Wind and Structures, *Vol. 30, No. 1 (2020) 29-35*
DOI: https://doi.org/10.12989/was.2020.30.1.029

Comparative structural analysis of lattice hybrid and tubular wind turbine towers

R. Kumaravel[a] and A. Krishnamoorthy*

School of Mechanical Engineering, Sathyabama Institute of Science and Technology, Chennai, India

(Received January 3, 2019, Revised July 2, 2019, Accepted July 30, 2019)

Abstract. This paper presents a comparative structural analysis of lattice hybrid tower with six legs with conventional tubular steel tower for an onshore wind turbine using finite element method. Usually a lattice hybrid tower will have a conventional industry standard 'L' profile section for the lattice construction with four legs. In this work, the researcher attempted to identify and analyze the strength of six legged lattice hybrid tower designed with a special profile instead of four legged L profile. And to compare the structural benefits of special star profile with the conventional tubular tower. Using Ansys, a commercial FEM software, both static and dynamic structural analyses were performed. A simplified finite element model that represents the wind turbine tower was created using Shell elements. An ultimate load condition was applied to check the stress level of the tower in the static analysis. For the dynamic analysis, the frequency extraction was performed in order to obtain the natural frequencies of the tower.

Keywords: structural dynamics; wind energy; wind loads; finite element methods; lattice hybrid tower

1. Introduction

Wind energy is one of the potential sources in the field of green and renewable energy. The wind turbine tower holds the wind turbine at the necessary elevation and supports all the loads that the wind turbine experiences. In order to produce larger amount of energy from wind turbines, the tower should be taller. Because the wind speed is lower and more turbulent at close to the ground level. In other way there is necessity for development of wind turbines suitable for low wind regions. It can be achieved by placing the turbine at higher elevations where more wind can be captured. In general, the cost of the tower is about 20-30% of the total cost of the wind turbine project. The wind turbine tower plays an important role in reducing the cost of wind energy. As the size of wind turbine grows, the cost of the tower increases because of the increasing cost of material, transportation, assembly and complexity involved in erection. But a higher height results in higher loads imposed on the tower. Therefore, it is very important to select and optimize the tower to develop a structurally economically reliable wind turbine.

2. Wind turbine towers

In the wind turbine industry towers are constructed with different material and different construction systems.

There are widely four types of towers available in market for the Horizontal axis onshore wind turbines. They are Tubular tower, Lattice tower, Lattice Hybrid tower and Concrete hybrid tower.

2.1 Tubular tower

Tubular steel tower is most preferred type of tower. It consists of cylindrical and conical sections which are formed by bending and rolling steel plates and joined at the site using ring flange connections. Tubular towers are preferred due to their safety for climbing and pleasing look as they have enclosed profile. And have more strength and durable properties, they are more commonly preferred in the industry. However, for very large turbines the manufacturing cost increases as the thickness of tubular section increases. Because of this, transporting and erecting these heavy tubular steel sections at the site becomes more challenging.

2.2 Lattice tower

Lattice towers consist of standard steel sections available in market and formed by bolted and welded connections. Because of large base area, lattice towers can with stand the lateral loads and the wind loads are also reduced due to the lattice topology. Considering the use of standard profiles and bolted connections, the manufacturing cost is less than tubular sections because it requires less material for similar stiffness. Although the initial material cost may be lower for the lattice tower, the assembly and maintenance cost may be higher as each bolt needs to be torqued to a specification and checked periodically. Additionally the foundation cost may be less than the tubular tower because inexpensive pile foundations at each frame foot are used. But lattice towers for higher heights have the problem of tower to blade tip clearance.전에

*Corresponding author, Professor
E-mail: akrish61@gmail.com
[a] Research Scholar

http://www.techno-press.com/journals/was&subpage=7 ISSN: 1226-6116 (Print), 1598-6225 (Online)

2.3 Concrete hybrid tower

The most widely used method in the world construction industry is reinforced concrete system. Concrete hybrid towers has concrete structure at the bottom and a tubular structure at the top, is proposed for large wind turbines, which is commonly known as Concrete Hybrid towers. Advantages of Concrete hybrid towers are transport cost savings due to on-site manufacture and fewer supply restrictions for market reasons. The greatest advantage of this type of towers is the prevention of local buckling.

