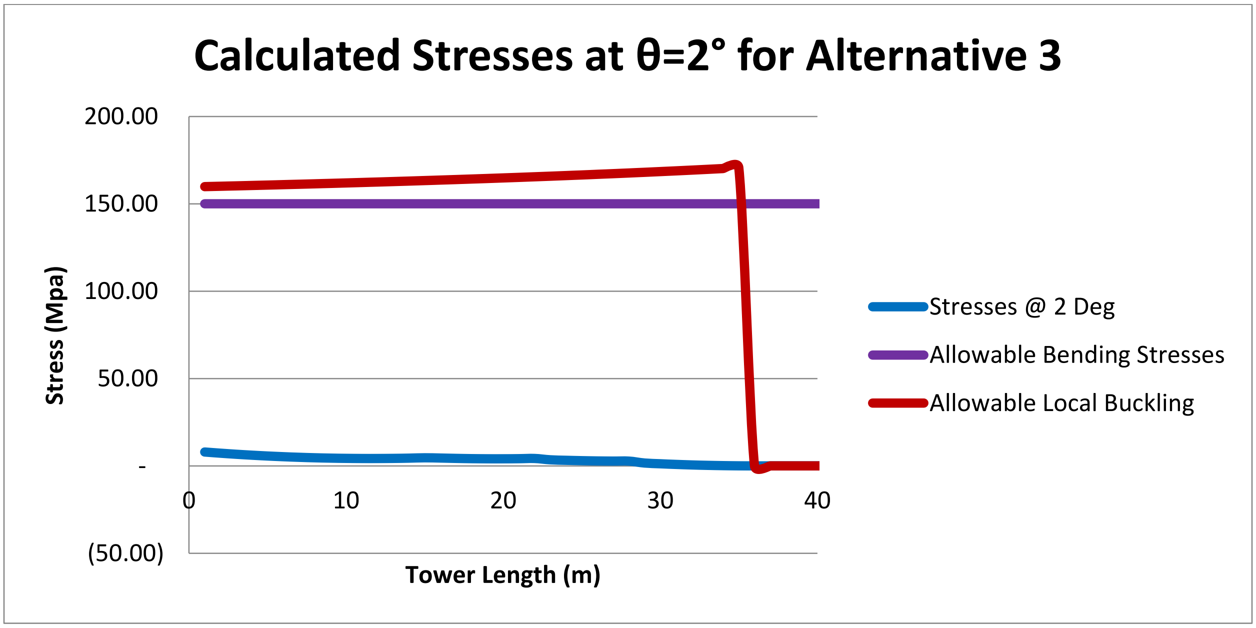


Figure 61: Calculated vs. Allowable Stresses at 2° for Alternative 3.

