Preliminary Design of 1.5-MW Modular Wind Turbine Tower

Chawin Chantharasenawong*, Pattaramon Jongpradist and Sasaraj Laoharatchapruek

Department of Mechanical Engineering, King Mongkut's University of Technology Thonburi, Bangkok, Thailand 10140

*Corresponding Author: E-mail: chawin.cha@kmutt.ac.th, Tel: +66 24709123, Fax: +66 24709111

Abstract

This research aims to obtain a novel modular wind turbine tower design for a 1.5-MW wind turbine to be installed in Thailand. The tower is designed for an IEC Class III wind turbine corresponding to low speed wind region. The new design is economically superior to existing models due to its more flexible transportation options. The feasibility of manufacturing and the availability of materials in the country are considered. The steel structure is 76.9 m high and has a tapered tubular shape with variable wall thicknesses along its height. The tower consists of six longitudinal sections which are further divided into several curved panels. Finite element method simulations are used to conduct stress analyses and to optimise the tower geometry. Linear elastic analysis is performed in all FE models. The structures are analysed for static loads representing the effects of gravity, the operational and survival aerodynamic conditions according to IEC 61400-1 and Eurocode 1. Design constraints on shell buckling and local buckling of the tower are taken into account conforming to Euler and Brazier theory. It has been found that the optimised modular tower with 5.59 meter base diameter and the shell thickness ranging from 8 mm at the base to 16 mm at the top enables the tower to be built with less steel, lowering raw material costs significantly. Increased base diameter allows for thinner tower wall thicknesses, not only resulting in a tower mass reduction of up to 24% but also improvement in structural stabilities with 12% higher tower natural frequencies and 13% lower maximum tip deflection. The result indicates that this modular wind turbine tower design has potential to be economically attractive and the manufacturing is also technically feasible. However, further work to investigate the effects of tower connections should also be conducted.

Keywords*:* Wind turbine tower, Modular tower, Finite element analysis, Structural optimisation.

1. Introduction

Wind power is a clean energy source that can be relied in for the long-term future. The average wind speed in Thailand ranges from low to moderate, generally lower than 3 meters per second in most regions [1]. However, according to the report on the wind resource assessment of Thailand by the Department of Energy Development and Promotion (DEDP) in 2001 [2], there are some areas where there is high wind potential for practical electricity power generation, mainly along the southern coastlines in particular to the south of Nakhon Sri Thammarat Province with an annual wind speed of 6.4 m/s at 50 meters height. The Electricity Generating Authority of Thailand (EGAT) has several wind turbine power plants for power generation such as at Lam Takhong and at Promthep alternative energy station. Recently EGAT set a target of wind power generating capacity of 128.5 MW by 2022 and the target of purchase capacity from small power producers (SPPs) upto 1,192 MW by 2030 [3]. This commitment indicates an opportunity for wind turbine parts manufacturing in Thailand. As stated in the IEC standards [4], the IEC class III turbine is suited for Thailand because of its low wind speed requirement. The rotor diameter for IEC class III turbine must be larger to capture the lower energy winds in comparison with higher IEC wind classes (Class I and Class II) at the same rated power. The tower weight for an IEC class III turbine will also feature a height increase because the rotor must take advantage of the high wind speed at higher altitude. Therefore, the hub height of the turbine is one of the most significant factors in terms of power production. The wind power P is directly proportional to the cube of the wind speed [5] and is given by

$$P = \frac{1}{2} C_P \rho A V^3 \qquad \text{Eq. (1)}$$

where C_P is the power coefficient, ρ is the air density, A is the rotor swept area, and V is the wind speed.

Current tapered free-standing steel tubular towers for megawatt class wind turbines are limited in height due to transport restrictions. Typically, the tower base diameter is limited to about 4.3 m [6] and Thai laws restrict the height of transported cargo to be under 4.2 m from the road surface [7]. Hence, oversized load transportation permits and fees, longer routes to avoid overheight and lane restrictions, or specialized trailers are required. The transportation, height and base diameter issues can be solved with a novel modular wind turbine tower concept.