2.4 Lattice hybrid tower

Lattice-tubular hybrid structural system, lattice structure at the bottom and a tubular structure at the top, is proposed for large wind turbines, which is commonly known as Lattice Hybrid towers. Usually a lattice hybrid tower will have a conventional industry standard ‘L’ profile section for the lattice construction with four legs. In this work, the researcher attempted to identify and analyze the strength of six legged lattice hybrid tower designed with a special profile instead of four legged conventional ‘L’ profile for corner bars and standard L profiles for horizontal and diagonal members.

3. Design calculation

The wind load on the tower is calculated according to EN 1991-1-4:2005 clause 7.11 /8/ (EN1991:2005 – Reference 17). Because there are no data about a 6 legged lattice tower, the tower is assumed to be composed from two 3 legged towers as shown in the below image.

The wind loads are calculated by use of the aerodynamic wind turbine load program BLADED. To implement these wind loads in the design calculation are loaded at the R-Stab model to arrive at the structural member dimensions and number of bolts for each joints. The load calculations are performed for the load cases mentioned in the wind turbine standard IEC 61400-01 Edition 03 (Reference14). The environmental conditions for those load cases are mentioned in Table 1. The bladed software is set to simulate the whole below mentioned load cases with different combinations of turbine conditions and environmental conditions. After simulation of the whole load cases, the extreme loads (minimum and maximum) of the whole load cases were extracted.

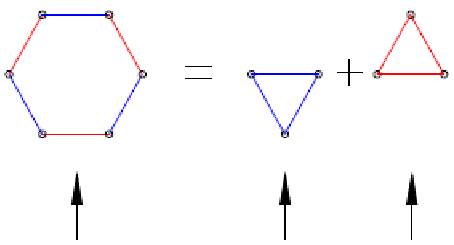


Fig. 1 Wind load calculation

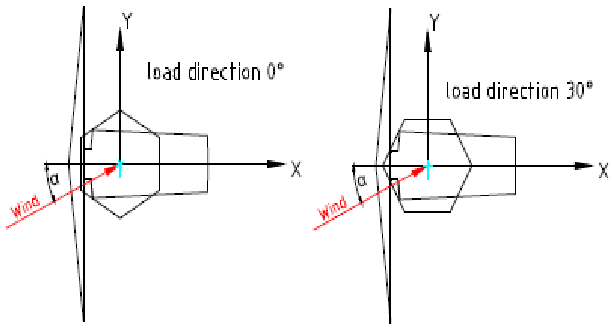


Fig. 2 Wind load direction in R-Stab model

This enabled the designer to arrive at the maximum thrust, maximum moment that occurred at rated wind speed. This max thrust and moment (6590 kNm) are obtained from the load calculations and applied on the structure to carry out the structural analysis

Each load cases are calculated for two tower positions, 0^0 (Edgewise) and 30^0 (Orthogonal to wall). This is done by turning the R-stab model 30^0 along the Z axis of the global coordinate system as shown in the below image.

4. Geometric and FE modeling of lattice hybrid tower

If we increase the number of legs to six, we cannot use standard L angle. According to polygon angle theorem, the interior angle of each element has to be 120 degree to form hexagon shape or tower with six legged configuration. For the six legged configuration of tower, various profiles were studied. Among them a special star profile is considered for the tower, which has the better sectional properties than other sections. By increasing the number of legs from four to six better rigid and lighter towers can be achieved.

This paper attempts to compare structural behavior of Lattice hybrid tower with Tubular tower using Finite element analysis. The three dimensional CAD model of Lattice hybrid tower and Tubular tower of 130 m height are modeled using Pro-E. The developed models are for 1.5 MW capacity wind turbine.

4.1 Description of the tower model

4.1.1 Lattice hybrid tower

The Lattice hybrid tower has a height of 77 m lattice part and base diameter of 26.2 m, the adapter cone has a height of 3.5 m. Finally, the tubular top has a height of 49.5 m and diameter of 2.34 m on top. It becomes to a total height of 130 m. The lattice part consisting of special Star profile with the three beams has the dimensions of 225x20 mm for six corner bars. This is formed by bending steel plate to 120 degree and the welding the steel plate on the bend plate. The horizontal and diagonal members are standard L angle of 90x8 mm dimensions. Simplified bolts by direct volume connectivity is used to model the connections. The total weight of Lattice tower is 184 ton.

