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Analytical Displacement Model of Wind Turbine Towers under Loading Conditions

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Abstract

The goal of this work is in twofold: 1) to determine the directional deformation (deflection) and bending stress of 1.25 MW Suzlon wind turbine tower under loading conditions for different cross-sections through finite element analysis method; 2) to develop and validate the analytical model allowing to estimate same for different cross-sections. Wind shear force has been calculated in the prevailing direction of the wind for tower structures through integral equations, are then used as input for 3-dimensional finite element model to compute the tower deflection and bending stress. To improve the estimation of tower deflection, a mathematical model is developed based on cantilever beam theory. Results are then compared with those obtained from numerical analysis method. The wind turbine tower deflection is found maximum at the tip of the structure and increasing with the hub height. Results indicate that the square cross-section tower is superior with respect to tower deflection with a maximum deflection of 0.064 mm. Numerical analysis method is used to verify the results of mathematical tower deflection model showing very less percentage of error. Thus, the new mathematical model has the advantage of estimating the tower deflection by just knowing the average wind speed of a wind farm for any wind turbine tower structure.

Keywords:* *Wind Turbine Tower, Finite Element Analysis, Analytical Method, Tower Loading, Deflection, Bending

1. Introduction

The generation of clean energy future has identified as one of the greatest challenges of the world. To complete this challenge a comprehensive new energy plan was developed by world energy council. Previous studies do not consider the enormous increase over last year, a large part of the massive turbine that rises to height. As wind turbines rise to new heights, to tap into greater wind speeds available at these heights, a safe and more efficient optimal design of these structures will become of increasing importance of wind power in all over the world. Design and developments in the construction of taller structures for the wind turbine with better lightweight materials and improved turbine techniques are now required at reduced costs. The wind turbine tower is a static structure which supports the entire weight of the wind turbine (blades, generator, hub, etc.) and should be robust enough to sustain the wind shear also. Manufacturing and installation of the wind turbine tower costs 30% of the total wind turbine cost. Installation cost of wind turbine tower increases with the height of the tower. Various designs and techniques have been proposed to reduce the manufacturing and installation cost of the wind turbine tower. For example, Qingxu Jin et al., 2019 [1] assessed the durability of ECC/concrete dual-layer system for tall wind turbine towers; while Binbin Qiu et al., 2019 [2] predicted a method for the damage of Off-shore wind turbine by neural network. In 2018 J.Feliciano et al., [3] generalised an analytical displacement model for wind turbine towers under aerodynamic loading and J.Chou et al., [4] simulated the structural failure of onshore wind turbine under strong winds. In 2018 Breiffni Fitzgerald et al. [5], improved the reliability of wind turbine towers with active tuned mass dampers. Also, M.Gkantou et al., 2017 [6] investigated the structural response on tall hybrid onshore wind turbine tower consisting of 60m lattice and 60m tubular structure for Class II 5 MW wind turbine. Robert Fontecha et al., 2017 [7] evaluated the aerodynamic properties of wind turbine tower with wind tunnel experiment. In this manner, Alvarez Anton et al., 2016 [8] proposed the design of a new hybrid tower containing prefabricated quarter circle elements, steel beams and steel tube at the top of the tower whose weight has been reduced by 40% as compared to the traditional full-concrete tower or complete steel tower and Andrew Myers et al., 2016 [9] developed a new technique (Spiral welding) for onsite manufacturing and installation for wind turbine steel tubular towers which completely eradicated the transportation barriers to limited size tower. Similarly, Angelina Jay et al., 2016 [10] studied the buckling strength and fatigue strength of a tapered steel tubular tower through on-site fabrication using spiral welding technique which remove the limitation on the tower with a diameter-to-thickness ratio up to 300 and enables easy installation of the very large turbine with a diameter-to-thickness ratio up to 500 and Samal AK et. al., 2016 [11] validate a stress and deflection analysis of a cantilever beam using Ansys. In 2015, Amlan Das et al. [12], discussed free-standing and guyed wire tower for different cross-sections (triangular, rectangular, trapezoidal) which pose a low value of deflection while Meng Ran et al., 2014 [13] compared the steel and concrete tower and developed a new optimised design process for pre-stressed concrete tower to reduce 15% total cost as compared to steel tubular tower. Also, K. Chen et al., 2014 [14] studied the tower height matching problem in wind turbine positioning optimization. Various models are introduced, and the algorithm is employed to solve the wind turbine positioning optimization at a specified tower height. The optimization objective is to maximize the Turbine-Site Matching Index (TSMI), which includes both the production and the cost of the wind farm. Lanhui Guo et al., 2013 [15] studied the behaviour of thin-walled steel circular hollow sections (CHS's) which are widely used in wind turbine towers and are subjected to bending mainly. Quilligan et al., 2012 [16] studied the relative performance of steel and concrete tower solutions for a selection of heights and wind speeds by using a flap-wise numerical model and P.E. Uys et al., 2006 [17] worked on the design process that will minimize the cost of a wind turbine steel tower using the tower structure with the slightly conical ring-stiffened welded steel shell. Lavassas et al., 2003 [18] designed a prototype of 1 MW wind turbine steel tower, and FEA (Finite element analysis) was used for the comparison. In this present work, structures of the wind turbine (towers) under loading condition have been analysed through Ansys Workbench using Finite Element Modelling (FEM) method. In general, tapered circular section towers are used in wind turbine, and not square cross-section or any other cross-section towers due to their high-stress concentration at the corners of the structure. As per the concern of only bending strength, the square section structures are dominant as compared to the circular cross-section, while a circular section is superior to the triangular cross-section. This work includes the comparison of circular cross-section wind turbine tower with the square and triangular cross-section wind turbine towers for a hub height of 73 meters as to increase the strength and so forth the life of the wind turbine tower under critical conditions. Also, a general mathematical approach has been developed to evaluate the deformation (deflection) and bending stress.

