Loads Analysis and Weight Optimization of 5 MW Wind Turbine Lattice Tower

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Abstract: ***Wind turbines Transform mechanical energy of the wind into electrical energy. It's placed on the top of a mast or tower where they are more affected by the wind. The tower construction doesn't just carry the weight of the nacelle and the rotor blades, but must also absorb the huge static loads caused by the varying power of the wind. Lattice tower is the alternative support structure for wind turbine tower. This paper investigates the stiffer and lighter lattice tower that could be achieved in the design of lattice tower shape and cross-section of the building Material. Model of Six Lattice towers which are modeled in two different shapes and three different cross sections are designed and analyzed under static and dynamic load using ANSYS Mechanical APDL 15.0 software. Combination of tower shape and cross - section which gives optimum stiffer and lighter tower is identified by comparing the results of the analysis using the quantitative and graphic method.***

Keywords: Wind turbine loads, Lattice tower, Structural analysis, Optimization of lattice tower's weight

1. Introduction

The fuel shortage in the near future combined with the negative environmental impacts caused by the use of the traditional electricity production methods forced all those involved in the energy production field to start exploring new directions in energy production. The so-called renewable energy has become a preferred way to produce energy [1], [2]. Wind power obtained from wind turbines is one of the renewable energy sources, which grows at a rate of 27 % annually. This global interest in wind energy brought a huge competition among wind power generating machine manufacturers [3] [4].

The wind turbine is formed by a set of blades connected to a rotor through a gear system. All these machines have to place on the top of a mast or tower at an optimum height where they can capture sufficient energy from wind [5]. The tower construction doesn't just carry the weight of the nacelle and the rotor blades. But must also absorb the huge static and dynamic loads caused by the varying power of the wind. The size of the structural components affects the overall dynamic characteristics of the wind turbine and the inherent dynamic amplification caused by the rotor. In a typical wind turbine project, the cost of tower varies somewhere from 25 to 30 percent of the total cost of wind energy generating system. Therefore, selection of the tower structural system is very important for an economical and structurally reliable wind energy implementation [6], [7].

Two types of structural systems, lattice and tubular are often used for wind turbines (Figure 1). Lattice systems are formed by connecting steel truss through bolting. The truss action and larger base dimensions of this system help resist the applied loads more effectively leading to a lighter structural design. In addition, the wind loads are reduced due to the lattice topology [8].Considering the use of standard profiles and bolted connections, the manufacturing cost is less than tubular sections. Since the lattice tower can be transported to the field in multiple small pieces, they also offer savings in terms of construction costs. So that regarding the cost of production and construction, lattice tower is preferable than tubular tower [9].

Reliable and economical wind turbine tower can be achieved through designing of stiffer and lighter lattice tower. The heavier lattice towers are costlier and have higher stiffness. The weight of the lattice tower has to be optimized in order to get a stiffer structure in a possible least cost [10].The weight of the lattice tower is determined by summing the weight of steel trusses and bolts used to construct it. In another hand, the weight of steel truss varies with the types of cross section and its length.

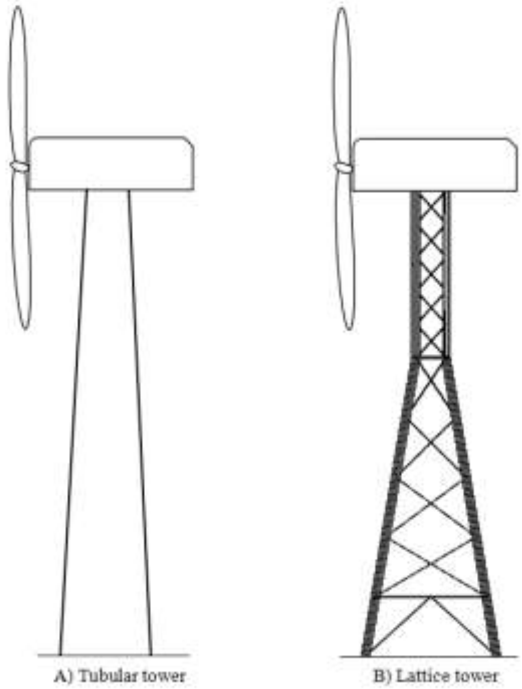


Figure 1: Illustration of the most common type of wind turbine tower

The shape of the tower determines the length of the truss member used to build the tower, though it is important to point out that stiffer and lighter lattice tower may be designed when the engineer considers the effect of the tower shape and cross-section of the steel. The objective of this study is to investigate and compare the quality of cost and stiffness of hybrid shape and pyramidal lattice towers which are made within hollow rectangular, circular tube and I-section steel separately.

The comprehensive effect of tower shapes and section types of steel in the stiffness and cost of the towers have been studied by A. Das [11]. He used STAAD Pro software to modeled and analyze the lattice tower frequency. Triangular, rectangular and trapezoidal Shape of 20-meter high lattice towers which are modeled as Pipe and Angle sections separately have been analyzed under static and dynamic loads. He presented only natural frequency and displacement of the towers caused by the free vibration. The study identifies the stiffness quality of six types of structures through the analysis, then he compares the analysis result and the weight of the towers using a graphic method. The comparison result identifies the combination of tower shape and steel section which give the best quality.

In this study finite element structural analysis and graphical methods are used to investigate and compare the quality of the structures sequentially. Eigenvalue, nonlinear buckling, free vibration and forced vibration analysis are carried out to find the stress of each steel truss, displacement of the nodes, natural frequency and resonance of the lattice towers. To the knowledge of the authors, there is no any other previous study investigated and compare the impact of both the tower shape and cross-section simultaneously using those four finite elements structural analysis method. This paper presents hybrid and pyramid shapes of the lattice structure (Figure 4).The vertical members (legs) of pyramidal and hybrid shape lattice towers are modeled as hollow rectangular section, circular tube section, and I-sections steel separately. The rest of the members, for all six towers, are modeled by hollow rectangular section steel. The height of the tower is 87.6m. The tower is designed for a high wind system of approximately 310, 000 kg (weight of the hub and the nacelle) which generate 5MW power. The models are optimized and the obtained results are compared.

