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DESIGN AND ANALYSIS OF 2-MW WIND TURBINE TOWER

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Abstract— The wind turbines are used to convert the wind energy into electrical power. Wind turbines are mounted at the top of the vertical structure called Wind Tower. Increasing demand of high power generation in is compelling the towers to be made taller, so as to catch strong winds at higher altitudes. It focuses on designing a tower for Uttara Kannada, the Western Ghats of Karnataka State, which is one of the potential source of wind energy. It begins with understanding of the physics involved, in their function. Analyses of the stress and strain behaviour of the welded fixture have been done at bolted ring flange connections under different loading conditions. The maximum stress and fatigue life were estimated, using the Finite Element Analysis (FEA). Processing is done using ANSYS WorkbenchV14.5. Also various checks have been performed to validate the results. Optimization of thickness of wind tower shell and number of bolts for the specific joints were done with the objective of minimising structural weight and cost as well. The optimum number of bolts found suitable for middle flange and for top flange joints were 100 and 80.

Keywords— Wind Tower, Design, FEA, Fatigue Life.

I. INTRODUCTION

The wind turbines are used to convert the wind energy into electrical power. Amount of electrical power generation depends on the rotational velocity of the turbine blades. Vertical structures, on which the turbines mounted, are called wind tower[1] In order to meet high power generation demand, the towers will have to become taller in order to catch stronger winds at higher altitudes. The towers will have to accommodate larger capacity turbines and rotor blades

The general idea behind this design is that, the tower has to be relatively easy to assemble at the mounting site and that a round tower without any visible joints is more pleasing to the eye. But in recent years the development of mass-produced wind turbines have moved towards making them bigger and bigger, both in output and in size[2]. This process calls for better and more cost-efficient components and manufacturing methods, and particularly in the field of wind turbine towers. Manufacturing facilities for large modern wind turbine towers with free height of 8m require large building, access to lifting equipment and highly specialised and expensive rolling equipment[3]. Furthermore, welding reduces the towers fatigue limit and strength, which in turn leads to usage of more thicker plate. The main goal of the study is to design of a wind turbine tower of 2 MW for Uttara Kannada, the Western Ghats of Karnataka State, which is one of the potential source of wind energy. Then analyse the design using FEA software.

The wind towers are tubular structures, made up of steel tubes. The tubes are built by rolling the steel plates and welding them together. Then these tubes are welded with the flanges on the extremities to form the tubular segments. These segments are built in a factory and then delivered to construction site, where they are assembled by bolting flanges together to form a tower. However the road transportation regulations lay a limit on maximum size of the diameter of the tower body as 4.5m.In case of larger diameter towers the tube segments will have to rebuilt at the site of construction. Cross section varying in continuous way from a larger diameter rat tower bottom to a smaller diameter at tower top tends to ease out assembling of the steel tube segments and lowers the centre of gravity of the tower and improves the static stability.

Amount of energy available to a wind turbine increases with the cube of winds peed. The present trend of 0.5 to1.5MW turbines, require 40m long bladesand60-70mtall structure. New generation wind farms may require turbines in the range of 5MWandabove with blade lengths in the range of 60 m and tower heights beyond 100 m[2].

II. DESIGN

Wind speed is seasonal dependent, which is normally at its maximum during monsoon season. Wind speed varies from 3.96m/s (Nov) to 11.34m/s (July)as per Meteorological data of Uttara Kannada, at an altitude of 40m[5]. However to increase the factor of safety the range of wind load is increased to (0, 20m/s) for design considerations.

2.1 Calculation of Loads

Figure 1 shows elements of the Windmill. It consists of rotor, blades, nacelle and tower. Nacelle consists of rotor and drive. The mass of individual units of the 1.5 MW mill are as follows - mass of each blades, $(m_b/3)$is 5.78 Tonnes, mass of the rotor, m_r is 32.34 Tonnes and mass of the nacelle m_n is 52.50 Tonnes, which has an height of 76.70m [7]. By increasing the height to 80 m, it is possible to generate 2MW power.

Total dead load on top of the tower can be obtained as, $W_1=(m_b+m_r+m_n)$ g, where, m_b is [7]. Hence, $W_1=(17.34+32.34+52.50)9.81=1002.39$ kN

Dead load on foundation can be obtained by adding the self-weight of the tower to W_1[5].