Fig. 1 Modular wind turbine tower [8]

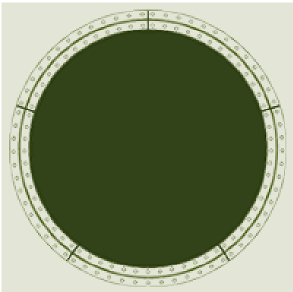

Fig. 2 Northstar modular tower cross section [8]

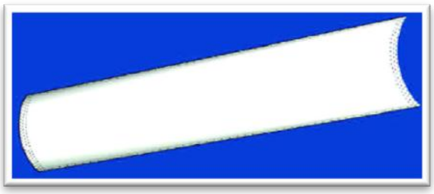

Fig. 3 Modular curved panel [8]

Fig. 4 Transportation of tower components [8]

(a) novel modular tower

(b) conventional tubular tower

The modular tower is similar in appearance to the conventional steel tubular tower as shown in Fig. 1, however it consists of longitudinal sections and each of which is divided into several curved panels as shown in Fig. 2 and Fig. 3. Presently, modular wind turbine towers are commercially available, for example by Northstar Wind Tower. The design reduces the raw material (steel) by 20% to 30%. Fig. 4 (a) shows that the multi-panel sections are stackable which allow all tower sections to be transported easily on standard road legal flat bed trailers and transportation costs can be 50% to 75% lower than that of the conventional tubular tower depending on distance and route, see Fig. 4 (b) [8].

This paper presents a preliminary design of the novel modular tower for 1.5-MW onshore wind turbine to be installed in Thailand. European Standard high strength structural steel grade S355J2 with yield stress of 355 MPa is used for all structures in this work. However, Thai Industrial Standard steel grade SS540, SM490YA and SM490YB, with minimum yield stress of 355 MPa, are available in the country and can also be used. Currently, local manufacturing capability to form a conical section of wind turbine tower in thickness up to 46 mm.

2. Methodology

2.1 Basic assumptions

The basic assumptions employed in the tower design are as follows:

1) The structural model of the tower is cantilevered to the ground, and is carrying a concentrated mass at its free end approximating the inertia properties of the nacelle and rotor unit. This mass is assumed to be rigidly attached to the tower top.

2) Tower material is linearly elastic, isotropic and homogeneous. The tower has a thin-walled circular cross section.

