Big Turbine

Design & Analysis of a Wind Turbine with FEA ANSYS software

P. Sklavounos, R. Lam, P. Xu and S.H Yang

Cooper Union for The Advancement of Science and Art

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ABSTRACT

. Context: A wind turbine for Enercon has been designed for the client's specifications and requirements. The design is to be optimized to reduce the cross-sectional area and weight by using ANSYS FEA. Due to the location of the wind turbine, it is to withstand the extreme weather conditions of the high wind speeds and temperature fluctuations. For safe operation, the tower is to not match the natural frequency operating range if a blade detaches.
. Method: To achieve this, various primary analysis techniques were explored using ANSYS workbench and ANSYS APDL, namely the deflection, stresses, factor of safety, modes of natural frequency, and buckling.The material used for all parts were 316 Stainless Steel.
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1. Introduction

This group will propose a design of a wind turbine for Enercon that will be optimized to minimum cost, cross-sectional area, and weight. The natural elements that it will be able to endure are those of temperature and wind speeds that range from normal to extreme. The three cases explored will be:

- The normal condition (Temperature: 60F, Wind speed: 70mph)
- The cold extreme condition (Temperature: -10F, Wind speed: 125 mph)
- The hot extreme condition (Temperature: 135F, Wind speed: 125mph).

The necessary assumptions were made when analyzing these cases:

- The tower is analyzed as a cantilever beam.
- The material is linear, elastic, and isotropic.
- The ground is rigid, and the baseplate of the tower is fully fixed.
- Gravity is equal to 32.174 $\frac{ft}{s^2}$
- The air density and wind speed are constant over the height of the tower.
- The ground is rigid, and the base of the tower is bolted to the ground.
- The load due to the power generation was ignored, as its value is negligible compared to other loads.
- The initial temperature of the site is 60 °F
- The tower is installed at the sea level.

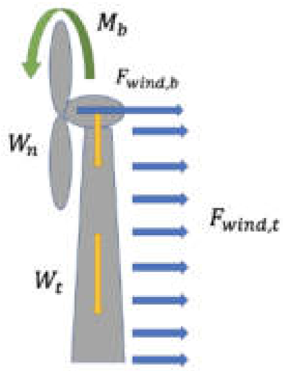


Fig. 1: Load conditions on the Wind Turbine

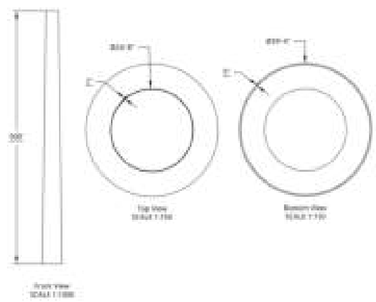


Fig. 2: Scaled drawings of the tower portion of the wind-turbine

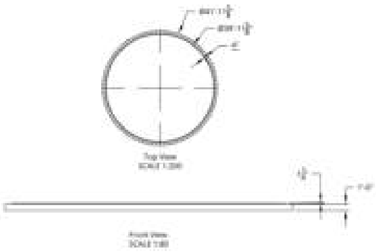


Fig. 3: Scaled drawings of the baseplate of the wind-turbine

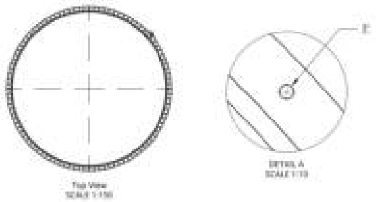


Fig. 4: More detailed drawing of the baseplate of the wind-turbine

1.1. *Finalized Design Parameters*

1.1.1. Tower Design

Variable	Value
Height	500 ft
Top outer diameter	24 ft 8 in
Bottom outer diameter	39 ft 4 in
Top wall thickness	2 in
Weight	
Footprint	1383.465 ft^2
Bottom wall thickness	5 in
Top cross-sectional area	12.828 ft^2
Bottom cross-sectional area	50.942 ft^2

1.1.2. Baseplate

Variable	Value
Outer diameter of turbine	40 ft
Wall thickness	4 in
Flange width	1 ft
Flange thickness	1 ft
Number of bolts	100
Bolt diameter	3 in
Washer diameter	8 in