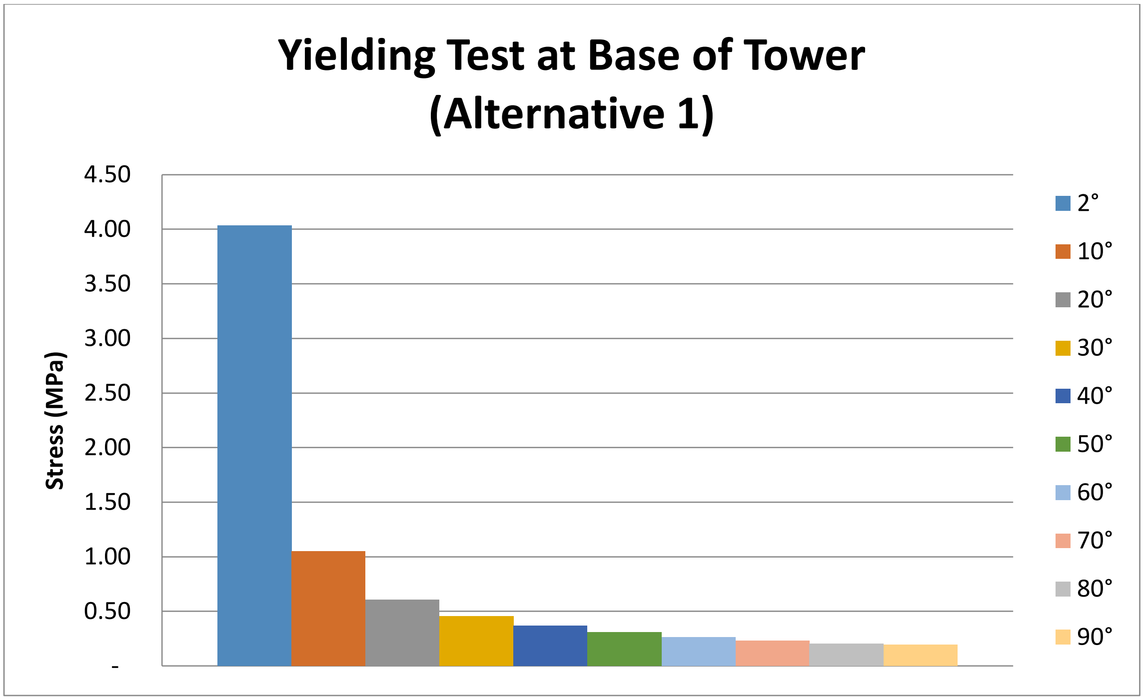


Figure 62: Yielding Test (Alternative 1).

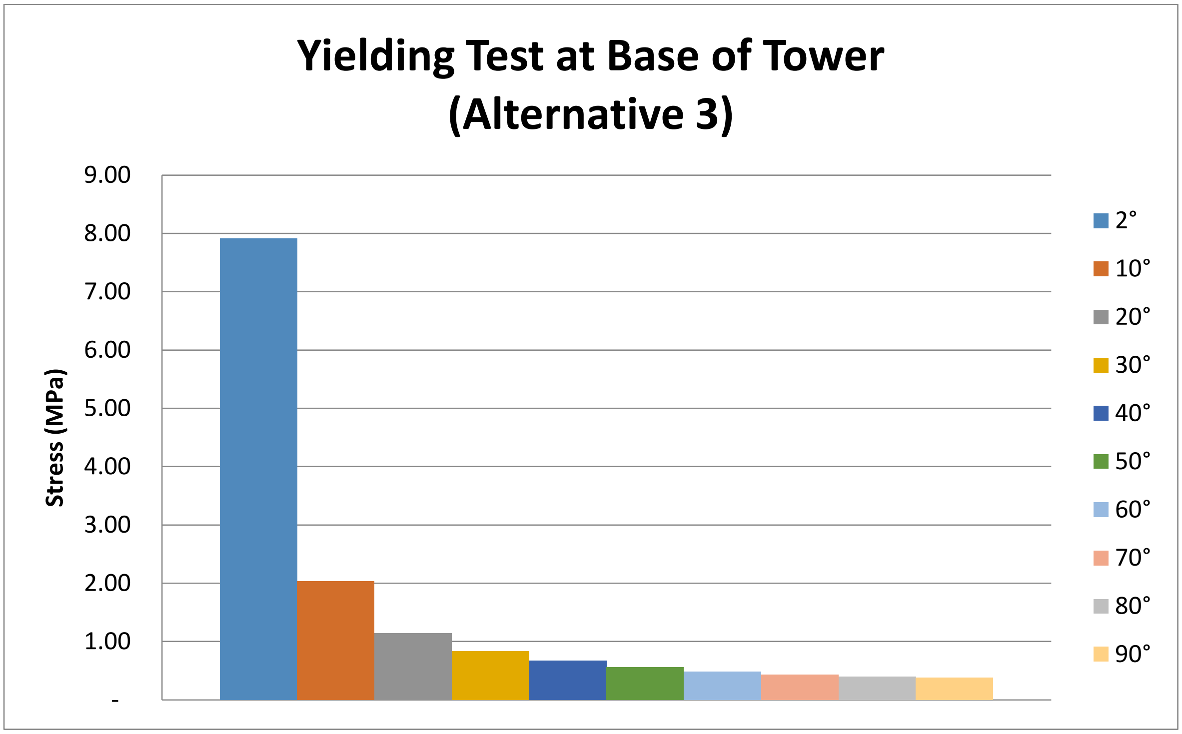


Figure 63: Yielding Test (Alternative 3).