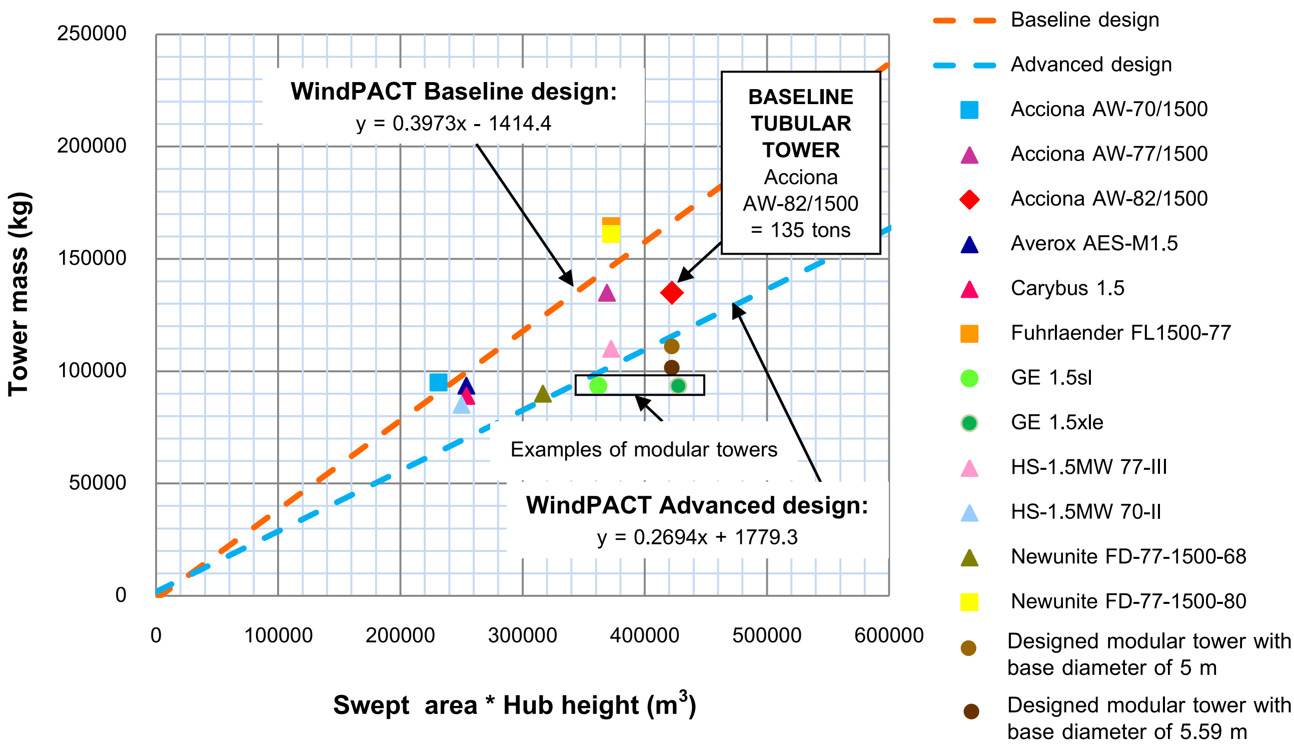

Fig. 5 Tower mass scaling relationship [9]

3) The Euler-Bernoulli beam theory is used for predicting deflections and verify the FE models. Secondary effects such as axial and shear deformations, and rotary inertia are neglected.

4) Distributed aerodynamic loads are caused by drag forces only.

5) Under any load combination (including any load safety factors), the material of the load bearing structural elements of the tower should remain in the linear elastic region of its stress-strain diagram i.e. no plastic deformation has occurred.

2.2 Description of structure

This paper is focused on the study of increased tower base diameter effects on its wall thickness and tower mass. The comparison is based on the tower base diameter, in which the modular type has to be used. The limitation on construction of a larger tower base diameter is local buckling criterion which becomes dominant when the tower diameter increases. Note that considerations on the effects of welding and connections for modular tower are beyond the scope of this research.

To design and analyse the modular tower, it is important to first set a baseline tower model for comparison. The initial WindPACT [9] scaling relationship studies provide a crude estimate of tower mass. All towers considered herein are either steel tubular or steel modular towers. The tower mass is scaled with the product of the swept area and hub height, the baseline design scaling relationship represents most current commercial turbines while the advanced design scaling relationship is achievable through technology innovation such as flap-twist coupling in the blade and reduced blade solidity in conjunction with higher tip speeds. Commercial turbines are compared with these WindPACT scaling relationships as shown in Fig. 5. In this study, Acciona AW-82/1500 [10] is selected as the baseline wind turbine because of its IEC class III classification with rated capacity of 1.5 MW which is the wind turbine specification this research is focuing on. Moreover, the mass of this tubular tower lies in the middle of two WindPACT design trend lines i.e. neither the design is too conservative nor much lower than what is commercially available today, suitable for use as the baseline. This steel tower has a height of 76.90 m and is formed as a truncated cone with an external diameter of 4.30 m at the base D_b and 2.60 m at the top D_t. The shell thickness of the steel tower ranges from 25 mm at the base t_b to 15 mm at the top t_t. The tower mass is 135 tons and other characteristics as taken from Acciona technical specification are given in table 1. The operating and component data are also applied in the current study. However, two green circle marks in Fig. 5 show the tower masses of two GE's modular towers which are below the trend line of the advanced design. This indicates that the modular tower concept enables the lower tower mass.