Notations

U	Wind speed at elevation of Z
U_h	Wind speed at elevation of Z_h
α	Empirical wind shear exponent
σ	Bending Stress
M	Bending moment
Z	Section modulus
y	Directional deformation
E	Young's modulus of elasticity

I	Area moment of inertia
R_b	Outer radius at base of circular cross-section
r_b	Inner radius at base of circular cross-section
R_t	Outer radius at top of circular cross-section
T_{ts}	Thickness at top of square cross-section
S	Side length at top of triangular cross-section
s	Side length at base of triangular cross-section
T_{bt}	Thickness at base of triangular cross-section
T_{tt}	Thickness at top of triangular cross-section
D_h	Elemental diameter of circular cross-section at hub height of h
A_h	Elemental circular area at hub height of h
F	Lateral load on circular cross-section tower
F_{hs}	Lateral load on square cross-section tower
F_{ht}	Lateral load on triangular cross-section tower
y_c	Directional deformation of circular cross-section tower
y_s	Directional deformation of square cross-section tower
σ_c	Bending stress on circular cross-section tower
σ_s	Bending stress on square cross-section tower
σ_t	Bending stress on square cross-section tower
A	Side length at top of square cross-section
a	Side length at base of square cross-section
ρ	Air density
T_{bs}	Thickness at base of square cross-section

2. Theoretical consideration

2.1 Wind speed extrapolation

For the analysis of the wind turbine, the wind speed has always been an important parameter. In this work, wind speed data of two locations as shown in Figure [1] have been studied. One at MANIT, Bhopal and other location is at Mamatkheda in Ratlam district of Madhya Pradesh at 23o 41' N Latitude and 75o 03' E Longitude at a mean sea level of 560 m in Table (1). As per the data obtained from two different locations, the location site of Mamatkheda found to be suited for the analysis of the wind turbine tower based on the average wind speed, kurtosis, and skewness. For this work, a wind turbine tower with 73 meters hub height is considered for the comparison on the basis of bending strength. Therefore, an average value of 12.582 m/s wind velocity (of Mamatkheda location) has been extrapolated for all further calculations of the wind load. The basic equation of the wind shear power law for the extrapolation [19] is given by equation [1]

$$U = U_h \left(\frac{Z}{Z_h}\right)^{\alpha} \quad (1)$$

Table 1: Descriptive statistics of wind speed data at two stations

Station	Max. Wind Speed (m/s)	Mean Wind Speed (m/s)	Std. deviation (m/s)	Skewness	Kurtosis
Manit	18.734	4.262	1.919	0.332	0.151
Mamatkheda	33.675	12.582	5.694	0.264	-0.397

Fig.1: Satellite image of the locations

2.2 Deflection and Simple Bending theory

The tower is assumed as a cantilever beam with linearly varying cross-section and horizontal wind shear on the entire surface of the tower. The base of the tower is assumed to be a fixed support whereas the upper section of the tower is free to deflect due to the applied load of wind. The material is considered as structured steel to follow Hook's law of elasticity and Euler's Bernoulli's equation of bending (Samal Eswara et. al. 2016) [11]