2. FEA simulations

<u>Iteration method</u>

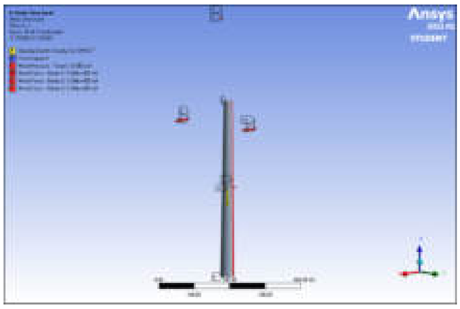
Variable	Description
R_{top}	$[120 \rightarrow 150]$ in
R_{bottom}	$[210 \rightarrow 240]$ in
t_{top}	$[1 \rightarrow 2.5]$ in
t_{bottom}	$[2 \rightarrow 6]$ in
T_{env}	$[-10, 60, 135]$°F
P_{wind}	$[10.648, 33.955]$ psf
$F_{wind \rightarrow blade}$	$[4.102 \cdot 10^4, 1.308 \cdot 10^5]$ lbf

R_{top}, R_{bottom}, t_{top}, and t_{bottom} represents the top radius, bottom radius, top thickness, and bottom thickness of the tower, respectively. T_{env} represents the respective lower extreme, normal, and upper extreme environmental temperatures. P_{wind} and $F_{windßblade}$ represent the wind pressure on the tower and wind force exerted on the center of mass of the blades, respectively, for both extreme wind and normal wind conditions.

To optimize parameter selection, the above variables were parametrized in ANSYS Workbench and set to automatically run over 100 iterations of simulations that independently vary the tower geometry parameters within their determined ranges.

The raw output was then exported to a CSV, where Excel filters were then applied to filter out any iterations that failed the design requirements (expressed as constraint conditions on output values below). Out of the remaining iterations, the optimal one was selected by applying an additional filter for minimal tower mass, which corresponds to the least amount of material usage.

<u>Load case</u>



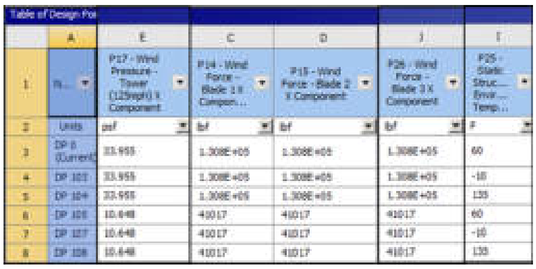


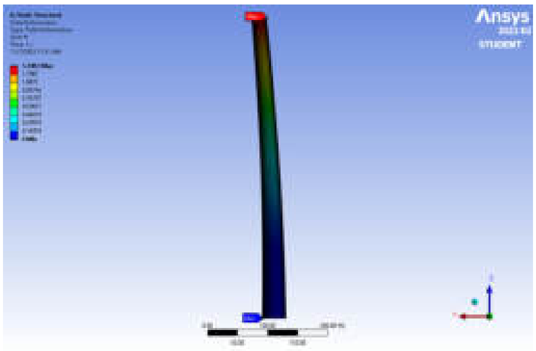
Table of Design Poi

	A	E	C	D	J	I
1	N...	P17 - Wind Pressure - Tower (125mph) X Component	P14 - Wind Force - Blade 1 X Compon...	P15 - Wind Force - Blade 2 X Component	P26 - Wind Force - Blade 3 X Component	P25 - Static Struc... Envir... Temp...
2	Units	psf	lbf	lbf	lbf	F
3	DP 0 (Current)	33.955	1.308E+05	1.308E+05	1.308E+05	60
4	DP 103	33.955	1.308E+05	1.308E+05	1.308E+05	-10
5	DP 104	33.955	1.308E+05	1.308E+05	1.308E+05	135
6	DP 105	10.648	41017	41017	41017	60
7	DP 107	10.648	41017	41017	41017	-10
8	DP 108	10.648	41017	41017	41017	135

The load case along with the table of all cases considered for a particular design iteration is shown above. The weight of the blades and nacelle is simulated by adding point mass values at the center of mass of each blade as well as the nacelle followed by applying a universal gravitational acceleration for the entire model. The wind effect on the tower is simulated as a wind pressure exerted over half of the exterior tower face while the wind effect on the blades is simulated as a remote force exerted on the center of mass of each of the blades. This configuration also allows for easy analysis of the case when 1 blade falls off as the mass of the one blade and the wind force on it can simply be suppressed in ANSYS.