2.3 Load calculations

Two sets of static loads are considered:

(a) Self weight of the tower components, consists of a concentrated load at the top of the tower representing the rotor and nacelle self-weight W_r of 832 kN and the distributed weight of the tower along its height where the density of steel is 7,850 kg/m^3.

Table. 1 Technical data of Acciona AW-82/1500

Rated capacity (MW)	1.5
Wind class	IEC IIIb
Rotor diameter (m)	82
Swept area (m^2)	5,289
Hub height (m)	80
Operating data	
- Rated wind speed (m/s) - Average wind speed (m/s) - Cut-in wind speed (m/s) - Cut-out wind speed (m/s) - Survival wind speed (m/s)	10.5 7.5 3.0 20 52.5
Component data	
Blades - Material - Blade length (m) - Aerodynamic brake	 GFRP 40.3 Full feathering
Tower - Material - Tower height (m)	 S355J2G3 76.9
Nacelle - Height of nacelle and hub (m)	 4
Mass - Blade (t/blade) - Rotor (t) - Nacelle (t) - Tower (t)	 5.78 32.34 52.50 135.00

(b) Steady tower loads arise primarily from the rotor axial thrust on the rotor and a torque in the direction of rotor rotation. The loading on the tower is evaluated under two conditions: at rated power operation and stationary at survival wind speed. Extreme load condition, considered as an ultimate load case when designing the wind turbine tower, is at the cut-out wind speed of 20 m/s which is a typical value for a class III wind turbine. It is the highest wind speed at hub height under operation at rated power, therefore the turbine is operating with high rotor thrust, which is the dominant load on tower bending and overturning moment.

The thrust force on the rotor T can be calculated from the relation [10]

$$T = \left(\frac{1}{2}\rho V^2\right) C_T (\pi R^2) \qquad \text{Eq. (2)}$$

where ρ is 1.164 kg/m^3, V is the cut-out wind speed, C_T is the trust coefficient and R is the rotor radius.

The maximum rotor thrust of GE 1.5 MW sle (IEC class II, rotor diameter of 77 m, cut-out wind speed of 25 m/s) has been suggested as 508 kN [11]. For the baseline wind turbine AW-82/1500, the value of T = 369 kN is obtained according to Eq. (2) by using the same thrust coefficient. The wind loads acting on the tower are calculated conforming to the IEC 61400-1 [12] and the Eurocode 1 Part 1-4 [13].

The wind velocity is varied along the tower height. The wind profile power law relationship [12] is defined as

$$V(z) = V_{hub} \cdot \left(\frac{z}{z_{hub}}\right)^{\alpha} \qquad \text{Eq. (3)}$$

where $V(z)$ is the wind velocity at height z, V_{hub} is the wind velocity at hub height, z is the height above ground, z_{hub} is the hub height and the power law exponent α is 0.2.

The uniformly distributed wind load along the tower height F_d per unit length is directly proportional to the square of wind velocity at height z, $V(z)$, as

$$F_d = \frac{1}{2}\rho\, V(z)^2 C_d\, D(z) \qquad \text{Eq. (4)}$$

where C_d is the drag coefficient for circular cross section related to Reynolds number [13] and $D(z)$ is the external diameter at height z as the tower is tapered.

3 Finite element analysis

3.1 Finite element model

The static and stability analyses are performed by using three-dimensional (3D) finite element models created with Finite Element Analysis (FEA) program ABAQUS. The dimensions of the model are the same as the baseline tower for primary analysis. Fig. 6 shows the tapered cylindrical tower geometry including the diameter, the thickness, and the overall length of the tower.

The FE model comprises of three parts: the first part is the tower structure meshed by shear deformable shell elements, the second part is a rigid plate attached to the tower top for applying the top head mass and the last part is a rigid wire for defining the rotor thrust at the hub height, see Fig.7.