Appendix J: Operational Stresses for Alternative Tower Designs

Alternative Tower Design 1

Table 24: Loading Conditions for Alternative 1

Alternative Tower Design 1					
Lateral Wind Loading				Dynamic Loading	
Section	F (N)	**Section**	F (N)	**Thrust Force**	17,831.83 N
1	1516.37	**19**	1608.42	**Magnification Factor**	1.1
2	1502.19	**20**	1604.96	**Equivalent Static Load**	19,615 N
3	1488.00	**21**	1600.56	Dead Loading	
4	1473.82	**22**	1595.30		
5	1459.63	**23**	1589.24	**Tower Section Weight**	≅ 867 kg/m
6	1492.99	**24**	1582.44	**Nacelle Weight**	3,628 kg
7	1521.91	**25**	1574.96	**Rotor Weight**	564 kg
8	1544.80	**26**	1566.82	**Total Turbine Weight**	≅ 35,4010 kg
9	1562.99	**27**	1558.08		
10	1577.41	**28**	1548.76		
11	1588.71	**29**	1538.91		
12	1597.39	**30**	1528.54		
13	1603.82	**31**	1517.69		
14	1608.3	**32**	1506.38		
15	1611.07	**33**	1494.64		
16	1612.32	**34**	1482.47		
17	1612.21	**35**	1469.91		
18	1610.87	**36**	1456.97		

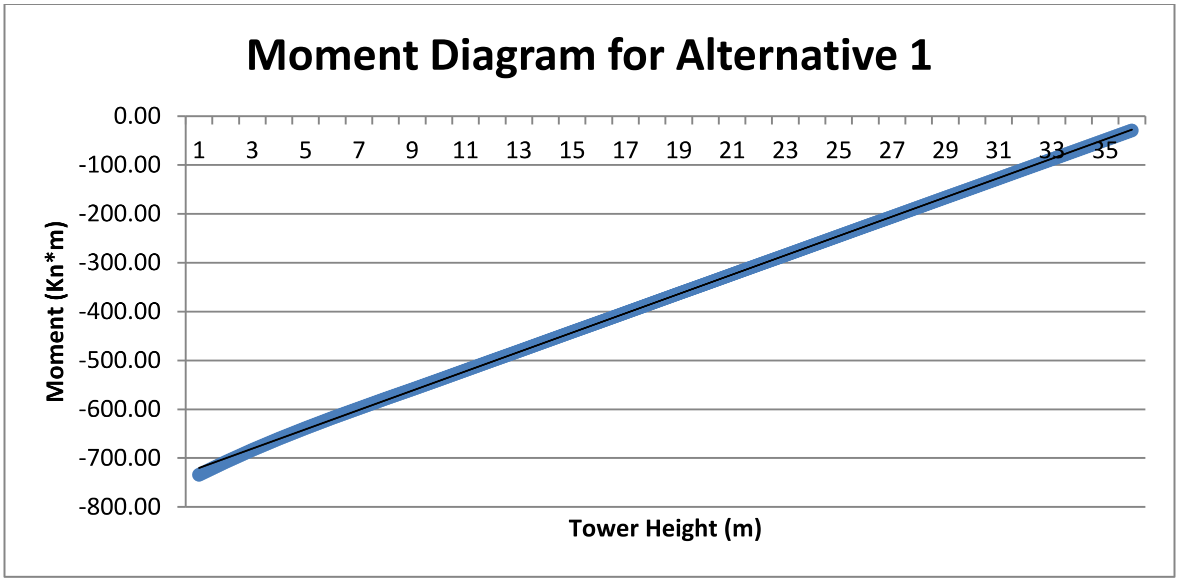


Figure 64: Moment Diagram (Alternative 1).