The tower wills way due to the thrust force of the wind. The maximum wind speed is 11.34m/s as per meteorological data of Uttara Kannada, the Western Ghats of Karnataka State. Maximum wind speed is approximated to 20m/s for increasing the safety [7].Then the thrust force on the turbine can be obtained as,

$$F_t = 0.5\ \rho\ V^2 C_T \pi R^2$$

where, ρ is density of air (=1.169 kg/m^3); V is maximum wind speed (=20 m/s);$C_T$is Co-efficient of Thrust (=0.64); and Ris Rotor radius (= 41 m)[7]. Therefore, $F_t = 0.5 \times 1.169 \times 20^2 \times 0.64 \times \pi \times 41^2 = 790.21$ kN.

Bending moment at top flange section is given by, $M_{y,t}=F_t \times L_1$, where ,L_1 is Length of top segment (= 27760 m). Therefore, $M_{y,t}=790.21 \times 10^3 \times 27760$ or21842.4kN-m.

Similarly, Bending Moments at Middle and Bottom flanges can be obtained as, $M_{y,m}$=42971.62kN-m and $M_{y,b}$=60174.5 kN-m, respectively.

Nacelle will rotate on the tower, due to change in the direction of the wind. Due to this nacelle rotation torsional moment will occur on the tower. The torsional moment can be calculated by, $M_t=F_t \times r_o$, where, $r_o$is Outer radius of the tower shell (=1.814 mm). Therefore, M_t=1433.25kN-m

2.2. Shell Material and Number of Bolts

S355 High-grade steel is most commonly used material in wind turbine towers. It is a plate with a high-strength low-alloy European standard structural steel covering four of the six "Parts" within the EN 10025-2004standard. With minimum yield strength of 355 MPa, it meets requirements of both chemical and physical properties similar to ASTM A572 / 709.

Flanges are connected by means of bolts, where number of bolts depends on the diameter of the shell. Calculation ofthe number of bolts of the tower is given by formula[13],

No. of bolts = 0.028 * Max Diameter of shell

III. MODELLING ANDANALYSIS

A three dimensional(3D) model of tapered cylindrical tubular tower with increasing diameter and thickness towards the base was created using Catia V5 as shown in Figure. 1.

Results of stress analysis depend mainly on the quality of mesh. In order to achieve high accuracy the meshing of the element should be as fine as possible. Tetrahedron elements were used to mesh the tower structure and statistics shows that 418677 elements and 791170 nodes were there in the meshed model shown in Figure. 2.

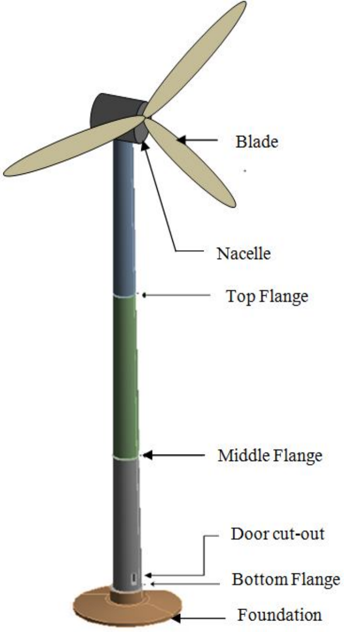

Fig.1: CAD Model of Wind Turbine Tower

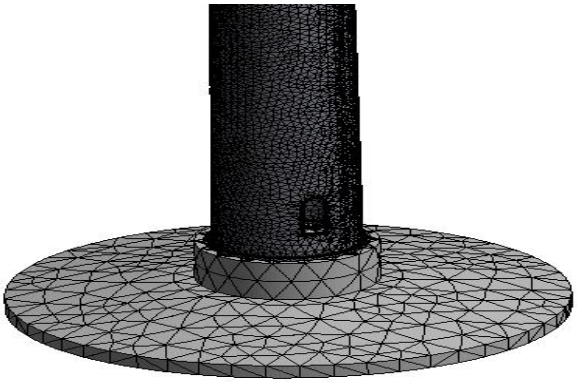

Fig.2. Meshed Tower Model

Stress concentration in the wind tower flange was analysed for different loading conditions by varying the number of bolts, i.e., flange was fixed at the base (A) and compressive force (B) bending moment (C) torque (D) were applied at the topas shown in Figure. 3, similar actual field situations.