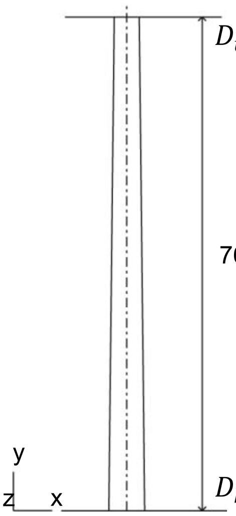

Fig. 6 Dimensions of baseline tower

Fixed boundary conditions are assumed at the lower end of the tower for all analyses. Quadrilateral shell elements (4-node element) are used for the tower wall. High strength structural steel grade S355 with yield stress of 355 MPa is used for all structures.

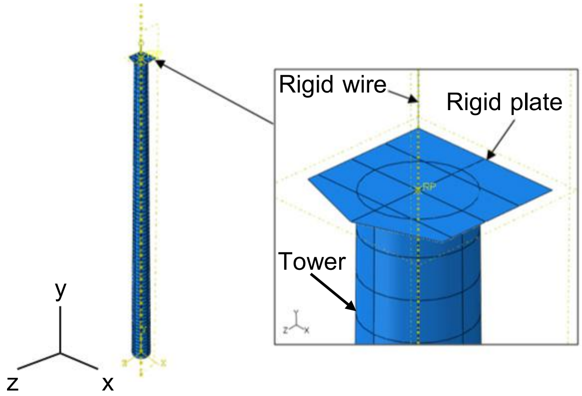

Fig. 7 FE model components

3.2 Analysis of the steel tower responses

3.2.1 Natural frequency analysis

The fundamental natural frequency of the tower with the concentrated mass of the nacelle and rotor mass at the top, should be designed as the criterion of a *soft tower*. The tower natural frequency must be above the rotational frequency and below the blade-passing frequency. Moreover, the turbine's excitation frequencies (the rotational frequency or the blade-passing frequency) should generally not be within 5% of tower natural frequency during prolonged operation [5].

3.2.2 Buckling analysis

The axially compressed cylindrical shell with end clamped can fail either by global buckling, or by local buckling, or by the yielding of the material of the shell. Therefore, the ratio of radius to thickness (R/t), determines the instability mode of the cylindrical shell and should be checked in conjunction with the local buckling strength according to the Brazier's theory [15]. The value of critical local buckling stress σ_{cr} of all tower sections must be higher than the yield stress of the tower material to prevent the occurrence of local buckling in the elastic region.

$$\sigma_{cr} = 0.33\, E\, \frac{t}{R} \qquad \text{Eq. (5)}$$

where E is the modulus of elasticity.

3.2.3 Static analysis

Aerodynamic and gravity loads are considered in static analysis. Considering at the cut-out wind speed of 20 m/s, the rotor thrust of 369 kN is applied as the concentrated load at the elevation of the hub height and the uniformly distributed drag forces are applied along the tower height in the direction of the wind. The top head weight of 832 kN is assumed to be concentrically loaded at the top of tower. The self-weight of tower is also included in the analysis as shown in Fig. 8.

The values of maximum Von Mises stress and the maximum horizontal deflection of the FE structural models are checked against the recommendations of industry standard design codes, i.e. IEC 61400-1 and Eurocode 1.