2.1. Analysis of Tower

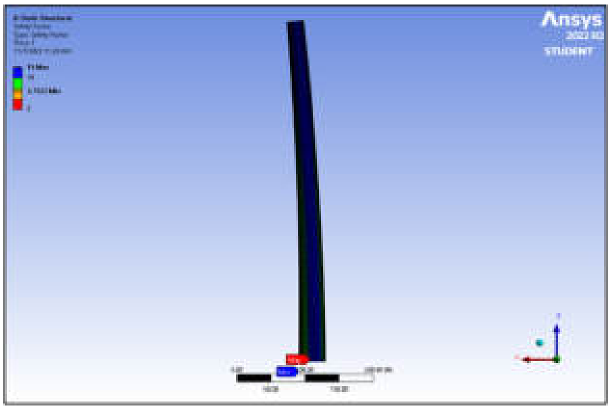
2.1.1. Deflection of tower under weather event loading conditions



As a part of the design requirements, the deflection of the tower should not exceed 1 ft under the normal weather condition and 1.351 ft under the extreme weather condition. The maximum deflection of the tower under the normal weather condition and the extreme weather condition was 0.422 ft and 1.330 ft, respectively, which meets the design requirement. The figure above shows the deflection of the worst case scenario.

Maximum Deflection [ft]	Normal Weather (Wind speed = 70 mph)	Extreme Weather (Wind speed = 125 mph)
Low Extreme Temperature (-10°F)	0.417	1.314
Normal Temperature (60°F)	0.419	1.320
High Extreme Temperature (135°F)	0.422	1.330

2.1.2. Minimum Stress Factor of Safety



In order to calculate the minimum factor of safety against stresses, maximum stress at different temperature and wind speed was calculated. As a result, the minimum factor of safety against stress under the normal weather condition and the extreme weather condition was found to be 8.903 and 3.752, respectively, which satisfies the design requirement.

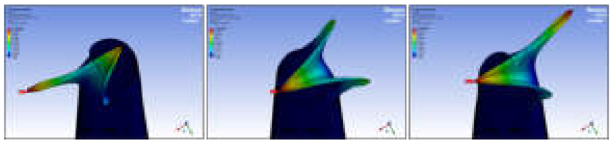
Minimum Stress F.O.S	Normal Weather (Wind speed = 70 mph)	Extreme Weather (Wind speed = 125 mph)
Low Extreme Temperature (-10°F)	8.903	3.752
Normal Temperature (60°F)	8.903	3.752
High Extreme Temperature (135°F)	8.903	3.752

2.1.3. Factor of Safety against Buckling Failure

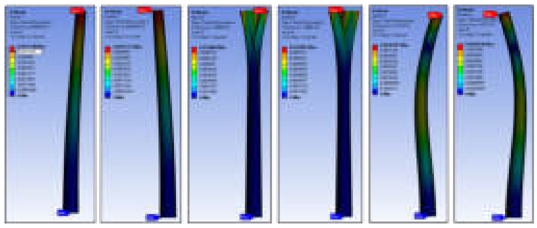
The factor of safety against buckling of the tower is 118.180 in a normal weather condition and 42.184 in an extreme weather condition, which satisfies the buckling F.O.S design specification. This factor of safety against buckling indicates that the tower is able to withstand the load up to 118.180 times greater than the critical load under the normal weather condition and 42.184 times greater than the critical load under the extreme weather condition.

Buckling F.O.S	Normal Weather (Wind speed = 70 mph)	Extreme Weather (Wind speed = 125 mph)
Low Extreme Temperature (-10°F)	119.580	42.685
Normal Temperature (60°F)	119.050	42.495
High Extreme Temperature (135°F)	118.180	42.184

The figure below graphically shows the first three modes of the eigenvalue buckling analysis of the worst case.