4.1.2 Tubular tower

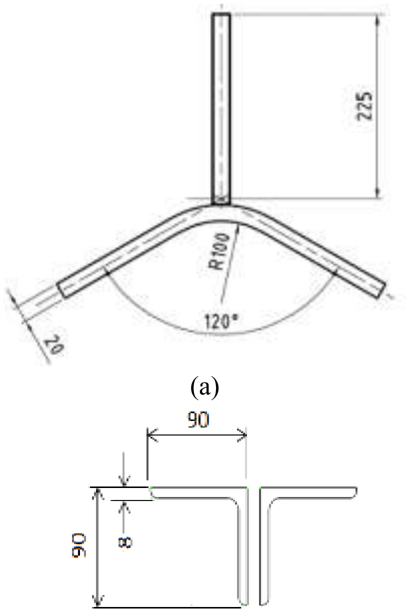
The tower used in this study is a tubular steel tower of

Table 1 Design load cases

Design situation	DLC	Wind condition	Other conditions	Type of analysis	Partial safety factors
1) Power producti-on	1.1	NTM Vin < Vhub < Vout	Extrapolati-on of extreme events	U	N
	1.2	NTM Vin < Vhub < Vout		F	P
	1.3	ETM Vin < Vhub < Vout		U	N
	1.4	ECD Vhub = Vr – 2 m/s, Vr, Vr + 2 m/s		U	N
	1.5	EWS Vin < Vhub < Vout		U	N
2) Power producti-on plus occurren-ce of fault	2.1	NTM Vin < Vhub < Vout	Control system fault / loss of electrical network	U	N
	2.2	NTM Vin < Vhub < Vout	Protection system / internal electrical fault	U	A
	2.3	EOG Vhub = Vr±2 m/s and Vout	External / internal electrical fault including loss of electrical network	U	A
	2.4	NTM Vin < Vhub < Vout	Control, protection / electrical system faults	F	P
3) Start up	3.1	NWP Vin < Vhub < Vout		F	P
	3.2	EOG Vhub = Vin, Vr ± 2 m/s and Vout		U	N
	3.3	EDC Vhub = Vin, Vr ± 2 m/s and Vout		U	N
4) Normal stop	4.1	NWP Vin < Vhub < Vout		F	P
	4.2	EOG Vhub = Vr ± 2 m/s and Vout		U	N
5) Emerge-ncy stop	5.1	NTM Vhub = Vr ± 2 m/s and Vout		U	N
6) Parked (standin-g still or idling)	6.1	EWM 50-year recurrence period		U	N
	6.2	EWM 50-year recurrence period	Loss of electrical network	U	A
	6.3	EWM 1-year recurrence period	Extreme yaw deviation	U	N
	6.4	NTM Vhub < 0,7 Vref		F	P
7) Parked & fault conditio-ns	7.1	EWM 1-year recurrence period		U	A
8) Transpo-rt, assembl-y, mainten-ance and repair	8.1	NTM Vmaint to be stated by the manufacturer		U	T
	8.2	EWM 1-year recurrence period		U	A

***

DLC Design load case
ECD Extreme coherent gust with direction change
EDC Extreme direction change
EOG Extreme operating gust
EWM Extreme wind speed model
EWS Extreme wind shear
NTM Normal turbulence model
ETM Extreme turbulence model
NWP Normal wind profile model
Vin Cut-in wind speed
Vout Cut-out wind speed
Vhub Hub height wind speed
Vref Reference wind speed
F Fatigue
U Ultimate strength
N Normal
A Abnormal
T Transport and erection
P Partial safety for fatigue



(a)

(b)

Fig. 3 (a) Special Star profile and (b) Standard L profile

Table 2 Tubular tower dimensions and weight

Segment	Height in m	Weight in ton
1	22	58
2	28	54
3	30	56
4	20	45
5	25	43
Total	130 m	256 ton

130 m height and approximately 260 ton weight including the flanges. The tubular steel tower consists of cylindrical and conical sections which are linked at the site using ring flange connections. The tubular steel tower consists of three cylindrical sections of 22 m, 28 m and 30 m length and two conical sections of lengths 20 m and 25 m.

The wall thickness varies between 14 mm and 44 mm along the height of the tower. The individual segments are connected to each other using full seam butt welding. The tower dimensions are listed in the following table.