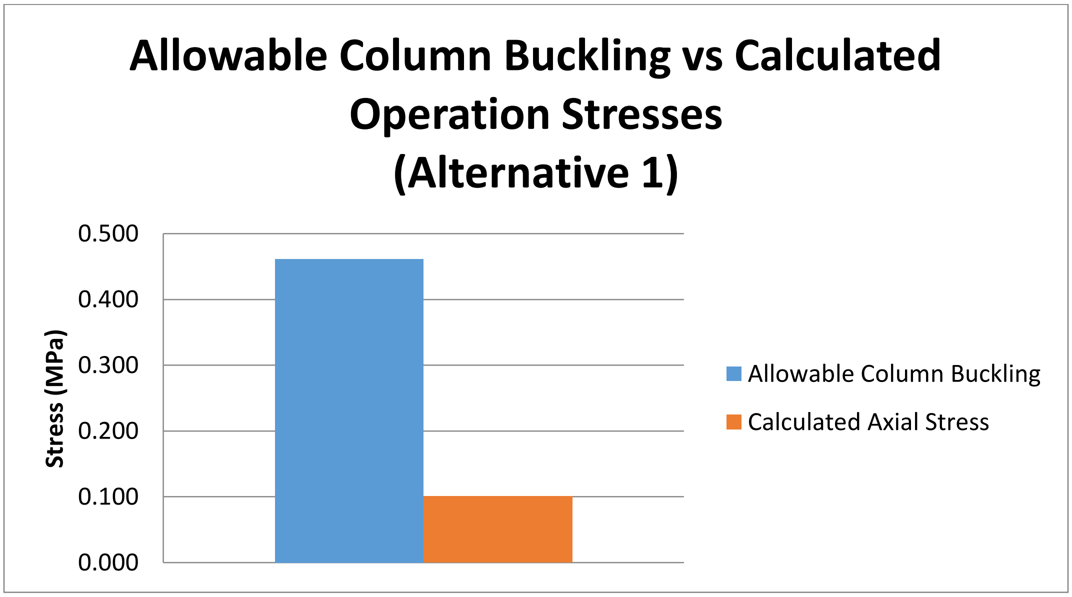


Figure 65: Allowable Column Buckling Stresses vs. Operational Stresses (Alternative 1).

Alternative Tower Design 3

Table 25: Loading Conditions for Alternative 3

Alternative Tower Design 3					
Lateral Wind Loading				**Dynamic Loading**	
Section	F (N)	**Section**	F (N)	**Thrust Force**	128,295 N
1	1476.49	**19**	1560.42	**Magnification Factor**	1.1
2	1462.43	**20**	1556.67	**Equivalent Static Load**	141,124 N
3	1448.37	**21**	1552.01	**Dead Loading**	
4	1434.31	**22**	1546.51		
5	1420.25	**23**	1540.23	**Tower Section Weight**	≅ 425 kg/m
6	1452.44	**24**	1533.23	**Nacelle Weight**	9,072 kg
7	1480.30	**25**	1525.55	**Rotor Weight**	5757 kg
8	1502.28	**26**	1517.24	**Total Turbine Weight**	≅ 29,700 kg
9	1519.67	**27**	1508.33		
10	1533.38	**28**	1498.86		
11	1544.06	**29**	1488.87		
12	1552.17	**30**	1478.37		
13	1558.09	**31**	1467.41		
14	1562.10	**32**	1455.99		
15	1564.45	**33**	1444.14		
16	1565.31	**34**	1431.89		
17	1564.84	**35**	1419.25		
18	1563.17				