Simple Bending equation

$$\boldsymbol{\sigma = \frac{M}{Z}} \quad (2)$$

Macaulay's double integration equation for Directional Deformation (deflection)

$$\frac{d^2y}{dx^2} = \frac{M}{EI} \quad (3)$$

3. Mathematical Modelling

3.1 Dimensional calculations

Firstly, a wind turbine steel tubular tower of circular cross-section with linear elastic, isotropic and homogeneous material has been considered as shown in Figure [2]. On the basis of tower dimensions in Table [2], Square and triangular cross-section tower dimensions for a hub height (73 meters) has been calculated by using the Equation [4], [5], [6] and [7]. Also, a fillet is provided throughout the tower height from base to top equals to the thickness of towers to reduce stress concentration in the structures for the square and triangular cross-section.

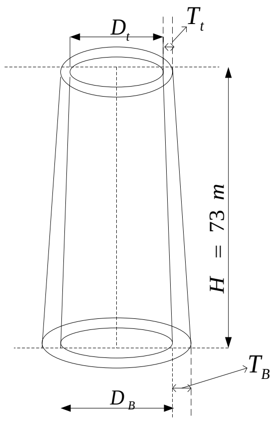

Fig.2: 1.25 MW wind turbine tower of Suzlon wind farm

Square cross-section tower

$$\pi(R_B^2 - r_B^2) = A^2 - (A - 2T_{bs})^2 \quad (4)$$

$$\pi\left(R_t^2 - r_t^2\right) = a^2 - (a - 2T_{ts})^2 \quad (5)$$

Triangular cross-section tower

$$\pi(R_B^2 - r_B^2) = \frac{\sqrt{3}}{4}[S^2 - (S - 2T_{bt})^2] \quad (6)$$

$$\pi(R_t^2 - r_t^2) = \frac{\sqrt{3}}{4}[s^2 - (s - 2T_{tt})^2] \quad (7)$$

Table 2: Dimensions of Circular section wind turbine tower

Circular cross-section tower	
Rated Power	25 MW
Cut in wind speed	4 m/s
Rated wind speed	12 m/s
Cut-off wind speed	20 m/s
Tower type	Steel tubular tower
Tower height	73 m
Base diameter	5.486 m
Base thickness	0.45m

3.2 Wind load calculations

A wind turbine tower is the main structure which supports the entire weight of the wind turbine and wind shear. Wind energy is the kinetic energy of air, which imparts a shear force (pressure) on the entire turbine structure and increases non-linearly with the hub height. Force developed on the wind turbine tower can be calculated by Pressure Velocity energy equation

$$\frac{P}{\rho g} = \frac{U^2}{2g} \quad (8)$$

$$F = K_d K_a K_c \frac{\rho A U^2}{2} \quad (9)$$

Also, the value of the constants Kd, Ka, Kc has been evaluated by using the Table [3].

Table 3: Design data based on IS and IEC standards for wind turbine tower

Abbreviation	Condition	Value
K_d (wind directionality factor)	It is specified for buildings, solid signs, open signs, lattice frameworks, and trussed towers (Triangular, square, rectangular). For circular or near – circular forms	0.90 1.0
K_a (area averaging factor)	This parameter greatly influences the design wind pressure. As the area becomes larger, the value	1 ($10 \leq m^2$) 0.9 ($25\ m^2$)

	of this constant decreases and vice-versa.	0.8 (100 m^2)
K_c (Combination factor)	Value of combination factor depends upon the confined effect of K_d and K_c	1

4. Methodology

4.1 Finite Element Analysis

Structural problems solved by using finite element computational analysis under the branch are popularly known as Static Structural analysis. Like other computational technique, the static structural analysis also performed in steps. First, engineering data for the material are being set. After this, geometries are prepared in Static Structural design module followed by Mesh generation. Finally, the boundary conditions are set for the particular problem. For the present analysis, Ansys Workbench with Finite Element Modelling Method using an iterative approach has been employed. The direction of the wind in the atmosphere is uncertain. Therefore, it is imperative to find the prevailing direction of the wind. One of the commonly used methods is to draw Wind Rose diagram (which shows the percentage of wind blowing from each of the leading 12 points in compass and also the prevailing direction of the wind i.e. the direction of the wind blow most of the time). In this work, wind turbine towers of different cross-section are assumed to be subjected to a horizontal wind shear. Also, specifying correct boundary conditions is an extremely crucial part of the Static structural analysis as it governs the solution accuracy and validity. The structure of wind turbine tower is assumed to be as a cantilever beam which is fixed at the base and is free to deflect at the top of the tower (due to applied wind load in the prevailing direction of the wind) as shown in Figure [3] and Figure [6].