4.2 Description of the finite element model

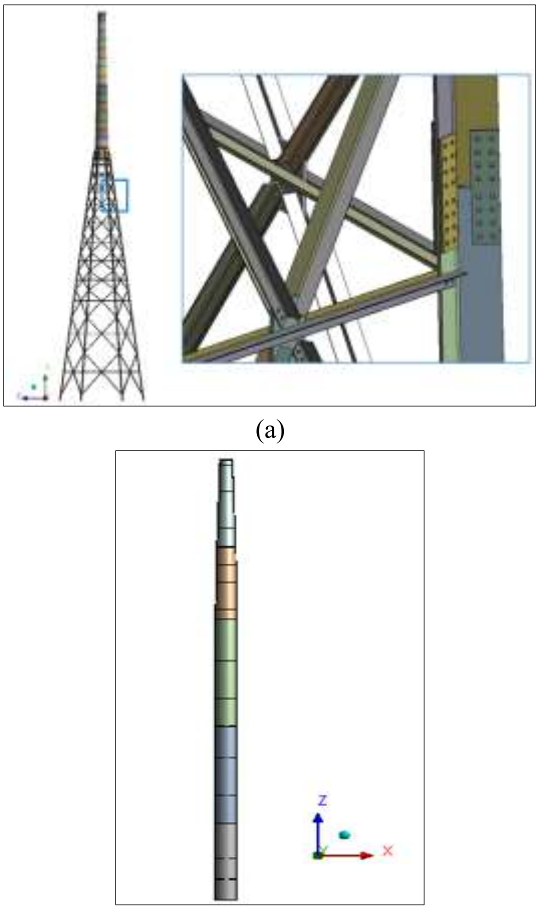
For FE analysis of the towers, the full finite element model has been developed. Due to the fact that wind turbine towers are generally thin-wall structures, they can be effectively and accurately modelled using shell elements.

The shell element is used to model structures where one dimension (thickness) is significantly smaller than other two dimensions.

Typically, if the thickness of the part is less than $1/10^{th}$ of the global structural dimensions, then the use of the shell element is acceptable. The element type used here is the shell element Shell181, which has eight nodes with six degrees of freedom at each node. Additionally, a regular quadrilateral mesh generation method is used to generate high quality element, ensuring the computational accuracy and saving on computational time. The number of nodes was 1200000 approximately with a mesh size of 60 mm.

For static analysis, the displacements, reaction forces and stresses of the tower structure under the static loads were calculated. Dynamic analysis, in our case, consists of a modal analysis, a set of undamped natural frequencies of the tower structures were calculated. The two analyses were performed using Ansys.

The flowchart of the design and analysis process is presented in Fig. 5.



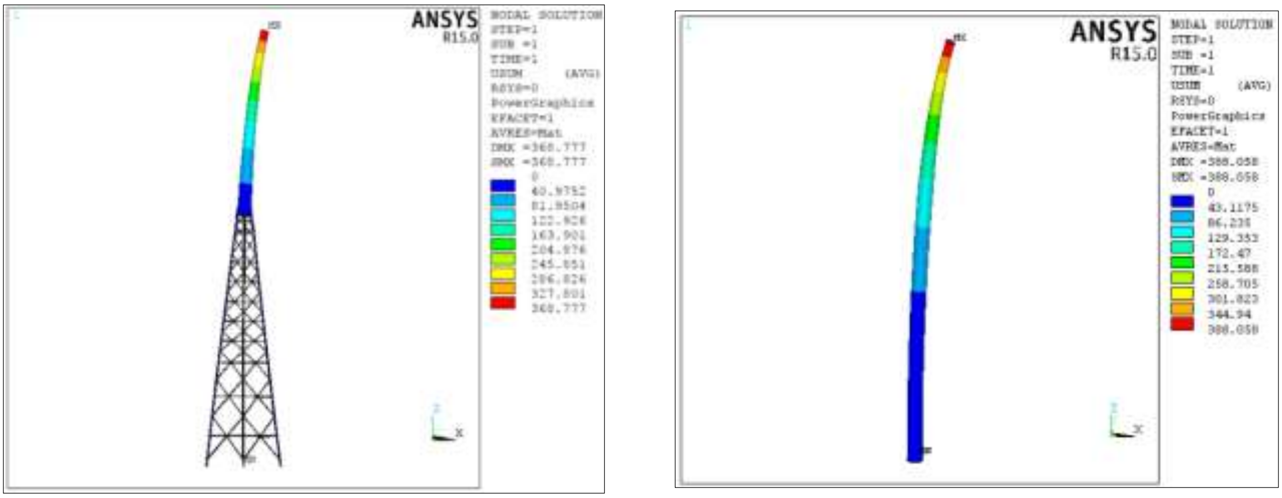
(a)