2. Wind turbine Structural loads and Design

2.1 Wind turbine tower loads

The most important loading for turbine towers is the wind loads, and notably the rotor thrust loading. The wind turbine tower has to encounter those loads during its lifetime [12]. The loads have to be calculated accurately and will be considered in the design process. The calculation model for the turbine tower is as shown below in Figure 2. Based on Davenport's wind chain principle, Some countries have developed their own codes and standards to calculate the ultimate designed wind load [13].such as American standard ASCE-7-05 and British standard BS. In the current study, the dynamic wind loads at different heights of the tower and the thrust load are calculated according to ASCE-7-05 [14], [15].

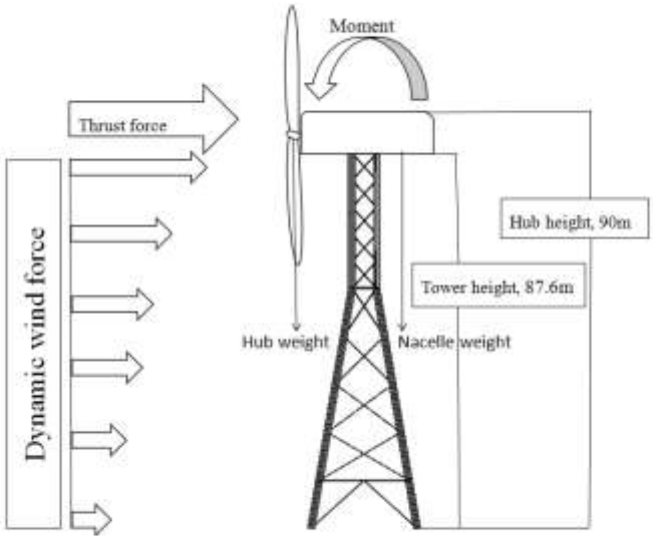


Figure 2: Calculation model of lattice tower

$$V_z = V_b * K_z * K_t * K_d * 1 \quad (1)$$

K_t = The factor accommodates the topographic of the structure location. Local abrupt topography affects the ground.
K_d = The factor to accommodate the cross-sectional of the structure
I = The factor accommodate the importance of the structure.
V_z = the design velocity at height of z
From Bernoulli's equation of flow, the wind pressure can be computed as:

$$q_z = 0.6 * V^2 \quad (2)$$

$$F = q_z * G * C_f * A_f \quad (3)$$

Whereas, F shows the ultimate wind force, G the gust effect, C_f the force coefficient, A_f the projected area normal to wind, and q_z the wind pressure at height z.

Basic wind speed (V_b) assumed to be 47m/s. The wind force calculated to be 2014 N at the top parts, 24.724kN at middle parts and 63.111 KN at the bottom of the tower.

$$T = \frac{dT}{dt} V^2 * \rho * \frac{C}{2} (C_L COS\theta + C_D SIN\theta) \quad (4)$$

T= the axial wind thrust [kNewwton], V= the apparent wind speed [m/s], θ = the inflow angle, C_L = the lift coeffcient, C_D = the drag coefficient, ρ = The air density [kg/m3], C = a constant

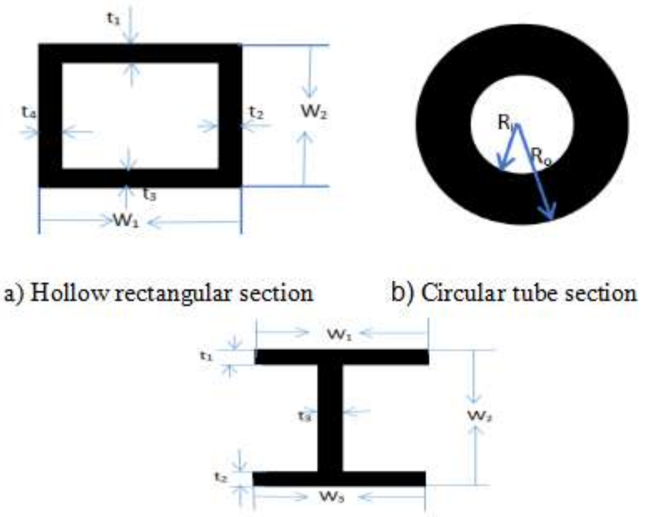
$$M_t = T * H_h \quad (5)$$

Whereas in equation 5, T is the thrust force, H_h the height of the hub, and M_t is the moment caused by the thrust force. The thrust force and the momentum at the top of the lattice tower are calculated to be 1530kN and 15, 700kN-m respectively.

2.2 Structural Design

Taking into account the construct-ability issues, the elements of lattice tower are divided into seven groups based on their location and function, and each group is assigned a specific section type and size during optimization [16].Table.1

provides the details of element groups. The section size was more at the bottom part and it was reduced with height. As noticed weight has a direct relationship with the stiffness. So in order to have the smooth comparison of hybrid shape and pyramidal lattice tower stiffness, their weights kept not to have significant difference during the design process.



a) Hollow rectangular section   b) Circular tube section

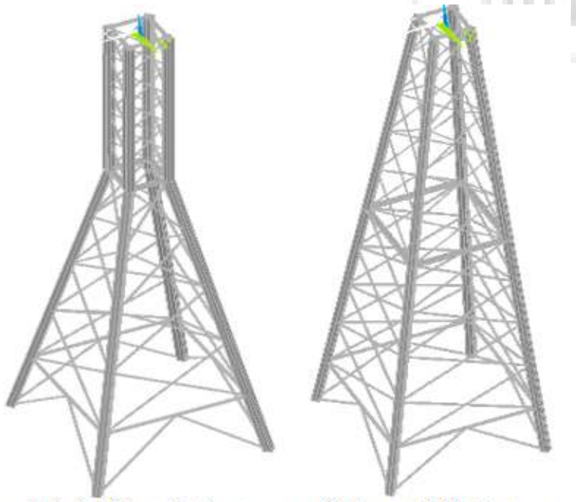
C) I-section

Figure 3: Sections types used in the design

Table 1: Element groups of the designed lattice towers

Group No	*Elements*
1	Vertical elements (base to the top)
2	Horizontal elements 1st (top of tower)
3	Horizontal elements 2nd (middle of tower
4	Horizontal elements 3rd (bottom of tower)
5	Cross brace 1st (middle to the top)
6	Cross brace 2nd (middle up to the legs)
7	Cross brace 3rd (at the legs)

Three Lattice towers are designed in each pyramidal and hybrid shape. The mainframes of the towers are modeled as hollow rectangular, circular tube and I-section steel separately. The hollow rectangular section is used to build all the rest elements of the towers.



a) hybrid shape lattice tower   b) Pyramidal lattice tower

Figure 4: Types of lattice tower shape used in the design

All the six towers have equal height, base diameter, and top diameter which are 87.6 m, 16, 9 m, and 3.87 m sequentially. Element group 2, 4, 5, 6 and 7 have similar size hollow rectangular section for the same types of lattice tower shape. Table 2 and Table 3 shows the rectangular hollow section size of those elements for hybrid shape and pyramidal towers respectively.