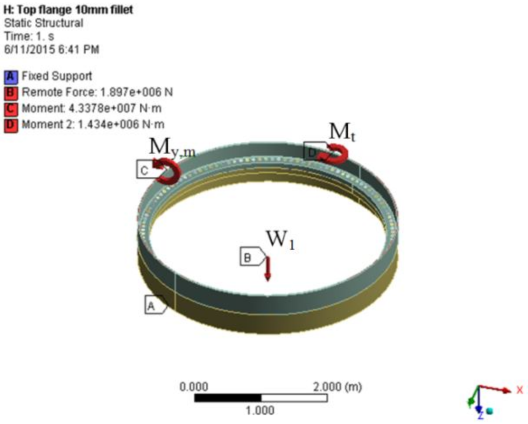

Fig.3. Boundary Conditions for Middle Flange

3.1 Estimation of Fatigue Life

The local wind speed varies over a season from minimum (3.96 m/s) to maximum (11.34m/s). In order to have better factor of safety, wind speed range is increased (0, 20) m/s.It is assumed that tower is under repeated loading, where in F_t varies from at 0 to 790.21 kN.

ASTM defines fatigue life, N_f, as the number of stress cycles of a specified character that a specimen sustains before failure of a specified nature occurs[14]. One method to predict fatigue life of materials is the Uniform Material Law (UML).

The resulting, maximum stress, σ_{max}, is the largest algebraic value of stress in the stress cycle and the minimum stress, σ_{min}, is the leastas shown in Fig. 4. Tensile stresses are taken to be positive and compressive stresses are taken tobe negative.

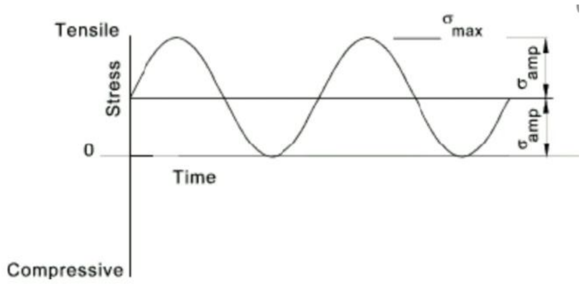

Fig.4. Repeated Load on Wind Tower

The mean stress is the algebraic average ofσ_{max} andσ_{min}. and is given by,$\sigma_{mean}= \frac{\sigma_{max}+\sigma_{min}}{2}$. The amplitude of the stress cycleequals half of the range and is given by, $\sigma_{amp}= \frac{\sigma_{max}-\sigma_{min}}{2}$. The R ratio is the ratio ofσ_{min} toσ_{max}, namely,R=$\frac{\sigma_{max}}{\sigma_{min}}$.

The Constant Life Diagram (CLD) is a representation of S-N data. The constant-life lines in the CLD connect points with the same estimated lifetime, as a function of the mean stress and stress amplitude.

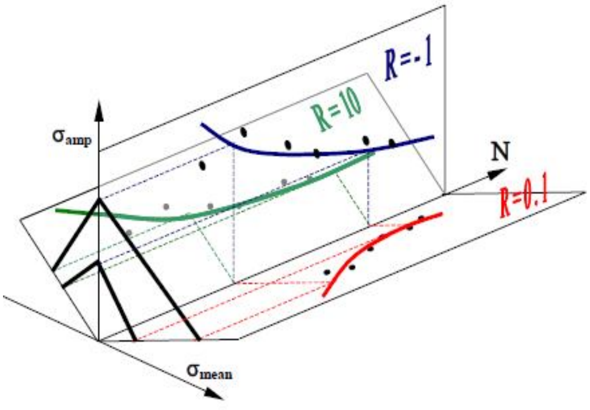

Fig.5. Relation between S-N Curves and CLD

Figure 5illustrates a three-dimensional representation of a group of S-N curves and lines connecting identical lifetimes.CLD can be seen as projection of the constant amplitude fatigue data on a plane perpendicular to the life axis, at N=1 mark. Each S-N curve is determined at a fixed R-value, and is therefore in a flat plane, at an angle to the horizontal plane. Different straight lines from the origin are lines of constant R-value, since mean stress and stress amplitude are directly proportional to each other. The ordinate is located with the R=-1 line (zero-mean stress line). The highest alternating stress value for N=1 (the 'top' of the CLD) is assumed to be on, or very near to, the ordinate. In metals, the CLD is typically symmetric if static strength in tension and compression are same.