(b)

Fig. 4 (a) Lattice Hybrid tower and (b) Tubular tower

4.4 Tower loads and boundary condition

This section describes the assumed loading on the tower. The tower loading consists of loads from the wind and self weight of turbine. The loads and boundary conditions considered for the Static analysis of the towers are as given below: Tower top mass = 825 kN and Bending moment = 6590 kNm and all degree of freedom is fixed at the tower bottom. Having defined geometry, materials, element types, mesh and boundary conditions, the FE tower model is solved using Ansys 15.0. The simulation results, such as tower deformations and stress distributions, are then plotted using post-processing functions of ANSYS software.



(a) (b)

Fig. 6 (a) Total deformations of Lattice hybrid tower and (b) Total deformations of Tubular tower

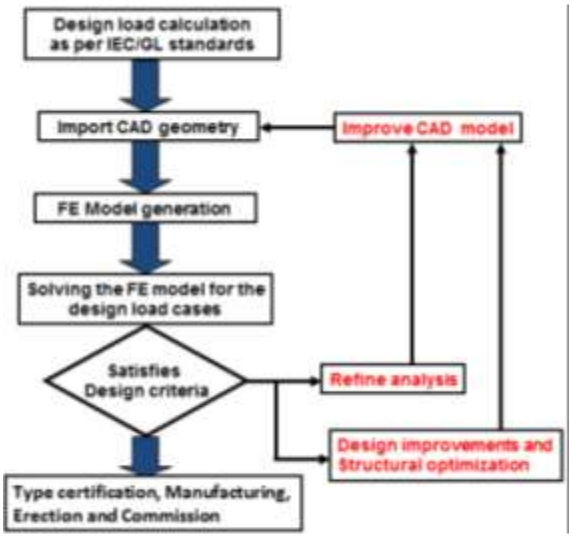


Fig. 5 Flowchart of tower design and analysis process

5. Results and discussion

5.1 Static analysis results

The 6590 kNm of maximum bending moment was determined to be the worst load case for the tower among others considered. The bending moment was applied in y-direction and tower top load applied along negative z-direction. The total deformation plots of both the tower types are presented in Figs. 6(a) and 6(b) respectively. The observed deflections in the Lattice hybrid tower is 366 mm, whereas Total deformation in Tubular tower is 368 mm observed at the tower top. This indicates that the Lattice hybrid tower is stiff when compared to Tubular tower deflection results.

The Vonmises stress plots of Lattice hybrid tower presented in Figs. 7(a) and 7(b). The vonmises stress plots of tubular tower are presented in Figs. 7(c) and 7(d). The max stress induced in the Lattice hybrid tower is 330 MPa, whereas in Tubular tower is 314 MPa observed at the nearer to tower top flange, which gives the factor of safety of 1.07 and 1.13 for Lattice hybrid and Tubular towers respectively on yield limit. This indicates that the stress is below the allowable limit for both models.

Table 3 Material properties of S355 steel

S355 Grade steel	
Young's modulus	2.1e5 N/mm^2
Poisson ratio	0.3
Density	7860 kg/m^3
Yield strength	355 MPa
Tensile strength	470 MPa