Table 2 : Hybrid shape Lattice tower's hollow rectangular sections size

Hollow rectangular sections size for Hybrid shape Lattice tower (mm)					
Horizontal elements 1st (group no.2)					
'1	'2	'3	'4	"1	"2
10	10	10	10	500	500
Horizontal elements 3rd (group no.4)					
12	12	12	12	250	250
Cross brace 1st (group no.5)					
6	6	6	6	100	100
Cross brace 2nd (group no.6)					
7.85	7.85	7.85	7.85	150	150
Cross brace 3rd (group no.7)					
8	8	8	8	150	150

Table 3 : Pyramidal Lattice tower's hollow rectangular sections size

Hollow rectangular sections size for Pyramidal Lattice tower(mm)					
Horizontal elements 1st (group no.2)					
'1	'2	'3	'4	w1	w2
11	11	11	11	300	300
Horizontal elements 3rd (group no.4)					
10	10	10	10	250	250
Cross brace 1st (group no.5)					
4	4	4	4	100	100
Cross brace 2nd (group no.6)					
5	5	5	5	150	150
Cross brace 3rd (group no.7)					
5	5	5	5	150	16

The six lattice towers mainframes are built within three types of section separately that varies in size. Table 4 - Table 6 shows the type and size of cross section of mainframes (vertical elements) and horizontal elements of the six lattice towers.

Table 4: Hollow rectangular section frame lattice tower sections type and size

Hollow rectangular section frame hybrid shape Lattice tower structure 1 (mm)						
Horizontal elements 2nd						
t_1	t_2	t_3	t_4	W_1	W_2	*Type of section*
22	22	22	22	500	500	Hollow Rectangular
Vertical elements						
20	20	20	20	800	800	Hollow rectangular
Hollow rectangular section frame pyramidal tower structure 2 (mm)						
Horizontal elements 2nd						
17.5	**17.5**	17.5	17.5	500	500	Hollow rectang ular
Vertical elements						
20	20	20	20	800	800	Hollow rectangular

Table 5: I – section frame lattice tower sections type and size

I - section frame hybrid shape Lattice tower structure 3 (mm)						
Horizontal elements 2nd (group no.3)						
t_1	t_2	t_3	t_4	W_1	W_2	Type of section
22	22	22	22	500	500	Hollow rectangular
Vertical elements (group no.1)						
t_1	t_2	t_3	W_1	W_2	W_3	Type of section
20	20	20	80	80	80	I-section
I – section frame pyramid Lattice tower Structure 4 (mm)						
Vertical elements (group no.1)						
20	20	20	80	80	80	I-section
Horizontal elements 2nd (group no.3)						
t_1	t_2	t_3	t_4	W_1	W_2	Type of section
17.5	17.5	17.5	17.5	500	500	Hollow rectangular

Table 6: Circular tube section frame Lattice tower sections type and size

Circular tube section frame hybrid shape Lattice tower Structure 5 (mm)						
Horizontal elements 2nd (group no.3)						
t_1	t_2	t_3	t_4	W_1	W_2	Type of section
22	22	22	22	500	500	Hollow rectangula
Vertical elements (group no.1)						
R_i			R_o			Type of section
374			400			Circular tube
Circular tube section frame pyramid Lattice tower Structure 6 (mm)						
Vertical elements (group no.1)						
374			400			Circular tube
horizontal elements 2nd (group no.3)						
t_1	t_2	t_3	t_4	W_1	W_2	
17.5	17.5	17.5	17.5	500	500	Holl. rectang ular

3. Structure Modeling and finite element analysis

3.1 Finite element structural analysis

Finite Element Analysis (FEA) is a computer simulation technique used in engineering analysis employing numerical technique of finite element method (FEM). One of the widely used mechanical engineering software to perform FEA is ANSYS In. In this work, ANSYS mechanical APDl 15.0 is used for the modeling and analysis task.

Four types of structural analysis for each tower are performed: Eigenvalue, nonlinear buckling, modal and harmonic analysis. The stress, displacement, natural frequency and resonance of each element, node and structure caused by the applied load and vibration of the structure are simulated. The stress in each element, the nodal displacement, resonance and the frequency of the structure are the factors to measure its stiffness. The maximum stress and displacement are occurred in a single element and node respectively. The stress of an element and the displacement of a node cannot fully describe the state of the structure. Therefore, in order to better understand the response of the structures to the applied loads, the average stress and displacement are calculated:

$$\delta_A = \sum_{n=1}^{102} (e_1 + e_2 + e_3 + ... + e_n)/n \qquad (6)$$

$$d_A = \sum_{n=1}^{102} (d_1 + d_2 + d_3 + ... + d_n)/2 \qquad (7)$$

δ_A-average stress, d_A-averrage displacment, e-stress in element, d - nodal dsplacment, n - number of element / nodes in the tower.

3.2 Wind turbine Lattice tower Modeling

The geometry of the structures, the material properties, and the boundary conditions are modeled using ANSYS APDL. The 104 steel truss connected each other using 48 nodes to construct each structure. The steel trusses are formed by BEAM188 element. BEAM188 has six or seven degrees of freedom at each node. These include translations and rotation in the x, y, and z directions and warping magnitude which is optional. It gives the option for unrestrained and restrained deformation of the cross-section. ANSYS offers a wide range of material properties to be used for a particular analysis. For the truss, the material is assumed to be homogeneous linear isotropic, hence the properties needed are; The Young's modulus of elasticity, shear modulus, Poisson ratio, and density of the steel are taken to be, respectively, 200*109 Pa, 77*109 Pa, 0.3, and 7800 kg/m3.