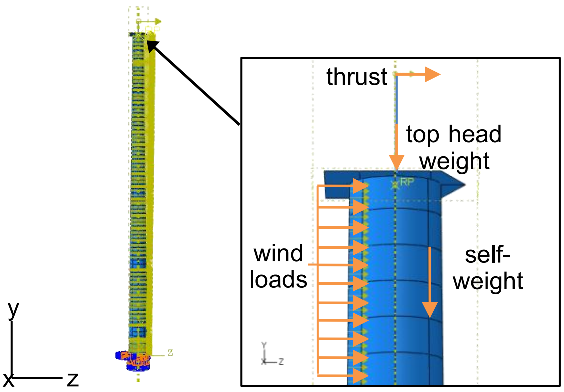

Fig. 8 Loads on FE model

3.3 Model validation

Simplified FE models have been investigated and comparison with exact solutions are made for validation purpose. The 76.9 m high tower with an external diameter of 4.3 m and constant thickness of 15 mm with 4-node shell elements has been considered. For this simple case, the tower can be approximated as a uniform cantilever with a point mass at the top and the tower natural frequency f_n can be determined by Baumeister's equation [5].

$$f_n = \frac{1}{2\pi}\sqrt{\frac{3EI}{(0.23m_{tower}+m_{rotor})L^3}} \qquad \text{Eq. (6)}$$

where I is the moment of inertia of tower cross-section, m_{tower} is the tower mass, L is the height of tower and m_{rotor} is the nacelle and rotor mass.

The tower natural frequencies of the simplified models are compared to that of the FE models, the error is under 3%.

For the accuracy of the FE buckling analyse, a comparison is made with the Euler's buckling formula specified in Ref. [14]. The critical buckling load P_{cr} of the cylindrical model is given by

$$P_{cr} = \frac{\pi^2 EI}{{L_e}^2} \qquad \text{Eq. (7)}$$

where L_e is the effective length.

The relative difference between the results of the critical buckling loads is 0.25%. Hence, these results have shown that the FE model and computation can provide sufficiently accurate results.

Furthermore, the compressive stresses of the FE tower model are formulated by the static stress analysis and observed to be in close agreement with the analytical results.

Hence, these agreements verify the accuracy of the FE model used in this work and the FE model will be used in the subsequent structural analysis with confidence.

4 Results and discussion

Finite element simulations performed in this work are validated as described in section 3.3 and then used to develop the preliminary design of the modular wind turbine tower. The FE model of the baseline tower has the height of 76.90 m with an external base diameter of 4.30 m and 2.60 m at the top. Since the characteristics of modular tower removes the maximum base diameter restriction, this work will investigate the effects of increased base diameter on its wall thickness and tower mass. A parametric study is carried out for three different towers with clamped end. The fixed parameters of the analyses are tower height, hub height, top diameter, material, safety factor and all applied loads. Three FE models with different base diameters of 4.30, 5.00, and 5.59 m are analysed as the bottom sections of which can be properly divided into 6 and 7 panels respectively with the width limit of standard trailers. Applying a trial-and-error approach in static stress analysis, the shell thicknesses of two developed tower models can be obtained after several iterations. While the optimisation criteria are that the value of maximum Von Mises stress is equal to that of the baseline model and R/t ratio of any sections through the tower height must be assessed to satisfy local buckling condition. Subsequently, the fundamental natural frequency analysis and the eigenvalue buckling analysis of all FE models are performed.

Table. 2 Comparison of the results for the baseline and modular towers.

Parameters	Tower 1 Baseline	Tower 2 D_b = 5 m	Tower 3 D_b = 5.59 m
Base diameter (m)	4.30	5.00 (+16.28%)*	5.59 (+30%)
Taper ratio	0.022	0.031	0.039
Wall thickness range (mm) Radius / tower thickness ratio	15-25 85.5	8-19 115.3-177.9	8-16 137.2-185.76
Tower mass (t)	135.02	109.56 (-18.85%)	102.47 (-24.11%)
Safety factor against bending	3.67	3.67	3.69
Safety factor against local buckling	7.98	3.83	3.70
Maximum deflection (m)	0.648 L/119	0.616 (-4.91%) L/125	0.560 (-13.39%) L/137
Tower frequency (Hz)	0.387	0.413 (+6.72%)	0.434 (+12.17%)

*Note that the percentages shown in Table. 2 are obtained by comparing the values of modular towers to the baseline values.