IV. RESULTS AND DISCUSSION

Typical structure of the tower given in Fig.1, consists of three parts, each welded by a flange at the ends. They are joined by bolting the corresponding flanges.

4.1. Optimization of Number of Bolts

Total dead load on the middle flange is given by,

$$W_m = W_1 + W_2 + W_3$$

Where, W_1 isdead load at the top, $W_2$is weight of the top segment and $W_3$is weight of middle segment of tower.

Therefore, W_m= 1897.43 kN

In addition to the dead load, horizontal outward bending load, My, m=4337.82kN-m, and outward torsional load,M_t=1434.25kN-mabout Z axis, inclinedat 42 degrees to vertical, also acts on the tower.

Ina complex loading condition, the most preferred failure theory is Von Mises. Von Mises stress arises from the Distortion Energy failure theory. It states that, a design will fail, if the maximum value of stress induced in the material exceeds yield strength of the material. It works well, especially forductilematerials. The material recommended for the tower shell is S355 High-grade steel. It is ductile in nature and hasminimum yield strength of 355 MPa. For safety the maximum Von Mises Stresses induced in the tower must not exceed 355 MPa.

Analyses of stress under the loads were done for120 bolts.The results of analysisof the Middle flangeare depicted in Fig. 5.

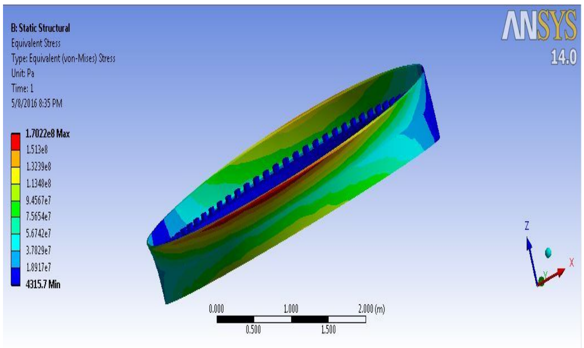

Fig.5. Equivalent Stress in Middle Flange

Similarly, analyses were done with different number of bolts for both top and middle flanges. Maximum stresses induced in each case are tabulated in Table 1.

Table 1. Results of Middle and Top Flange

Trial No.	Flanges			
	Middle Flange		Top Flange	
	No of bolts	Stress Induced (MPa)	No of bolts	Stress Induced (MPa)
1	120	170	98	174.15
2	**100**	**235.11**	**80**	**219.68**
3	80	352.32	60	274.77

4.2. Fatigue Behaviour of Wind Tower

The fatigue life was estimated by varying the wind load, $F_t$from 0 to 790.21 kN under the presence ofdead load $W_1$of 1002.39 kN, and horizontal outward bending load $M_{y,b}$of 60174.5 kN-m, and outward torsional load M_t of 1434.25 kN-m. Figure6 shows the results of the analysis.

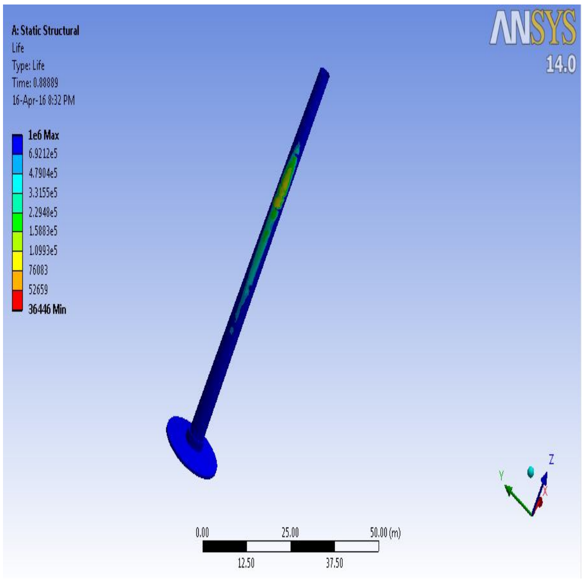

Fig 6.Fatigue Life Analysis

Component exhibits a maximum fatigue life of $1e^6$or $1X10^6$cycles,under the given loading conditions as shown in Fig.6. It is much above the theoretical estimation of $1.95e^5$or$1.95X10^5$cycles. Hence the design is safe even in fatigue loading.