2.1.4. Natural frequency of design

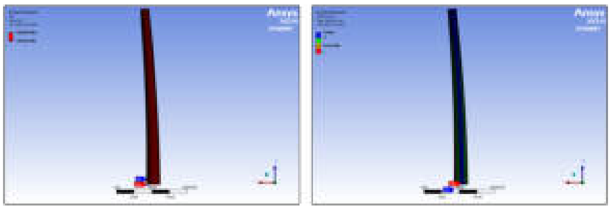


Modal analysis of the first 6 modes was conducted on the tower using pre-stress conditions taken from the static structural solution. As the above images show, inherent symmetries in the geometry results in corresponding pairs of frequencies and mode shapes being generated, thus while 6 modes were simulated, we only need to report modes 1, 3, and 5. Each natural frequency calculated across the 6 environmental cases considered for a single design iteration is then cross checked to ensure that they do not fall into the frequency range of the spinning blades.

Natural Frequency (Three Blades)	Normal Weather (Wind speed = 70 mph)	Extreme Weather (Wind speed = 125 mph)
Low Extreme Temperature (-10°F)	1st: 0.608 3rd: 1.995 5th: 2.403	1st: 0.608 3rd: 1.993 5th: 2.403
Normal Temperature (60°F)	1st: 0.607 3rd: 1.990 5th: 2.397	1st: 0.607 3rd: 1.988 5th: 2.397
High Extreme Temperature (135°F)	1st: 0.604 3rd: 1.983 5th: 2.390	1st: 0.604 3rd: 1.981 5th: 2.388

Natural Frequency (Two Blades)	Normal Weather (Wind speed = 70 mph)	Extreme Weather (Wind speed = 125 mph)
Low Extreme Temperature (-10°F)	1st: 0.611 3rd: 1.994 5th: 2.433	1st: 0.613 3rd: 1.992 5th: 2.433
Normal Temperature (60°F)	1st: 0.610 3rd: 1.989 5th: 2.427	1st: 0.610 3rd: 1.987 5th: 2.427
High Extreme Temperature (135°F)	1st: 0.606 3rd: 1.985 5th: 2.391	1st: 0.606 3rd: 1.983 5th: 2.390

2.1.5. Fatigue Analysis



Fatigue analysis of the tower was conducted using an experimental S-N curve obtained from existing literature. As the results below indicate, all 6 environmental cases considered for a single design iteration reach a minimum fatigue life cycle corresponding to the maximum value reported by the experimental S-N curve. Making a conservative estimate that the wind conditions may change approximately 600 times a day (25 times an hour), the minimum fatigue life of 7,893,800 cycles corresponds with a life of approximately 36 years, exceeding the average wind turbine life of 20 years.

Minimum Fatigue Life [cycles]	Normal Weather (Wind speed - 70 mph)	Extreme Weather (Wind speed - 125 mph)
Low Extreme Temperature (-10°F)	7,893,800	7,893,800
Normal Temperature (60°F)	7,893,800	7,893,800
High Extreme Temperature (135°F)	7,893,800	7,893,800

2.2. Analysis of Base Plate

To model the stress on the flange caused by stresses in the tower, the forces and stress on the tower simulation is resolved into a single moment and shear force that would cause the same deflection at the top of the tower. This was calculated using simple beam theory, assuming the tower is a hollow cylinder of 500ft with an outer diameter of 40ft and a wall thickness of 4in.
Additionally, the weight of the tower is calculated and resolved to a single force across the 4 inch thickness of the tower, at the base of the tower (shown in the figure below). The acceleration due to gravity is also added to the model.

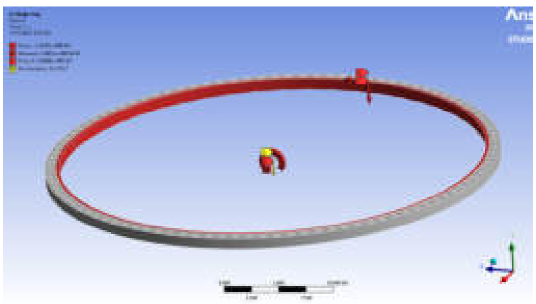
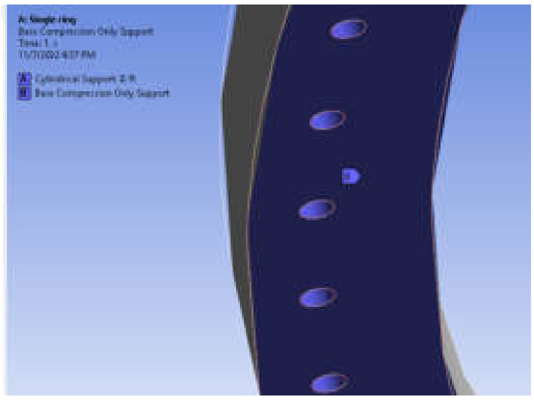