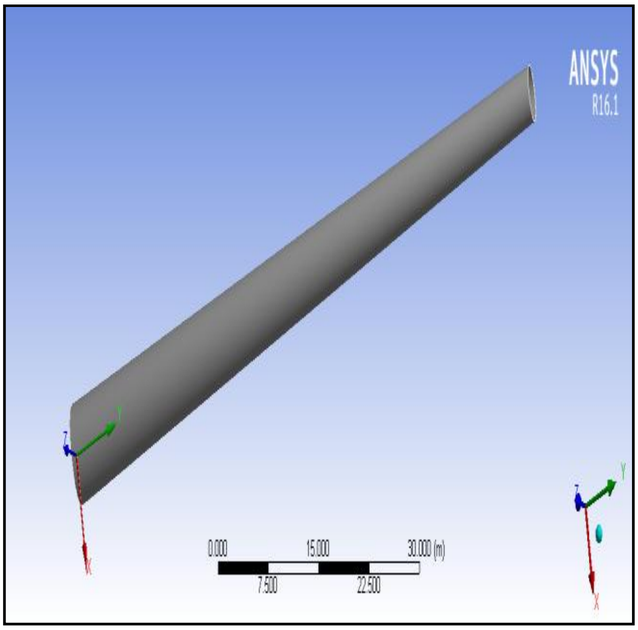

Fig.3: Steel tubular tower of 73 m height

In this similar manner, wind load is also applied to both the geometries of the wind turbine tower i.e. on the square and triangular cross-section tower in Figure (4) and (5). Like CFD, a solution of Static Structural analysis is highly dependent on the type of mesh used and also mesh must be sufficiently fine at critical points of the structure for precise results. In this, the smooth fine mesh has been made with 513170 numbers of nodes and 102480 elements. Also, a dense refinement is done at the critical points of the tower.