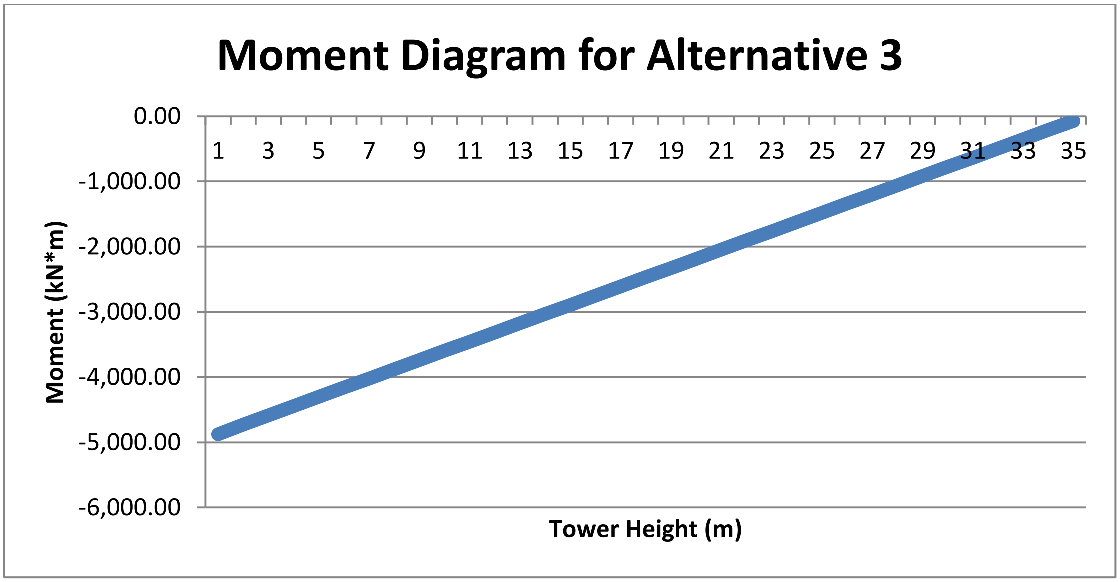


Figure 66: Moment Diagram (Alternative 3).

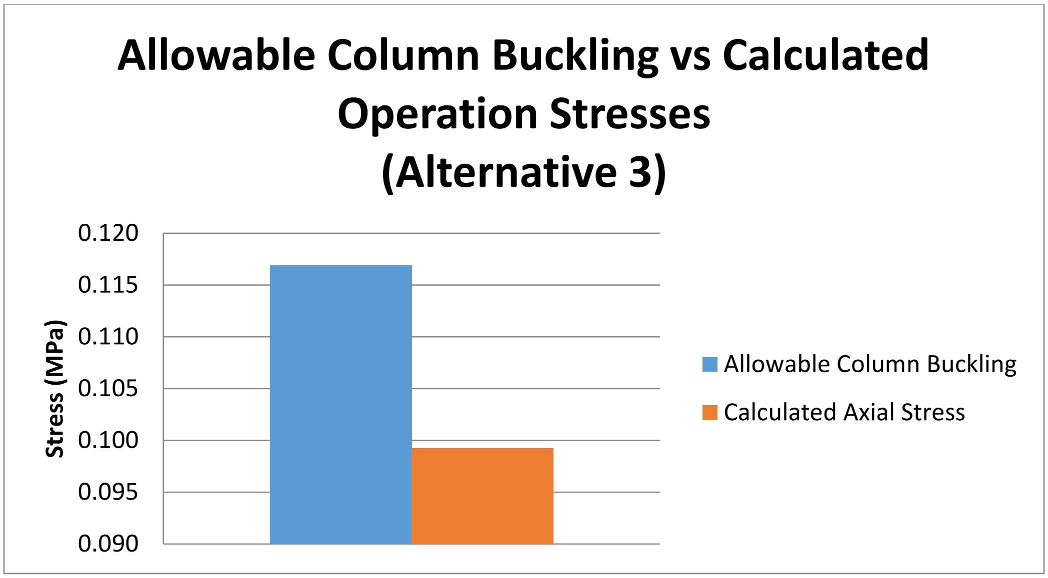


Figure 67: Allowable Column Buckling Stresses vs. Operational Stresses (Alternative 3).

Appendix K: *Excel* Spreadsheet

The Design *Excel* Tool and the User-Friendly *Excel* are attached to the electronic submission for this project.