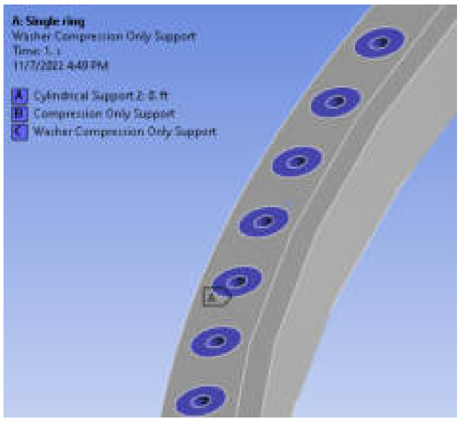
Fig. 5: Base plate force setup

To size the bolts, cylindrical supports were places on all of the bolt holes, constraining the axial and tangential movement, but not radial motion as bolts can still rotate. A compression-only support was places on the base of the flange to simulate the concrete base pad. The reaction solution at all of the cylindrical supports were used to dimension the bolts.



To analyze the flange itself, the constraints were changed to model washers across the top surface of the flange at all the bolt holes, while the bolt holes themselves were free to move axially.

This means the cylindrical supports at the holes are all free to move axially and radially, while not tangentially. Compression only supports were placed on the base of the flange. Compression only support were also placed on every washer at the bolt holes.



2.2.1. Maximum connection stresses

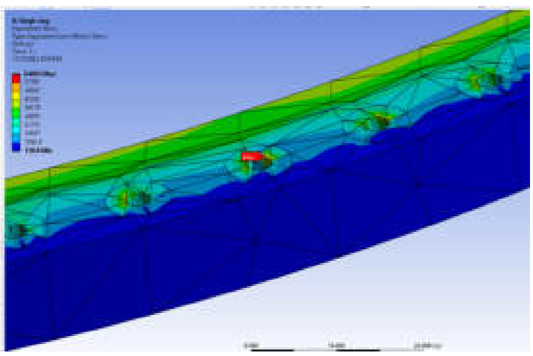


Fig. 6: Tension side inage of the washer face

Stress at the washer face exceeds the yield stress of stainless steel, but this is only at a single node. Increasing the washer size may distribute the stress more evenly across the bolt hole, which would reduce the peak stress experienced.

2.3. *Tower height change from thermal effects*

Thermal Expansion [in]	60 °F to -10 °F	60 °F to 135 °F
	-0.0708 in	0.1164 in

Fig. 7: Base plate force setup

3. Hand calculations for verification of design

Legend

n_{blades}	Number of blades
r_{bt}	Offset distance of blades from tower
W_{blade}	Weight of a single blade
$W_{nacelle}$	Weight of a nacelle
$A_{tower,top}$	Average surface area of the tower in z-direction
$A_{tower,front}$	Front surface area of the tower
$A_{bladesh}$	Front surface area of the blades and hub
d_{top}	Top outer diameter of the tower
d_{mid}	Middle diameter of the tower
d_{bot}	Bottom outer diameter of the tower
t	Thickness of the tower
I	Moment of inertia of the tower in z-direction
L	Height of tower
v	Wind speed

Load expressions

Using the density of 316 stainless steel and the volume of the tower, the weight of the tower can be calculating with a following formula:

$$W_{tower} = \rho A_{tower,top} L$$

The average top surface area of the tower was calculated by averaging the surface area of the top and bottom of the tower. The moment from the blades due to being offset from the tower was calculated by multiplying the total weight of the blades to the offset distance from the tower:

$$M_{blades} = n_{blades} r_{bt} W_{blades}$$

The load due to wind act on two main areas, the tower and the blades. The wind force can be calculated by multiplying wind pressure by the contact area. The formula for wind pressure and wind force on the blades and tower are following:

$P_{wind} = \frac{1}{2} c_d \rho_{air} v^2$, Wind pressure, where v = wind speed (air depends on temperature)

$$F_{wind,blades} = P_{wind} A_{blades}$$

$$F_{wind} = P_{wind} A_{tower} \; W_{wind} = P_{wind} d_{mid}$$

3.1. *Maximum stress during normal operating weather conditions*

The stress of the tower can be calculated by summing the bending stress and the axial stress of the tower. The bending stress of the tower is caused by wind on the tower, wind on the blades, and the moment caused by the blades being offset from the tower. The axial stress is caused by the weight of the tower and the nacelle. Since the largest axial stress is found at the bottom of the tower, the cross-sectional area of the bottom of the tower was applied for axial stress calculation. Each stress factor was calculated using the following formulas:

$$\sigma_B = \frac{d_{middle}}{2I}\left(P_{wind} A_{blades} L + \frac{L}{2} P_{wind} A_{tower} - M_{blades}\right)$$

$$\sigma_{axial} = \frac{W_{nacelle} + W_{tower}}{\pi(\frac{d_{bottom}}{2} - t)^2}$$

By adding the two stresses together, the total maximum stresses can be calculated:

$$\sigma_{total} = \sigma_B + \sigma_{nacelle} + \sigma_{tower}$$

FOS stress calculated using: FOS stress $= \frac{\sigma_Y}{\sigma_{total}}$

3.1.1. Base plate analysis

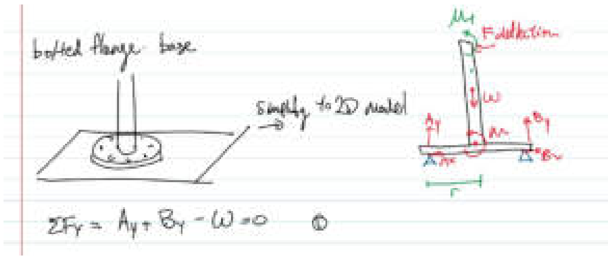


Fig. 8: FBD of flange base with bolts, sectional view

Initial calculations:

$$\Sigma F_y = A_y + B_y - \omega = 0 \; (1)$$

Assume body forces at box caused by deflection to be:

$$y = \frac{PL^3}{\delta EI} \rightarrow P = \frac{3EIy}{L^3}$$

$$M = p \cdot h = 500[ft] \cdot P + \omega_t \cdot 25[ft]$$

$$\Sigma M = 0, -Ay \cdot r_f - M + B_y r_f = 0(2)$$

$$B_y = \frac{M}{r_f} + A_y, A_y + (\frac{M}{r_f} + A_y) - (\omega + \omega_t)$$

$$\therefore A_y = \frac{(\omega+\omega_t) - \frac{M}{r_f}}{2} = \boxed{\frac{(\omega + \omega_t) r_f - M}{2r_f}}$$

$$\& B_y = \frac{M}{r_f} + \frac{(\omega+\omega_t) r_f - M}{2r_F} = \boxed{\frac{(\omega + \omega_t) r_f + M}{r_f}}$$

$$\Sigma F_x = 0 = P + A_x + B_x = 0$$

$$\text{Assume } A_x = B_x = \boxed{\frac{P}{2}}$$

$$\text{Max bending stress: } \boxed{\frac{Mc}{I}}, where c = \frac{h}{2}$$

Bolt stress is max at B since $B_y > A_y, giving$:

$$\sigma_{bolt} = \boxed{\frac{\frac{\omega_r + M}{r_f}}{\pi(\frac{d_{bolt}}{2})^2}}$$

Revision of hand calculations using beam theory:

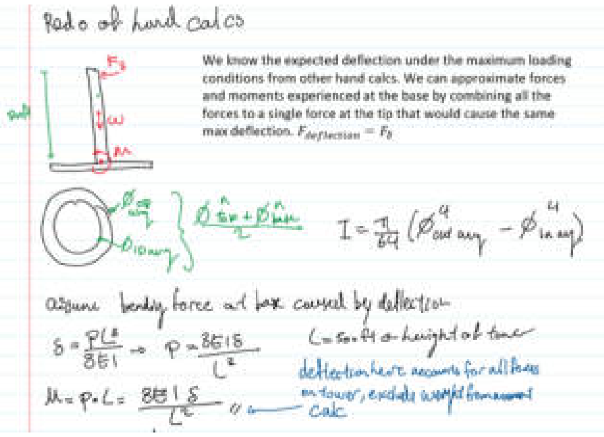
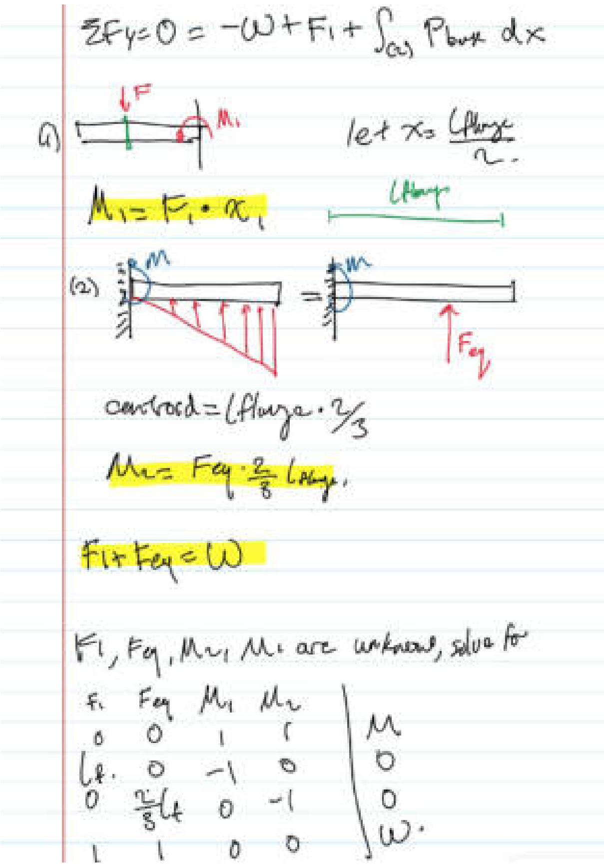


Fig. 9: FBD of flange base with bolts, with deflection being taken into consideration




```
baseOD =  40 *ft;
baseWallThick = 4 *in;
baseID = baseOD - 2*baseWallThick;

topOD=  25 *ft;
topWallThick = 4*in;
topID = topOD - 2*baseWallThick;

avgOD = (baseOD+topOD)/2;
avgID = (baseID+topID)/2;

I =  pi/64*(avgOD^4-avgID^4);

height = 500*ft;
deflection = 1.35*ft;

%condition 1, 3 blades, high temp, max wind pressure
F =  3*Est*I*deflection/height^3; %lbf
Mtot = F*height; %lbf*in
```

3.2. Maximum deflection during normal operating weather conditions

The deflection of the tower is caused by three factors: (1) wind on the tower, (2) wind on the blades, and (3) moment caused by the blades being offset from the tower. Assuming that the tower is considered as a cantilever beam, the deflection formula by each contributing factor is following:

$$\delta_{total} = \delta_{wind,t} + \delta_{wind,b} - \delta_{moment,b}$$

$$\delta_{wind,t} = \frac{M_{blades}L^2}{2EI}$$

$$\delta_{wind,b} = \frac{F_{wind,bladesL^3}}{3EI}$$

$$\delta_{moment,b} = \frac{w_{wind}L^4}{8EI}$$

$$\therefore \delta_{total} = \boxed{\frac{12M_{blades}L^2 + 8L^3F_{wind,blades} - 3L^3w_{wind}}{24EI}}$$

3.3. Expected tower height change from thermal effects

Assuming that the deflection of the tower due to thermal effects is considered as a linear expansion of a solid body, the deflection due to thermal effects can be calculated by the following formula:

$$\Delta L = \alpha L(T - T_0)$$

Where α is the thermal expansion coefficiuent, Ti is the temperature fo the site, and T_0 is the intial temperature of the site. The initial temperature of teh set is set to be 60 °F

3.4. Blade failure scenario, natural frequency

In order to calculate the natural frequency of the tower, the tower was considered as a beam with one fixed end and mass at one free end.

Natural frequency: $f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$, where m is the **effective mass** of the wind turbine and k is the **stiffness** of the wind turbine system. The stiffness k can be simplified to that of a cantilever beam:

$k = \frac{3EI}{L^3}$ and $\omega = k^2\sqrt{\frac{EI}{\rho A}}$, where A is the cross sectional area.