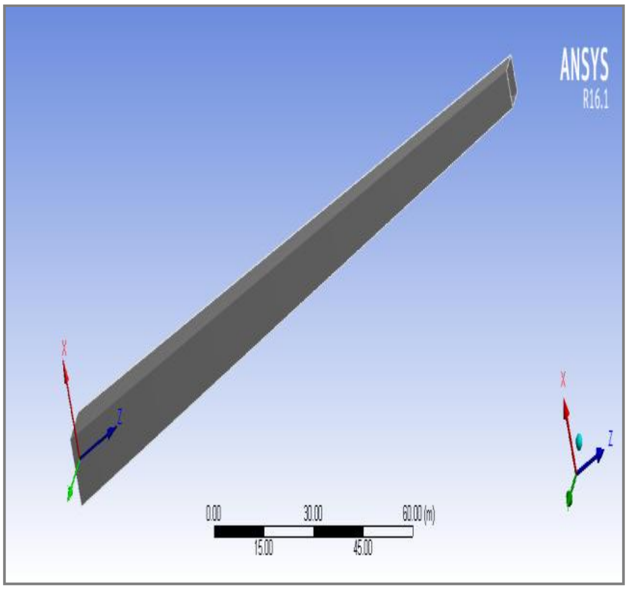

Fig.4: Square cross-section tower of 73 m height

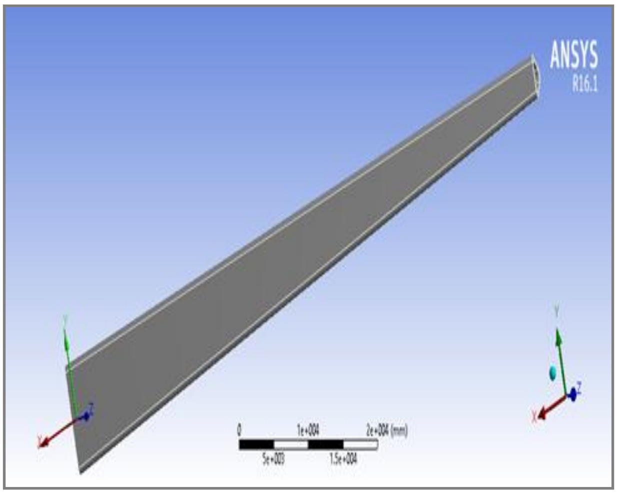

Fig.5: Triangular cross-section tower of 73 m height

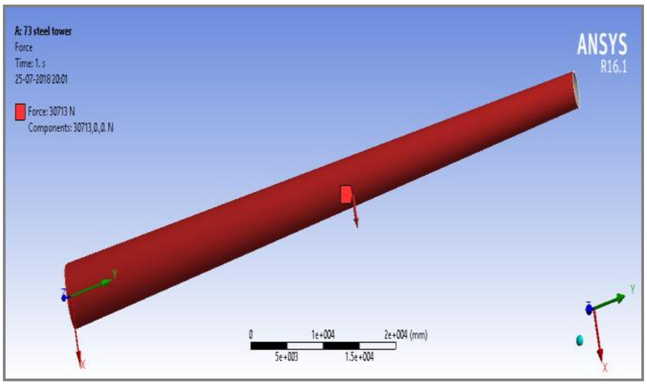

Fig.6: Wind shear on circular cross-section tower

4.2 Analytical Method

Average wind speed at a height of 25 meters has been extrapolated with the use of the Equation [1]. This average value of wind speed imposed a horizontal wind shear on the wind turbine tower causes a Bending Stress (normal to the direction of wind shear) and Deformation (deflection) in the direction of the wind load on the entire structure of the tower. The Equation [9] has been employed for the calculation of lateral load on the tower according to IEC (International Electro technical Commission) and IS-875 (Indian Standards). Also, an elemental section of width dh and diameter D_h is taken for the calculation of the wind load shown in Figure [7]. The general expression for the variable diameter, wind velocity and area (normal to wind shear) of the tower is given by

$$D_h = [D_B - (D_B - D_t)\frac{h}{H}] \quad (10)$$

$$A_h = [D_B - (D_B - D_t)\frac{h}{H}] \times \mathrm{dh} \quad (11)$$

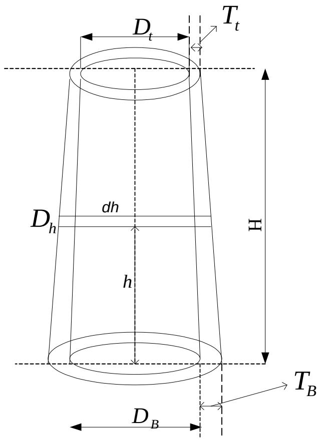

Fig.7: Elemental sections on wind turbine circular cross-section tower

Elemental cross-section area and wind load using Equation [9] for circular, square and triangular cross-section tower is shown in Table [4], [5] and [6].

Table 4: Wind load on circular cross-section tower

Wind turbine tower	Circular cross-section
Area (normal to wind load) at a height h from the base of the wind turbine tower	$A_h = [D_B - (D_B - D_t)\frac{h}{H}] \times dh$
Lateral wind load on tower	$F = \int_o^H \frac{K_a K_d K_c \rho A_h U_h^2}{2}$

A Bending Stress is also developed in +y-direction along the fibers of the tower structure. This stress may cause a severe failure on the structure of wind turbine. Therefore, similar to the previous consideration for load calculation, Equation (2) and (3) is considered for a section of width dh and diameter D_h at the height of h from the base of the tower for the computation of directional deformation and bending stress.

Table 5: Wind load on Square cross-section tower

Wind turbine tower	Square cross-section
Area (normal to wind load) at a height h from the base of the wind turbine tower	$\boldsymbol{A_{hs} = [A - (A - a)\frac{h}{H}] \times dh}$
Lateral wind load on tower	$F_{hs} = \int_o^H \frac{K_a K_d K_c \rho A_{hS} U_h^2}{2}$

Table 6: Wind load on triangular cross-section tower

Wind turbine tower	Triangular cross-section
Area (normal to wind load) at a height h from the base of the wind turbine tower	$A_{ht} = [S - (S - s)\frac{h}{H}] \times dh$
Lateral wind load on tower	$F_{ht} = \int_{o}^{H} \frac{K_a K_d K_c \rho A_{hT} U_h^2}{2}$

$$\frac{d^2 y}{dx^2} = \frac{M_h}{EI_h} \quad (13)$$

$$\frac{d^2 y}{dx^2} = \frac{K_a K_d K_c \rho A_h U_h^2 . h}{2EI_h} \quad (14)$$

$$\sigma = \frac{M_h Y}{I_h} \quad (15)$$

Directional deformation (deflection) and maximum Bending stress for different cross-section as shown in Table [7], [8] and [9] after using equation [14] and [15].