The static and dynamic loads of 5MW wind turbine loads are applied in negative Z-axis and positive Y-axis direction respectively (Figure.2).The weight of the nacelle and the hub applied at the top of the tower in the negative Z direction while the dynamic wind forces on the face of the tower at different heights and the momentum at the top of the tower are applied in the Y-axis direction. All the forces are applied at the nodes. If the centroidal axis is not collinear with the element X-axis, applied axial forces will cause bending. Applied shear forces cause torsional strains and moment if the centroid and shear center of the cross-sections are different. The nodes should, therefore, be located at the desired points where the force to be loaded.

3.2.1 Eigenvalue and nonlinear buckling analysis

Many structures require an evaluation of their structural stability. S. Deshpande studied the post-buckling and buckling properties of structural members. At the onset of instability, a structure will have a large change in displacement with no change in the load. At the point of critical load value, the structure suddenly experiences a large deformation and may lose its ability to carry load. A structure generally becomes unstable at a load lower than the critical load because of imperfection and nonlinear behaviors. Analysis techniques for pre-buckling and collapse load analysis included eigenvalue and nonlinear buckling analysis [17].

Eigenvalue analysis predicts the theoretical buckling strength of an ideal linear elastic structure. This method corresponds to the linear elastic buckling analysis [18]. The eigenvalue analysis is carried out under static and dynamic load of 5MW wind turbine tower to simulate the stress and the nodal displacement of the six lattice towers. 1.29 x10^8 Pa, 1.29x10^8 Pa, 1.63x10^8 Pa, 1.25x10^8 Pa, 1.68x10^8 Pa, and 1.51 x 10^8 Pa are the maximum stress occurs in the element of hollow rectangular section, circular tube section and I-section frame of hybrid shape and pyramidal lattice tower sequential. Some of the stress and the displacement simulation results of eigenvalue buckling analysis are shown in Figure 5 and Figure6.

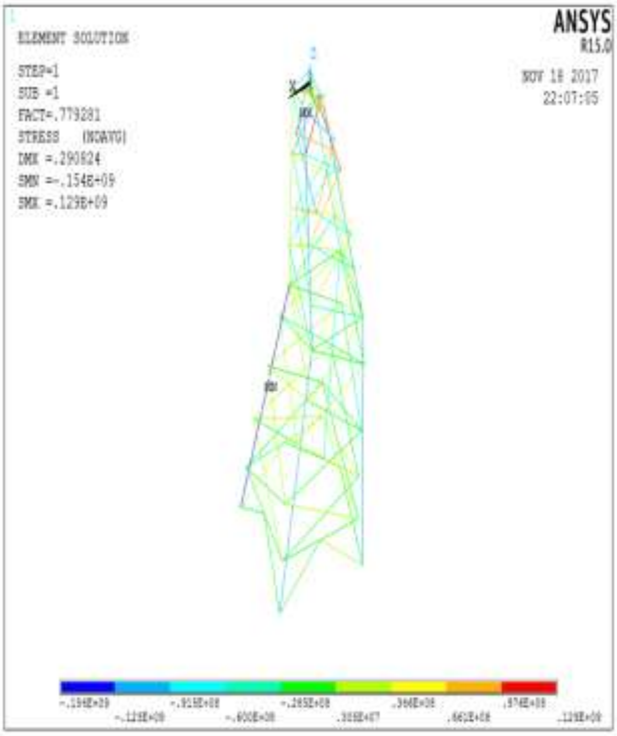


Figure 5: Stress of hybrid shape tower (Eigenvalue analysis)

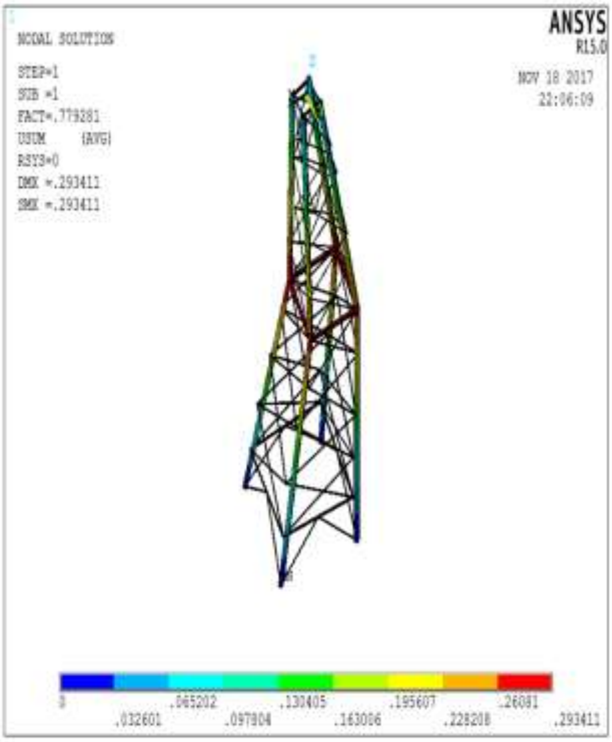


Figure 6: Nodal displacement of hybrid shape tower (Eigenvalue analysis)

Imperfection and nonlinear behavior prevent most real-world structures from achieving their theoretical buckling strength. Nonlinear buckling analysis technique provides more realistic results. It is more accurate than eigenvalue analysis and is therefore recommended for design or evaluation of structures [19].The applied load should be set to a value slightly higher (10 to 20 %) than the critical load predicted by the eigenvalue buckling analysis. The dynamic and static loads value are set to be 10 percent higher than eigenvalue buckling analysis loads for the current nonlinear buckling analysis. Figure 16 and Figure17 present the maximum stress and nodal displacement of nonlinear buckling analysis and also some of the stress and displacement simulations results are described in Figure 7 and Figure 8

