Numerical Analysis and Design of Small Wind Turbine Tower

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Abstract

In this paper, a proposed design methodology for the on-shore small wind turbine (SWT) tower is intensively studied and presented. The finite element analysis technique is used to analyze the static and dynamic structural responses in terms of the stress distribution, deflection, stability, and modal analysis of the tower structure. The design concept of such a tubular monopole tower design is based on the international electrotechnical commission code, namely IEC 61400-2, which is commonly used as a practical guideline for small wind turbine requirement and design load computation. The tubular steel tower formed as a truncated cone shape is designed in three portions where the individual section length is 10 m. Hub height of the tower is 30 m above the tower base. It was found from the strength analysis and design process that the base and the top diameter of the tower were 1.30 and 0.80 m, respectively for the optimal configuration of the involved SWT tower.

Keywords: Wind turbine tower, Finite element analysis, Tower design

1.Introduction

Currently, the provincial electricity authority of Thailand (PEA) has begun a new effort to develop the wind technology that will allow wind system to complete in regions of low wind speed. According to this sustainable energy resource policy, the contribution of this paper is to setup a design methodology for a prototype of small wind turbine steel tower with the hub height of 30 meters. The design approach of the self-supporting tubular steel tower is based on an international code of practice, namely the IEC-61400-2 [1] for the small wind turbine structure.

A tower is the main structure that supports the nacelle, the transmission system, the generator and the electronic control system and moreover the elevation of the rotating blades above the ground boundary layer. A successful tower structural design should ensure the safety, the operating efficiency and the reasonable cost of structural member fabrication.

Lavassas et al. [2] presents the design features of a large 44-m-tall monopole tower mounted with 1-MW wind turbine. In this paper, conical tubular steel tower with the base diameter of 3.30 m and the top diameter of 2.10 m is subjected to the across-wind condition with reference wind speed of 36 m/s. The wall thickness decreasing with the height which is 18 mm at the base and 13 mm at the upper portion of the tower. The Stress distributions and local buckling in the structure are investigated.

Lanier [3] conducted a feasibility study for the national renewable energy laboratory of the United States on different design approaches along with the total cost estimation in fabricating and erecting the 100 m-monopole wind turbine towers made of entire steel, concrete, and also hybrid concrete/steel structural system. However for the design of SWT structure, it is only IEC-61400-2 document provides detailed design concept covering the load calculation and structural testing method. A design methodology according to this guideline is established for the structural strength assessment in this study as follows.

2.Specification and Applied Loads

2.1 Structural design criteria and loads

Site survey and geographical data for the mean annual wind speed, the extreme wind speed in a recurrence period, the direction of seasonal wind, are monitored and recorded as basic design parameters. It is also revealed in the feasibility study on the wind energy potential conducted by the department of alternative energy development and efficiency (DEDE) of the ministry of energy for constructing a global wind map of Thailand [4] that annual mean wind speed for the on-shore region locating far away from the coastline is relatively low except some particular mountainous regions where the wind power potential is effectively profitable and competitive, e.g. KhaoKho in Petchabun province for a promising wind energy supply of 60-MW capacity produced by this wind farm.

Design requirement of the turbine incorporated with the site meteorological data is given in Table. 1.

Table. 1 Design platform specification

Data for the tower design		Unit
-Height of the tower	=30.00	m
-Proj. area of the blades	=1.95	m^2
-Mean wind speed [4]	< 5.0	m/s
@ 90 m above the ground		
-Maximum local wind speed	=120	$km.hr^{-1}$
-Tower head weight	=400	kg.
-Design rotor speed	=102	rpm

Table. 2 Simplified aerodynamic load calculation for the case of the extreme wind speed according to the IEC-61400-2

Design load case		Unit
H-Parked wind loading	$F_{x,shaft}$= 5256	N
Tower exposure to V_{e50}	F_{W1}=18678	N
	F_{W2}=17972	N
	F_{W3}=12654	N

Note: Wind loads acting on entire tower structure is calculated only for the case H-the survival wind speed condition

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Wind loads on the tower structure can be calculated by using the equations given in the appendix F of the IEC standard [1].