Table 7: Directional deformation and maximum bending stress on circular cross-section wind turbine tower

Wind turbine tower	Circular cross section
Directional Deformation	$y_c = \iint_0^H \frac{k_a k_d k_c \rho A_{hc} . U_h^2 . h}{2EI_{bc}[1 - (1 - r_c^4) \ni^4]}$
Maximum Bending Stress	$\sigma_c = \frac{d}{dh}[\frac{M_{hc} Y}{I_{bc}[1 - (1 - r_c^4) \ni^4]}]$

Table 8: Directional deformation and maximum bending stress on square cross-section wind turbine tower

Wind turbine tower	Square cross section
Directional Deformation	$y_s = \iint_0^H \frac{K_a K_d K_c \rho A_{hs} . U_h^2 . h}{2EI_{bs}[1 - (1 - r_s^4) \ni^4}$
Maximum Bending Stress	$\sigma_s = \frac{d}{dh}[\frac{M_{hs} Y}{I_{bs}[1 - (1 - r_s^4) \ni^4]}]$

Table 9: Directional deformation and maximum bending stress on square cross-section wind turbine tower

Wind turbine tower	Triangular cross section
Directional Deformation	$y_t = \iint_0^H \frac{K_a K_d K_c \rho A_{ht} U_h^2 . h}{2EI_{bt}[1 - (1 - r_t^4) \ni^4}$
Maximum Bending Stress	$\sigma_t = \frac{d}{dh}[\frac{M_{ht} Y}{I_{bt}[1 - (1 - r_t^4) \ni^4]}]$

5. Results and Discussion

A static Structural based analysis has been performed for different cross-sections of wind turbine tower by using Ansys Workbench of version-16.1. For the analysis of the wind turbine tower, dimensions of circular cross-section tower are considered as shown in Table [2] which represents a 1.25 MW wind turbine steel tower of Suzlon wind farm with hub height of 73 m. Similarly, for the dimension of square and triangular cross-section equations [4], [5], [6] and [7] have been employed.

Table 10: Dimensions of square and triangular cross-section tower

Cross-section of tower	Side length at base(m)	Side length at top(m)
Square	3.698	1.783
Triangular	7.951	3.529

The entire structure of the wind turbine is subjected to horizontal wind load which causes a deflection (deformation) in the prevailing direction of the wind and bending stress normal to direction of the applied load. The average wind speed of 12.582 m/sec at a height of 25 m (data represented in Table [1]) has been extrapolated by using the Equation [1] for the calculation of 73 m hub height wind turbine.

Table 11: Extrapolated average wind speed for a hub height of 73 meters

Height	25 m	73 m
Average wind speed (m/sec)	12.582	14.618

Structured steel material has been considered for the analysis of wind turbine tower with material properties of the Elastic modulus (E) 210GPa, Poisson ratio 0.3 and density 7.85x103 kg/m3. Mechanical APDL with program controlled type solver has been used to solve the above-considered geometries through finite element analysis. In this work, an iterative approach has been employed with an initial number of Sub-steps is equals to 8, a minimum number of sub-steps is equalled to 1, and the maximum number of sub-steps is equals to 25. Based on the value of average wind speed for 73 m hub height, wind load has been calculated by using the integral equations in Table [4], [5] and [6] for the different cross-section of the wind turbine tower.

5.1 Tower deflection and bending stress from FEA results

Wind turbine tower with circular cross-section, wind load of 39937 N has been evaluated from Table [4] and applied in the prevailing direction of the wind on the entire surface of the tower with appropriate mesh generation to obtain the deflection and bending stress. The deflection trend in the Figure [8] shows that the total deformation on the entire surface of the circular cross-section tower increases with hub height. The maximum deflection is at tip of the tower 0.53 mm and minimum at base of the tower structure. Maximum bending stress has also been developed in the normal direction of the applied wind load with 0.293 MPa at the base. Similarly, for deflection and bending stress of square and triangular cross-section tower wind load 33862 N and 76620 N (from Table [5] and [6]) respectively has been evaluated. Figure [9] represents the tower variation trend of total deflection and bending stress for square and triangular cross-section. Likewise in circular section, the maximum deflection for square cross-section is at the top 0.0695 mm, minimum at the base, and maximum bending stress 0.047 MPa.