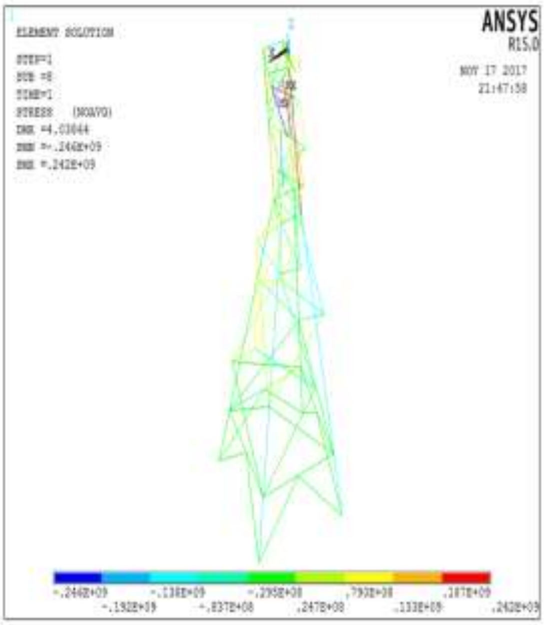


Figure 7: Stress of hybrid shape tower (nonlinear buckling analysis)

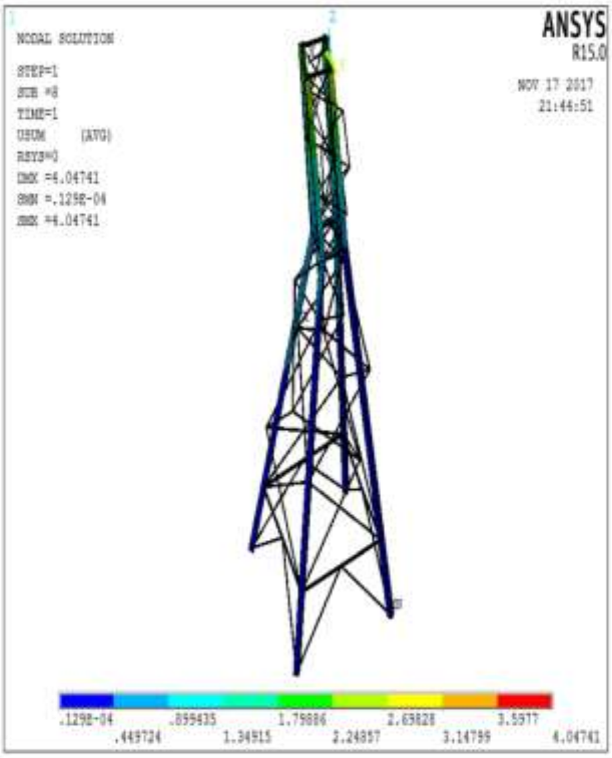


Figure 8: Nodal displacement of hybrid shape tower (nonlinear buckling analysis**)**

3.2.2 Modal and harmonic analysis

The goal of modal analysis in structural mechanics is to determine the natural mode shapes and frequencies of an object or structure during free vibration [20].Modal analysis has been conducted to determine the natural frequency and the 12 mode shape of the lattice towers. The frequencies of the 12 modes for all the structures are between the range of 0.42Hz - 1.66Hz. Figure 18 presents the six lattice tower natural frequencies. Some of modal analysis simulation results are shown below in Figure 9 and Figure 10.

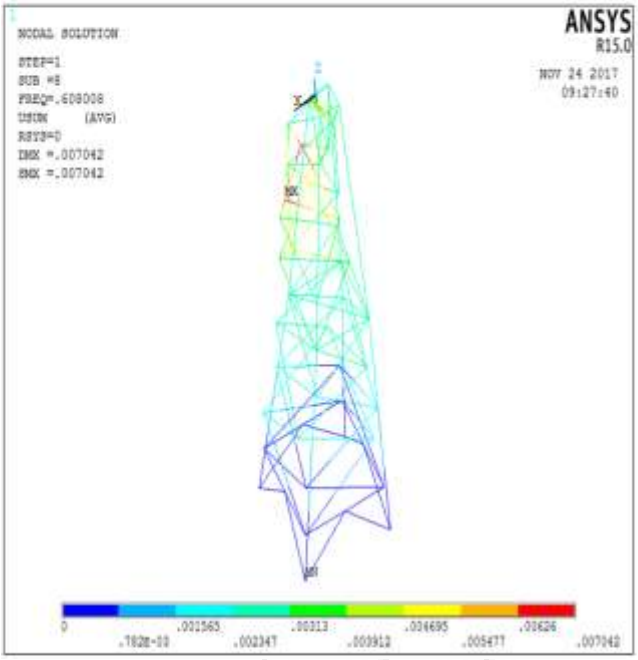


Figure 9: Nodal displacement of I-section pyramidal tower (Modal analysis)

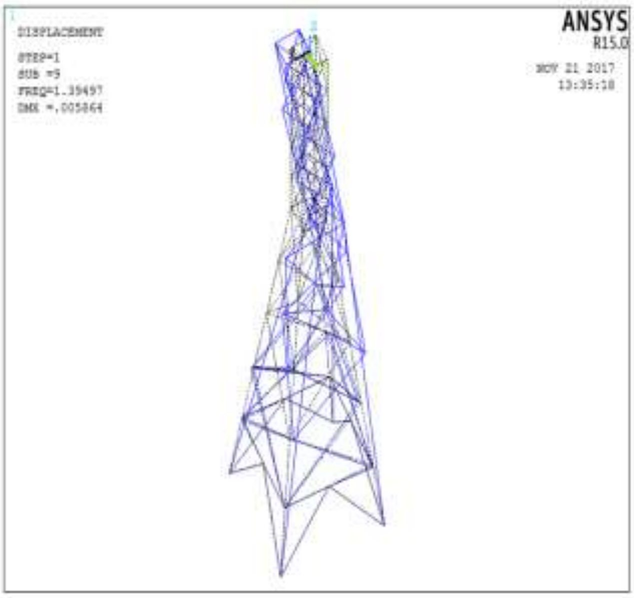


Figure 10: Free vibration of hybrid shape tower (modal analysis)

Harmonic analysis is used to determine the response of the structure under a steady-state sinusoidal (harmonic) loading at a given frequency. One should always run a free vibration (modal) analysis prior to a harmonic analysis to obtain an understanding of the dynamic characteristics of the model [21]. Harmonic analysis is conducted to determine the stress in element, nodal displacement and the resonance of the structures. The stress and the nodal displacement occurred due to forced vibrations are determined through harmonic analysis. The values of the resonance of all structures are presented and compared in Figure 19.Some of the harmonic simulation results are shown in Figure 11, Figure 12 and Figure 13.