Table. 2 shows comparison of the results for towers with three different base diameters and wall thicknesses. All cases have a maximum Von Mises stress of 96 MPa and the safety factor against failure in bending of 3.67. The increase in base diameter of 4.30 m to 5.00 and 5.59 m allows shell thickness reduction from the range of 15-25 mm to 8-19 mm and 8-16 mm, respectively. The total tower masses are 19% and 24% lower compared to the baseline tower mass, respectively. The characteristics of these new towers are plotted in Fig. 5 and they lie below the trend line of WindPACT advanced. It suggests that these towers feature favourable strength to weight ratios. The tower mass is computed by ABAQUS

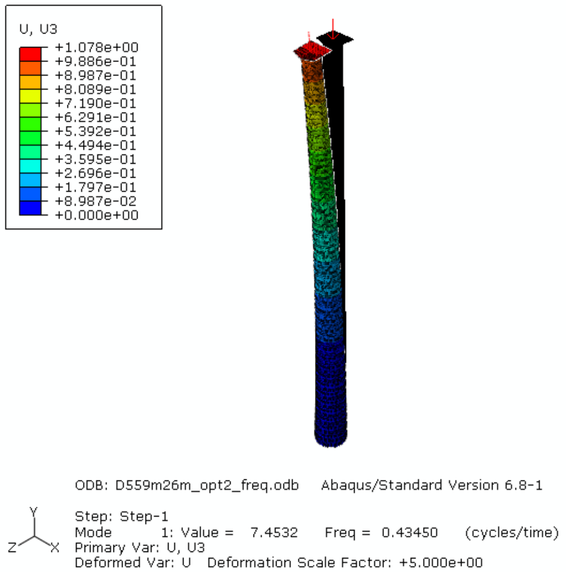

Fig. 9 The first eigenmode of the modular tower

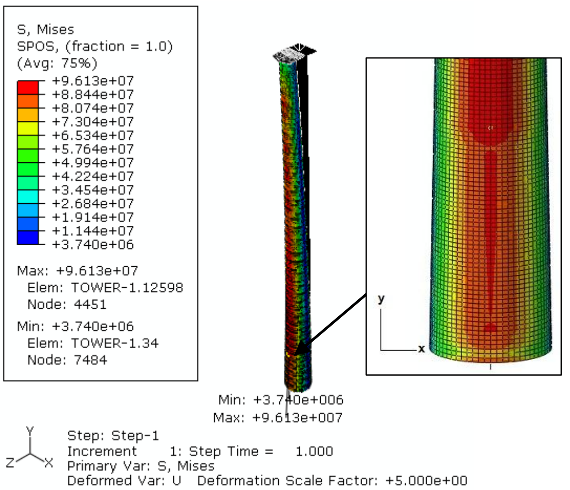

Fig. 10 Static stress analysis and Von Mises stress distribution

based on the geometry and the steel density of 7850 kg/m^3.

Increasing in base diameter, not only results in lower tower mass but also improves the structural stability with higher tower natural frequencies and lower maximum tip deflection. The natural frequency of the tower with base diameter of 5.59 m increases 12% which means the tower is more stiff whereas the mass decreases. In addition, the maximum horizontal displacement at the top of the two modular tower models are reduced by 4.91% and 13.39%. Fig. 9 and Fig. 10 show the representative FE analysis results of the 5.59-m base diameter modular tower.

However, tower designers should be aware of the limitation in reduction of shell thickness and tower mass since the local buckling becomes a dominant criterion instead of the maximum stress when the tower diameter increases.

5 Conclusion

As the modular tower design allows for thinner tower wall thickness, results in significant lower tower mass and material cost. All modular tower components can be transported using standard trailers, hence significantly lowering transportation cost. Obviously, the modular wind turbine tower is superior to conventional steel tubular tower for supporting megawatt class wind turbines. Further work involving more in-depth modular tower manufacturing costs, effects of tower connections, installation and maintenance costs will be required to assess the modular tower economic viability.

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