2.2 Load factors and load combination for ultimate design wind Load

Simplified load calculation is shown only for the extreme case and presented in Table.2. The ultimate load on the structure is the case H – the survival wind speed which is taken into account for the case of the structure experiencing the extreme local storm in once per 50-year period, namely V_{e50}. Partial safety factor for the wind turbine load is given from the IEC [1]. Since the tower is considered as a chimney structure subjected to lateral wind pressure from the point of view of the civil engineering design aspect. Partial safety factors for direct wind load on the tower and the dead load are chosen from the section 2.3 in the ASCE 7-02 [5]. Two ultimate design load conditions can be given as follows:

-Service or characteristic wind load condition (Extreme operating load EOG_{50} or EWM_{50}):

$$Load_{total} = DL + WL + WTL \quad (1)$$

-Factored load combination for extreme load (EWM_{50}):

$$Load_{total} = \gamma_{DL} DL + \gamma_{WL} WL + \gamma_F WTL \quad (2)$$

where

DL is the dead load (N)
WL is the direct wind load on the tower (N)
WTL is the wind-induced turbine load (N)
γ_{DL} is the dead load factorgiven in [5]
γ_{WL} is the tower wind load factor reported in [5]
γ_F is the partial load factor for the turbine given in [1]
EWM_{50} is the extreme wind speed model in once per 50-year extreme (m/s)
EOG_{50} is the operating gust in once per50-year extreme (m/s)

2.3 Mechanical properties of tower material

Commercial structural steel JIS grade SS400 is used for fabricating the tubular steel structure. Mechanical properties of this steel are given in Table. 3.

Table. 3 Mechanical properties of material

Properties of materials		Unit
Structural steel-JIS grade 3101 - SS400 properties		
-Yield strength of steel	=248	MPa
-Specific weight of steel	=7,850	$kg.m^{-3}$
-Modulus of elasticity	=200	GPa
-Poisson ratio	=0.3	-

3. Methodology of Finite Element Analysis

3.1 Model construction and mesh topology

Mesh topology for the model is the shell element type defined for the tower wall and the solid element type employed for the opening frame of the tower. Total number of elements in the model is 22,773 elements which yield the stability of the computational result in terms of the tower deflection, and stress.

3.2 Boundary conditions

Since the fixation of the tower structure to the concrete foundation is in a similar manner to a cantilever beam. Constrained conditions are applied for the nodal displacements at the base of the tower corresponding to the bolting system attaching the structure to the foundation. Therefore, the nodal displacements in *x*, *y*, and *z* directions on the lower surface of the tower are fixed.

3.3 Material behavior model

Stress-strain relationship describing the elastic behavior of the isotropic material, e.g. steel, can be written as

$$\sigma_{ij} = \frac{E}{1+\nu}\left\{\varepsilon_{ij} + \frac{\nu}{1-2\nu}\varepsilon_{kk}\delta_{ij}\right\} \quad (3)$$

where

σ_{ij} is the stress tensor (Pa)
E is the Young's modulus (Pa)
ν is the poisson ratio
ε_{ij}, ε_{kk} are the strain tensor
δ_{ij} is the Kronecker delta

4. Results and Discussion

Typical results of structural, modal, and stability analyses for the service load combination as well as the extreme wind load are shown in Fig. 1 and 2, respectively. It is disclosed from Fig. 1a and 2a that local safety factor for the extreme service condition case is 4.2 and for the structure under the unfavorable extreme load case is 2.3. Maximum magnitude of axial stress of both cases is relatively insignificant. Maximum stress can be found on the wall of the lower portion near the tower base as depicted in Fig. 1b and 2b.

For the design of a vertical structure against the wind, the maximum tip displacement, namely sway at free end, should be maintained as minimum value as possible. The structural analysis yields the tip deflection of 101.7 mm as shown in Fig. 1c which is less than maximum permissible sway value calculated by the height per 180. Local deflection varying non-linearly with the height of the tower can be visible in the Fig. 3a.