4.3 Design ofShell Thickness (t)

The design of thickness of wind tower shell was obtained for the same loads and boundary conditions. Analysis was done by considering the different shell thicknesses. The stresses induced for varied sets of shell thicknesses at bottom (t_b), middle (t_m), and top (t_t), are as shown in Table 2.

Details of FEA done using ANSYS for various cases are presented herein.

a) Case 1: t_b=30 mm, t_m=25 mm &t_t=15 mm

Figure 7 shows results of the analysis done.

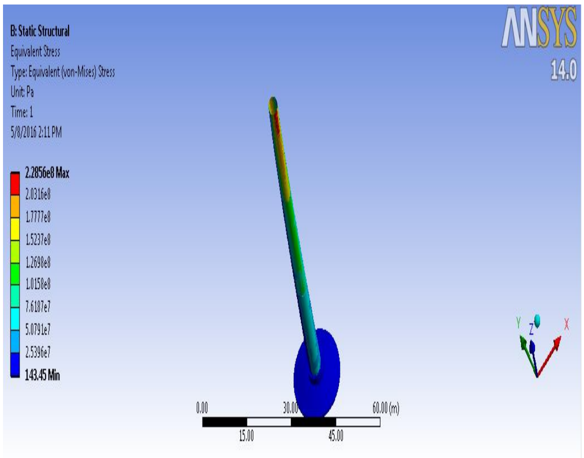

Fig.7. Stress Analysis for First Iteration

It is evident that Von Mises Stress reaches a maximum of $2.2856e^8$Pa or 228.56 MPa. The stress is well below the allowable limit 262.96 MPa. Hence the design is safe.

b) Case 2: t_b=25 mm, t_m=20 mm &t_t=10 mm

Similarly Figure 8 shows details of the analysis done.

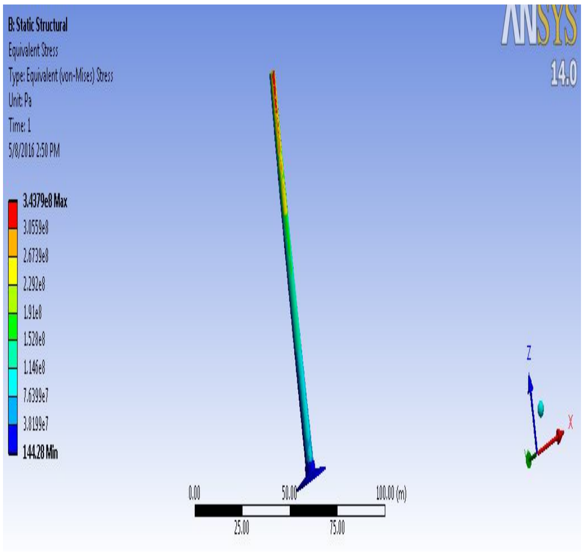

Fig.8. Stress Analysis for Second Iteration

The maximum Von Mises Stress is $3.4379e^8$ Pa or 343.79 MPa which exceeds the allowable stress 262.96MPa. Hence the design is unsafe. Table 2 gives the summary of the stress analysis.

Table 2. Results of Stress Analysis in Shell Wall

Case No.	Shell Thickness,mm				
	Bottom (t_b)	Middle (t_m)	Top (t_t)	Stress Induced (MPa)	Safe
1	30	25	15	228.56	Yes
2	25	20	10	343.79	No

It can be observed that, case 2 with a t_b= 30 mm, t_m = 25 mm, and t_t = 15 mmis found safe from the design point of viewandhence recommended for the purpose.