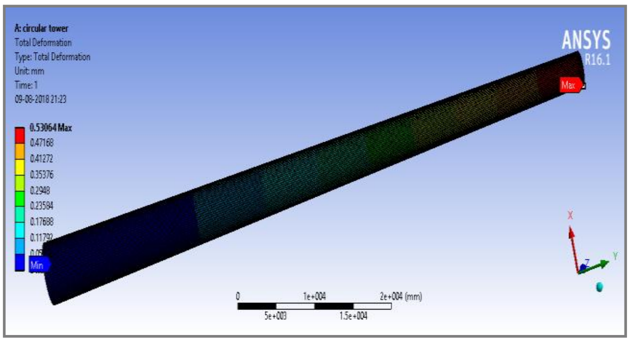

Fig.8: (1) Directional deformation of circular cross-section tower

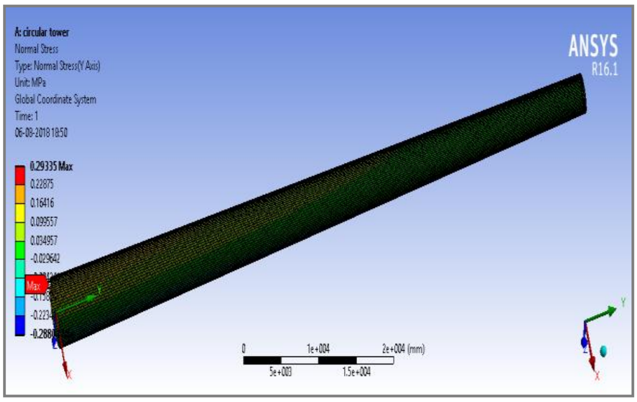

Fig.8: (2) bending stress of circular cross-section tower

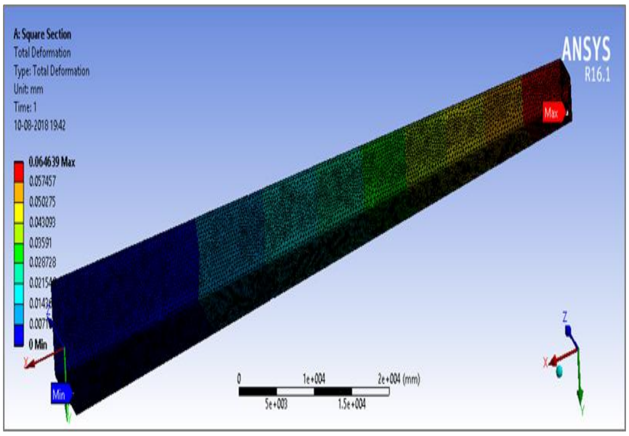

Fig.9: (1) Directional deformation of square cross-section tower

For triangular cross-section tower, the maximum deflection 1.0049 mm is at top and maximum bending stress 0.5589 MPa. The variation trend for total deformation and bending stress of triangular cross-section tower found similar to trend of circular and square section represented in Figure [10].