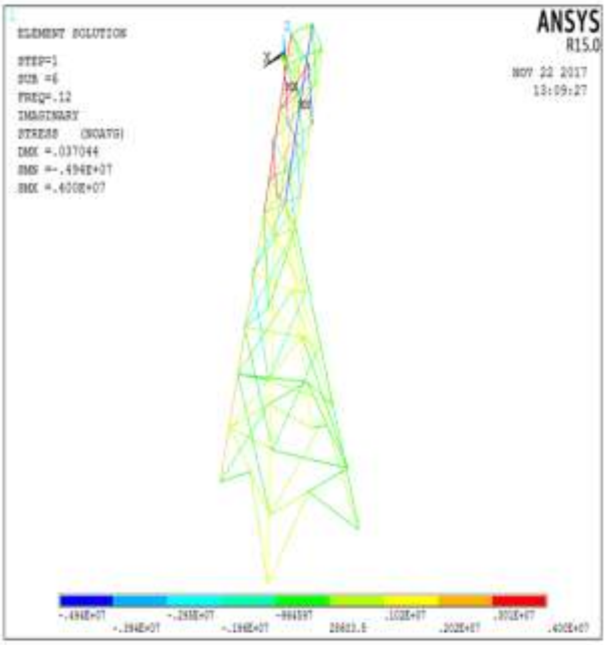


Figure 11: Stress of Circular tube section hybrid shape tower (Harmonic analysis)

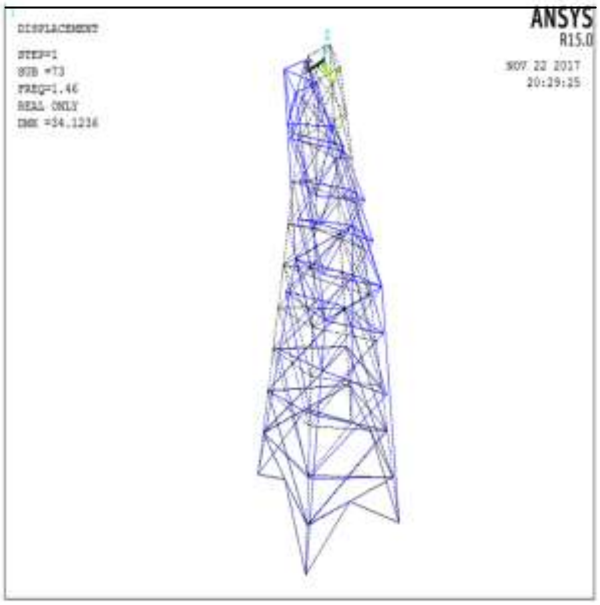


Figure 12: Forced vibration of I-section pyramidal tower (Harmonic analysis)

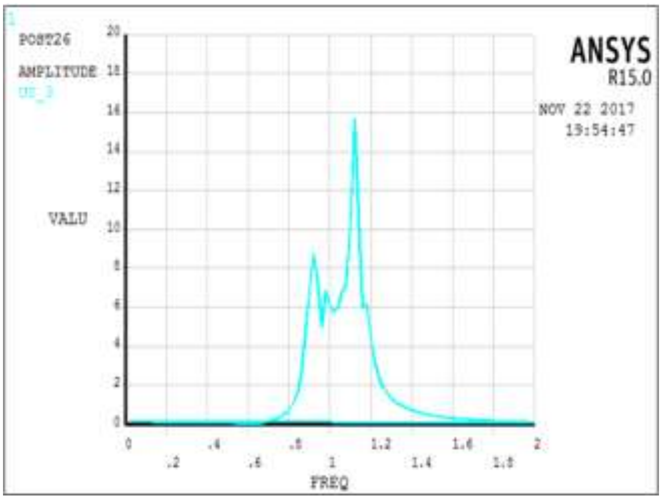


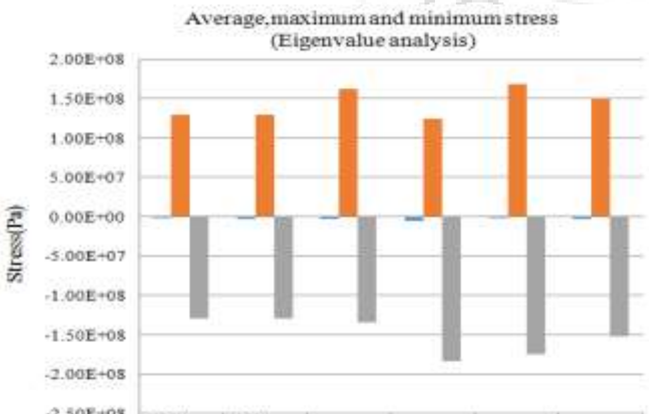
Figure 13: Amplitude-frequency graph for circular tube section hybrid shape Lattice tower (Harmonic analysis)

4. Results and Discussion

The finite element analysis results and the weight of the six lattice towers are compared graphically and quantitatively to identify the stiffer and lighter structure which give economical and reliable wind generating system. The stress in element, nodal displacement, frequency and resonance of the structures are the main factor to compare the stiffness. The weight of the structures is used to compare the costs.