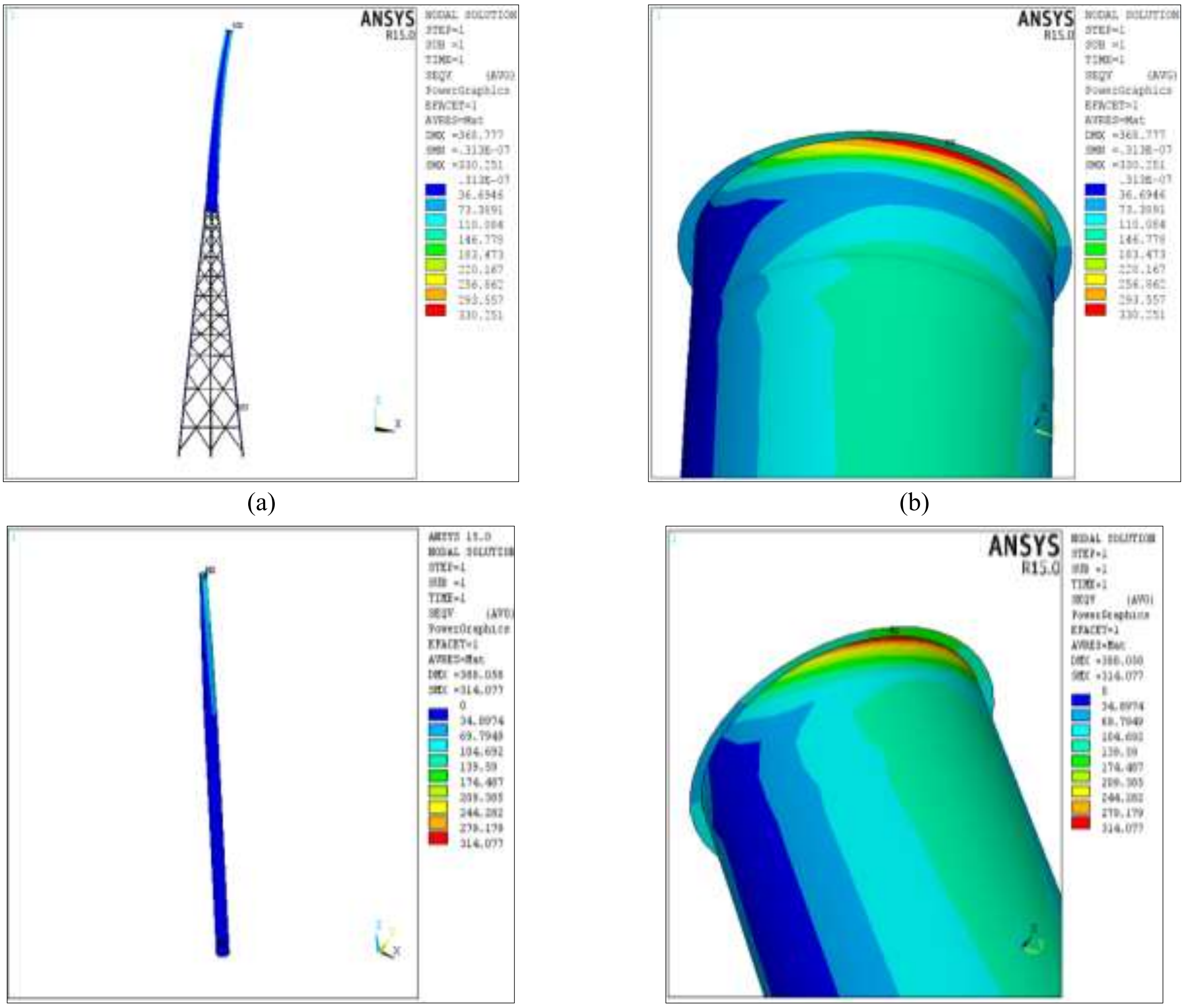
Table 4 Natural frequency of towers

Frequency	Lattice hybrid tower	Tubular tower	Percentage difference
1st bending	0.396 Hz	0.323 Hz	20.3%
2nd bending	2.012 Hz	1.909 Hz	5.3%

5.2 Dynamic analysis results

Dynamic analysis, in our case, consists of a modal analysis, a set of undamped natural frequencies of the tower structures were calculated. The modal analysis is used to calculate the natural frequencies and mode shapes of the tower. In this case, the tower is fixed at the tower bottom and free-vibration (no loads on the tower).

Table 4 presents the comparative results between the two towers provided by the FE modal analysis. With these results we can see that the lattice hybrid tower is stiffer than the tubular tower. Since natural frequency directly proportional to stiffness and inversely proportional to mass will result in a decrease in natural frequency. The natural frequency of lattice tower is higher than 3P frequency of the turbine blade rotation. This is checked during the load calculations in Bladed software through a campbell diagram



(a) (b) (c) (d)

Fig. 7 (a) Von-Mises stress of Lattice hybrid tower (b) Von-Mises stress of Lattice hybrid tower (Zoom), (c) Von-Mises stress of Tubular tower and (d) Von-Mises stress of Tubular tower (Zoom)

study.

6. Conclusions

This work aimed to compare the Lattice hybrid tower with Tubular steel tower. This assessment was carried out through the static and dynamic analysis using finite element method.