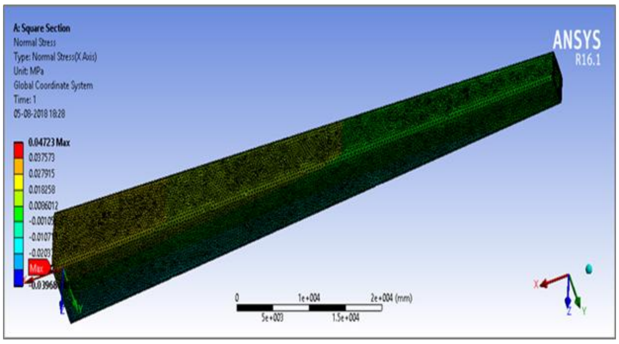

Fig.9: (1) Bending stress of square cross-section tower

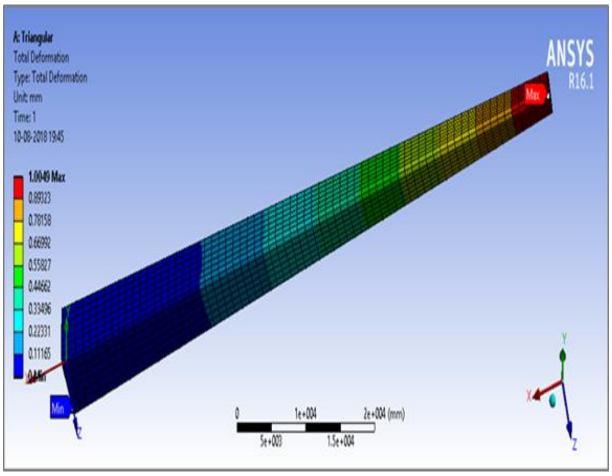

Fig.10: (1) Directional deformation of triangular cross-section tower

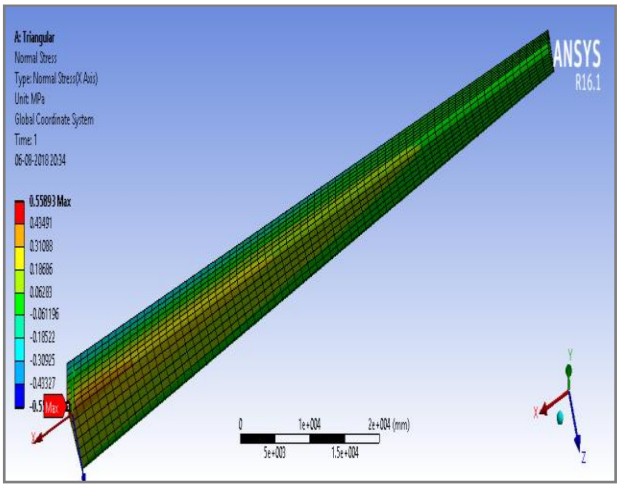

Fig.10: (2) Bending stress of triangular cross-section tower

5.2 Analytical approach

Finite element analysis of the wind turbine tower shows that the total deflection and bending stress are strictly related to wind load on the entire structure and also the boundary conditions. To evaluate the total deformation and bending stress on the entire structure of the tower, wind load for the different cross-section has been evaluated by integral equations mentioned in Table [4], [5] and [6].

5.2.1 Total deformation and bending stress

Total deformation on the entire structure of the wind turbine tower found maximum at the top section as per FEA results and increasing with the hub height. Table [7], [8] and [9] represents a mathematical model to evaluate the total deformation and bending stress for circular, square and triangular cross-section wind turbine tower.

Table 12: Comparison of total deformation and bending stress of circular cross-section wind turbine tower

Results	Circular cross-section		
	Modeling	Analytical	% Error
Total Deformation (mm)	0.5304	0.5303	0.0188
Bending Stress (MPa)	0.2933	0.2932	0.0340

Table 13: Comparison of total deformation and bending stress of square cross-section wind turbine tower

Results	Square cross-section		
	Modeling	Analytical	% Error
Total Deformation (mm)	0.0645	0.0642	0.4651
Bending Stress (MPa)	0.0472	0.04719	0.0211

The double integral mathematical model has been employed for total deflection of circular cross-section 0.5303 mm with error percentage 0.0188%, square cross-section 0.0642 mm with error percentage 0.4651% and for triangular cross-section 1.0037 mm with percentage of error of 0.1194%.

Table 14: Comparison of total deformation and bending stress of triangular cross-section wind turbine tower

Results	Triangular cross-section		
	Modeling	Analytical	% Error
Total Deformation (mm)	1.0049	1.0037	0.1194
Bending Stress (MPa)	0.5589	0.5588	0.0178

Similarly, the analytical results of bending stress for tower cross-sections have been found for circular cross-section 0.2932 MPa (with error percentage 0.034%), square cross-section 0.04719 MPa (with error percentage 0.0211%) and for triangular cross-section 0.5588 MPa (percentage of error 0.0178%). Comparative results of finite element method and analytical method are presented in Table [12], [13], and [14].

Conclusion

In this paper, the wind load sustainability of the wind turbine towers for circular, square and triangular cross-section has been compared with finite element modeling method under static loading condition. Different cross-sections of the wind turbine tower are compared on the basis of total deflection and bending stress. It appears that there is an acceptable level for measuring the aforesaid parameters related to tower with two different methods. The following conclusions can be drawn from this analysis:

1. The maximum deformation on the entire surface of the wind turbine tower has been found at the tip of the circular, square and triangular cross-section and the minimum at the base of the tower cross-section.
2. Bending stress has been also found maximum at the base of the tower cross-sections normal to the direction of wind load.
3. Wind turbine tower with 73 m hub height, square cross-section tower has been found superior to the other considered cross-section in terms of deflection. However, the circular cross-section is superior as per the axis of symmetry in all direction.
4. The analytical method that utilizes mathematical iterations for the calculation of total deformation and bending stress shows minor errors. Therefore, recommended for the necessity of high accurate results.

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