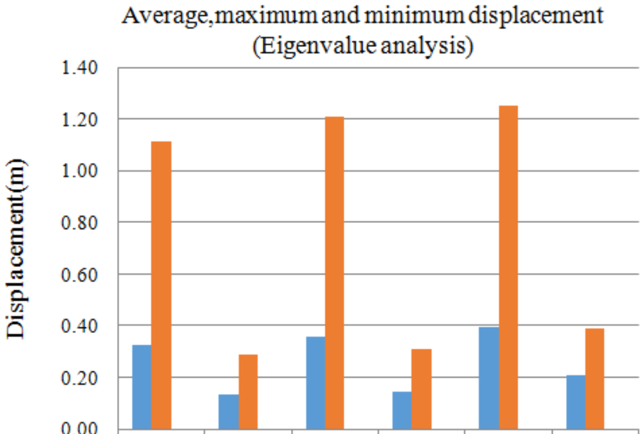
4.1 Buckling analysis results and discussion

The Eigenvalue buckling load produces stress in the lattice tower elements and displaced the nodes. Figures 14 and 15 contain graphs and tables for graphical and quantitative comparison of values. The Stress and displacement of hybrid shape tower are less than that of the pyramidal tower. The buckling stress and displacement of the hollow rectangular section frame towers are the smallest. While I-section frame towers have the highest stress and displacement.



	Hollow Rectangular section hybrid tower	Hollow Rectangular section pyramidal tower	Circular tube section hybrid tower	Circular tube section pyramidal tower	I-section hybrid tower	I-section pyramidal tower
average	-8.03E+05	-3.35E+06	-2.66E+06	-5.61E+06	-1.61E+06	-2.98E+06
maximum	1.29E+08	1.29E+08	1.63E+08	1.25E+08	1.68E+08	1.51E+08
minimum	-1.29E+08	-1.30E+08	-1.35E+08	-1.84E+08	-1.75E+08	-1.52E+08

Figure 14: Comparison of stresses (Eigenvalue buckling analysis)

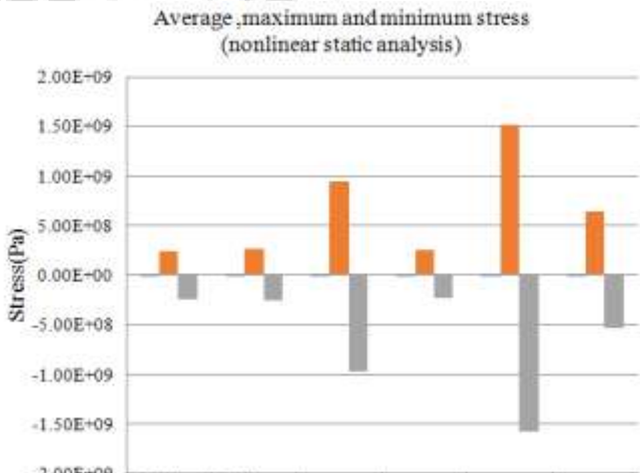


	Hollow Rectangular section hybrid tower	Hollow Rectangular section pyramidal tower	Circular tube section hybrid tower	Circular tube section pyramidal tower	I-section hybrid tower	I-section pyramidal tower
average	0.33	0.13	0.36	0.15	0.40	0.21
maximum	1.12	0.29	1.21	0.31	1.25	0.39
minimum	0	0	0	0	0	0

Figure 15: Comparison of nodal displacements (eigenvalue buckling analysis)

The comparison of nodal displacement and stress of the lattice structures that are generated by nonlinear buckling loads are presented in Figure 16 and Figure 17.

The stress in the elements and nodal displacement of hybrid shape lattice towers are very high compared to pyramidal lattice towers. The nonlinear buckling loads produced the highest stress and displacement in the elements and nodes of the I-section towers sequentially. While the stress in hollow rectangular section towers and the nodal displacement in circular tube section lattice towers are the least.



	Hollow Rectangular section hybrid tower	Hollow Rectangular section pyramidal tower	Circular tube section hybrid tower	Circular tube section pyramidal tower	I-section hybrid tower	I-section pyramidal tower
average	-8.59E+05	-1.74E+06	-3.88E+06	-4.94E+05	-1.04E+07	-8.52E+06
maximum	2.42E+08	2.64E+08	9.39E+08	2.49E+08	1.52E+09	6.40E+08
minimum	-2.46E+08	-2.58E+08	-9.69E+08	-2.31E+08	-1.58E+09	-5.31E+08

Figure 16: Comparison of Stresses (nonlinear Buckling analysis)

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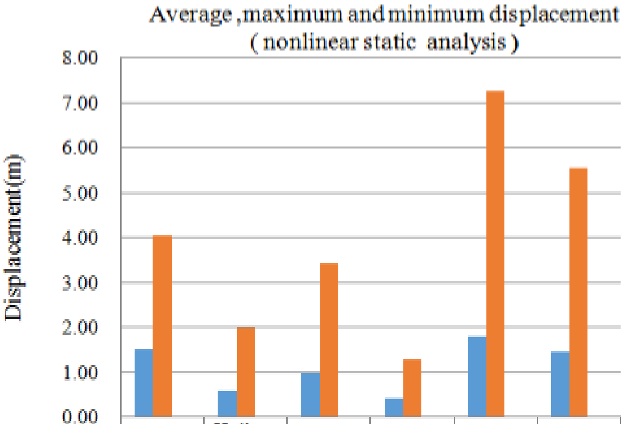

	Hollow Rectangular section hybrid tower	Hollow Rectangular section pyramidal tower	Circular tube section hybrid tower	Circular tube section pyramidal tower	I - section hybrid tower	I- section pyramidal tower
average	1.52	0.57	0.98	0.41	1.79	1.44
maximum	4.04	1.99	3.43	1.28	7.27	5.54
minimum	0	0	0	0	0	0

Figure 17: Comparison of nodal displacements (nonlinear Buckling analysis)

4.2 Modal and harmonic analysis results and discussion

Natural vibrations are different from forced vibrations which happen at frequency of applied force (forced frequency). If forced frequency is equal to the natural frequency, the amplitude of vibration increases manyfold. This phenomenon is known as resonance.

In this study, the finite element modal analysis is employed to find out the natural frequency and mode shape of the designed structures. The natural frequency of twelve mode shapes and their corresponding natural frequency of the six lattice towers are obtained and the results are compared as shown in figure 18.