Due to its tapering nature, rather than write it as a function of length, it shall be averaged and taken as if it were uniform.

Without the constant value of the system K, The natural frequency that leads to blade failure can be re-written using a following formula:

$$\omega_n = \frac{1}{2\pi}\sqrt{\frac{3EI}{m_{eq}L^3}}$$

where $m_{eq} = m_{blade} \cdot n_{blades} + m_{nacelle} + 0.23 m_{tower}$

Modes of natural frequency, where $K = \frac{k}{L}$:

Mode #	kL (ft)	K	$\omega (Hz)$
1	1.875	1.875/500	0.14
2	4.694	4.694/500	0.89
3	7.855	7.855/500	2.51
4	10.9996	10.9996/500	4.91
5	14.157	14.157/500	8.12

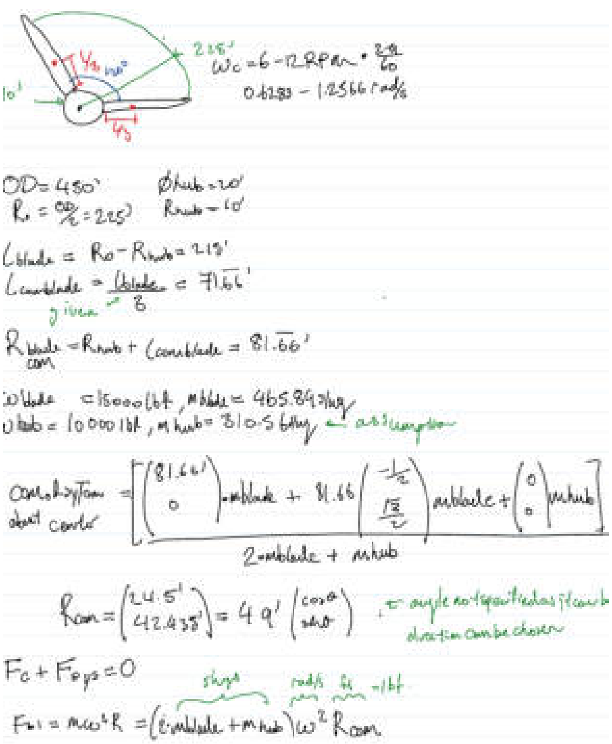
3.5. Maximum loading, Three blade analysis

The hub weight was chosen arbitrarily to be 1000lbm of the nacelle weight.

3.5.1. Hot weather conditions

3.5.2. Cold weather conditions

3.6. Maximum loading, Two blade analysis



$$\therefore F_c = -9.612 \cdot 10^4 \text{lbf}$$
$$M_c = 2.403 \cdot 10^6 lbf \cdot ft$$

3.7. Buckling check of tower

The maximum critical buckling load can be calculated using Euler's column formula. Assuming that a beam is pinned on one end and free on the other, the maximum critical buckling load formula is found to be:

$P_{cr} = \frac{\pi^2 EI}{L_e^2}$, where effective length $L_e = 2L$ since fixed and free end.

Factor of Safety for buckling was calculated using the following formula:

$$\text{FOS of buckling} = \frac{P_{cr}}{W_{total}},$$

where $W_{tot} = n_{blades} W_{blade} + W_{nacelle} + Wtower$

4. Hand calculations, numerical solutions

	Normal Weather (Wind speed = 70 mph)	Extreme Weather (Wind speed = 125 mph)
Maximum deflection	0.2234 ft	0.755 ft
Maximum deflection due to thermal effects	60 °F to -10 °F: -0.331 ft 60 °F to 135 °F: 0.354 ft	
Maximum stress	$2.149 \cdot 10^3$ psf	$6.631 \cdot 10^3$ psf
Stress F.O.S	20.115	6.520
Natural frequency (1st mode)	0.435 Hz	0.435 Hz
Maximum critical buckling load	$3.289 \cdot 10^8$ psf	
Buckling F.O.S	23.205	
Weight of the tower	6318 tons	

5. Design Time

The total design time was estimated to be 160 hours, including hand calculations, preliminary design, CAD modeling, and ANSYS Workbench analysis.

6. Sources

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