CONCLUSIONS

The study leads to a conclusion that-

1. FEM results shows that by decreasing the number of bolts the Equivalent stress increases. Hence an optimum number of bolts determined for each segments of bottom and middle flanges. They are 100 and 80 bolts respectively.
2. The effect of fatigue life on the prediction of damage from typical wind turbine load spectra is analysed using a detailed Goodman diagram for characterizing the behaviour wind turbine tower.
3. A detailed formulation of the fatigue behaviour is obtained by constructing a Goodman diagram using S-N curves at R-values. The expected fatigue life is very close to 10^5 cycles.
4. A tapered tubular tower with constant thickness is better than a constant diameter one. It saves material and reduces cost.

REFERENCES

[1] Melanie Hau“ Promising Load Estimation Methodologies for Wind Turbine Components” Institutfur Solare Energieversorgungstechnik(ISET).

[2] DetNorskeVeritasandCopenhagen“GuidelinesforDesignof WindTurbines”2ndEdition, Wind Energy Department, Riso National Laboratory, 2002.

[3] KyongHo Chang “Experimental and Numerical Study of the Aerodynamic Characteristics of an Archimedes Spiral Wind Turbine Blade”, 26 November 2014.

[4] Wylliam Husson “Friction Connections with Slotted Holes for Wind Towers” Structural Engineering2008:45.

[5] StaffanEngstrom,TomasLyrner,ManouchehrHassanzadeh,ThomasStalinandJohnJohansson“Talltowersforlargewindturbines”ReportfromVindforskprojectV-342 Högatorn for vindkraftverk Elforsk rapport 10:48, July2010.

[6] Silviu-cristian melenciuc, Vasile-mircea venghiav, Andrei-ionut stefancu and Mihaibudescu “Optimizing Bolted Joint Geometry for Fatigue Resistance” Integrated Systems ResearchInc, May, 2008.

[7] Chawin Chantharasenawong, Pattaramon Jongpradist and Sasaraj Laoharatchapruek,“Preliminary Design of 1.5-MW Modular Wind Turbine Tower” AEC17, 2nd TSME International Conference on Mechanical Engineering 19-21 October 2011.

[8] K. Lingaiah “Machine design data hand book” Volume-1, Fourth edition, 5 March 2006.

[9] ManouchehrHassanzadeh“Cracks inonshore wind power foundations Causes and consequences”Elforsk rapport 11:56 January2012.

[10] Zhikui Wang “The Flow Field Design and Analysis of a 2MW Offshore Wind Turbine Using Variable Wind Speed” Department of Electromechanical and Automobile Engineering, Yantai University, Yantai 264005,China.

[11] R. Lacalle , S. Cicero , J.A. Álvarez a, R. Cicero , V. Madrazo “On the analysis of the causes of cracking in a wind tower” Engineering Failure Analysis 18 (2011)1698–1710.

[12] M. Samorani the “Wind Farm Layout Optimization” Problem Alberta School of Business, University of Alberta, Edmonton, AB T6G 2R6, Canada.

[13] K.Lingaiah“Machine design data hand book”Volume-1, Fourth edition, Suma publishers, ISBN-13 1234567142681, 5th March -2006.

[14] Dr.KKumar “Structural Evaluation of Steel Adapterand Door TypeRing StiffenerinWind TurbineTowerfor Certification” IJERT Vol. 3Issue7, July 2014.

[15] R. Budynas, and K.J. Nisbett, “Mechanical Engineering Design”, 9th Edition, McGraw-Hill, New York, 2013.

[16] MdRiasat Azim“ Ananalyticalinvestigation onbolttensionofaflangedsteelpipejoint subjected to a bendingmoment” International Journal of Engineering andApplied Sciences,ISSN 2305-8269,Vol. 2, March 2013.

[17] Jui-ShengChou,Wan-TingTu“Failureanalysisandriskmanagementofacollapsed largewind turbinetower” Engineering FailureAnalysis18 (2011)295–313.

[18] Herbert J. Sutherland and John F. Mandell“effect of mean stress on the damage of wind turbine blades”Volume 18, Issue 1, January 2011, Pages 12–24.

[19] Shigley“Mechanical Engineering Design”Eighth Edition, ISBN 13 9780071077835 McGraw Hill publication, 28 May 2011.

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