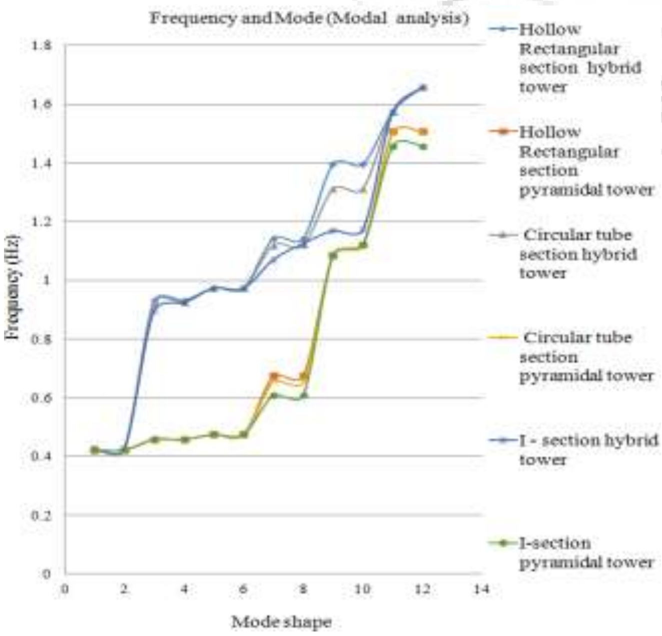

Figure 18: Comparison of natural frequencies of the six lattice towers

The natural frequency of Pyramidal tower is less than that of a hybrid tower of similar type of section. Hollow rectangular section towers have the highest natural frequencies. While the natural frequencies of circular tube section towers are less than I-section towers.

The harmonic analysis carried out mainly to determine the resonance of the structures. Figure 19 shows the comparison of the six lattice towers amplitude.

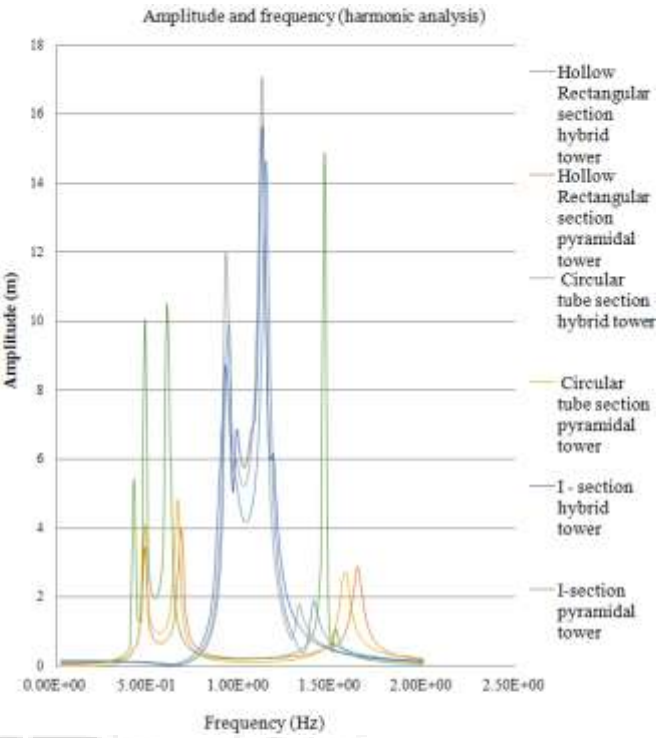

Figure 19: Comparison of the amplitudes/resonance of the towers (harmonic analysis)

Circular tube section hybrid towers have the highest resonance. While the resonance of hollow rectangular section towers is the least.

4.3 Lattice tower weight

There is no standard production, transportation and installation cost of lattice tower. The weights of the six lattice towers are compared to identify cost quality of the structures. As mentioned above the heavier towers are costlier.

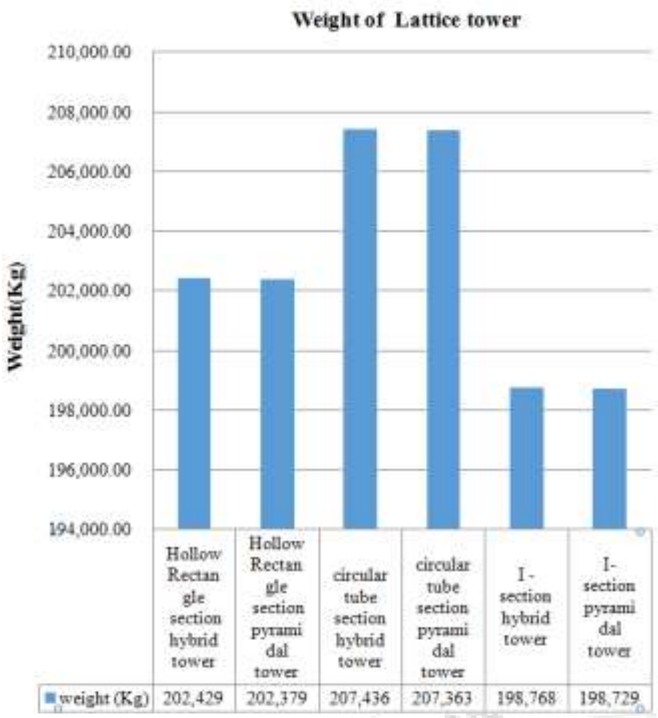

Figure 20: Comparison of lattice tower weights

Figure 20 presents the weight comparison of the six lattice towers. Circular tube section towers are heaviest while I-section towers are the lightest and the cheapest.

5. Conclusion

This study attempts to identify the combination of lattice tower shape and cross-section of the truss that gives the best quality of stiffness and cost, so as to get an economical and reliable power generation system. The following conclusions can be derived from the analysis and comparison.

- I-sections lattice towers are the lightest and have the least stiffness. Both pyramidal and hybrid shape I-section lattice towers are the most economical but the least reliable.
- Circular tube section lattice towers are heaviest towers and stiffer than I-section lattice towers. These towers are the most expensive and have the moderate quality of stiffness.
- According to stresses, displacements, amplitude and weight comparisons result, hollow rectangular section towers are the stiffest lattice structure and lighter than circular tube section lattice towers. The cost of hollow rectangular section towers are moderate and have the best quality of stiffness.
- In this study, Pyramidal and hybrid shape lattice towers are designed to be equal in weight. The pyramidal tower has better quality than hybrid shape tower to stand against all wind turbine loads.
- Combination of hollow rectangular section truss and pyramidal structure gives the best combination of quality of stiffness and cost to the 5MW wind turbine lattice tower.

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