The linear static and dynamic analyses were studied for lattice and tubular towers. This work is divided into two phases. In a first step linear static analysis of the tower was performed. The next step is the dynamic analysis such as the modal frequency of the system. In both phases of this work, lattice tower was compared with the tubular tower. The results of the static and dynamic responses of wind towers model were presented in terms of displacement and maximum stresses acting on the towers. For the two research fronts for validation of towers, the first was to validate the structure of the tower; this was done with static analysis. The second was to validate the performance of this tower as its dynamic response of the towers.

For the given loading conditions, the Stress in the both Tubular tower and lattice hybrid tower is below the allowable limit of 355 MPa. From the results it is evident that the lattice tubular tower is stiff enough to withstand the wind load and tower top load when compared to the same height of Tubular tower. The advantages of this Lattice hybrid tower with special star profile over the existing tubular tower is we can save 72 tons in a single tower and savings in tower weight is 32.7% and Lattice hybrid tower is easy to transport and assembly.

References

Alvarez-Anton, L., Koob, M., Diaz, J. and Minnert, J. (2016), "Optimization of a hybrid tower for onshore wind turbines by building information modeling and prefabrication techniques", SpringerOpen Visualization in Engineering, 4.3.

Bazeos, N., Hatzigeorgiou, G.D., Hondros, I.D., Karabalis, D.L. and Beskos, D.E. (2002), "Static, seismic and stability analysis of a prototype wind turbine steel tower", *Eng. Struct.*, **24**(8), 1015-1025. https://doi.org/10.1016/S0141-0296(02)00021-4.

Cook, R.D. (1995), *Finite Element Modeling for Stress Analysis,*

John Wiley and Sons Inc., New Jersey, USA.
Das, A. and Kumar, S. (2015), "Modelling and analysis of lattice towers for wind turbines", *Int. J. Sci. Res*., **4**(5), 999-1003.
DIN EN (1993), Design of Steel Structures - Part 1-6: Strength and Stability of Shell Structures.
Euro code 1: EN 1991-1-4 (2005), General Actions - Wind Actions, European Commission for Standardisation.
Euro code 3: EN 1998-1-8 (2005), Design of Joints, European Commission for Standardisation.
Gencturk, B., Attar, A. and Lort, C. (2015), "Selection of an optimal lattice wind turbine tower for a seismic region based on the cost of energy", *KSCE J. Civil Eng*., **19**(7), 2179-2190.
GL Guidelines (2010), *Guideline for the Certification of Wind Turbines*, Germanischer Lloyd Wind Energy GmbH, Germany.
Guidelines for Design of Wind turbines (2002), DNV/Riso, Denmark.
Hau, E. (2006), Wind Turbines: Fundamentals Technologies and Application, Springer-Verlag, Germany.
IEC 61400-01, Ed.3 - Part 1 (2005), Wind Turbine Generator System - Design Requirements. International Electrotechnical Commission, Geneva, Switzerland.
Jovasevic, S., Mohammad, R.S.M., Rebelo, C., Pavlovic, M. and Veljkovic, M. (2017), "New lattice tubular tower for onshore WEC", *Sci. Direct Proc. Eng.*, **199**, 3236-3241.
Lavassas, I., Nikolaidis, G., Zervas, P., Efthimiou, E., Doudoumis, I.N. and Baniotopoulos, C.C. (2003), "Analysis and design of a prototype of a steel 1-MW wind turbine tower", *Eng. Struct*., **25**(8), 1097-1106. https://doi.org/10.1016/S0141-0296(03)00059-2.
Muskulus, M. (2012), "The Full-height lattice tower concept", *Energy Proc*., **24**, 371-377. https://doi.org/10.1016/j.egypro.2012.06.120.
Negm, H.M. and Maalawi, K.Y. (2000), "Structural design optimization of wind turbine towers", *Comput. Struct*., **74**, 649-666.
Uys, P.E., Farkas, J., Jarmai, K. and Van Tonder, F. (2007), "Optimization of a steel tower for a wind turbine structure", *Eng. Struct*., **29**(7), 1337-1342. https://doi.org/10.1016/j.engstruct.2006.08.011.
Voss, S. (2011), *Adapter Configuration for a Wind Tower Lattice Structure, Inventor: Stefan Voss*, US Patent document no. US20120023860A1.
Zou, L., Liang, S., Li, Q.S., Zhao, L. and Ge, Y. (2008), "Investigation of 3D dyamic wind loads on lattice towers", *Wind Struct*., *Int. J.,* **11**(4), 323-340. https://doi.org/10.12989/was.2008.11.4.323.

CC