To avoid the structural failure due to extreme operating gust, the sway and the stability of the tower must be verified for their combined effect to ensure that this situation cannot cause the failure to the tower structure. Strength analysis by employing the static structural incorporated with the stability analysis is conducted for this task. It is disclosed that there is no local elastic buckling appearance in this case as shown in Fig. 1e and 2e. The weight of tower head and structure cannot cause the structural failure due to local buckling.

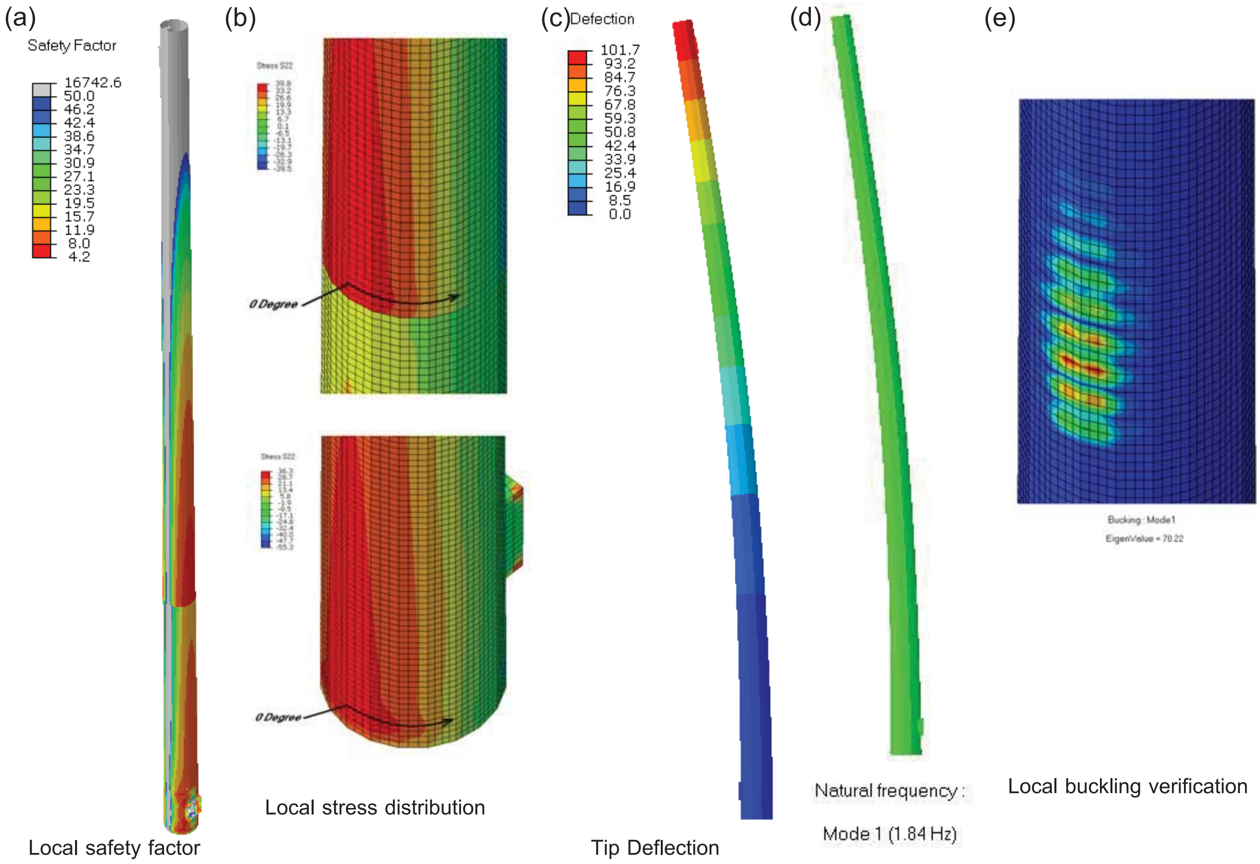

Fig. 1 Results of the static structural, the modal, and stability analyses for the load combination in service.

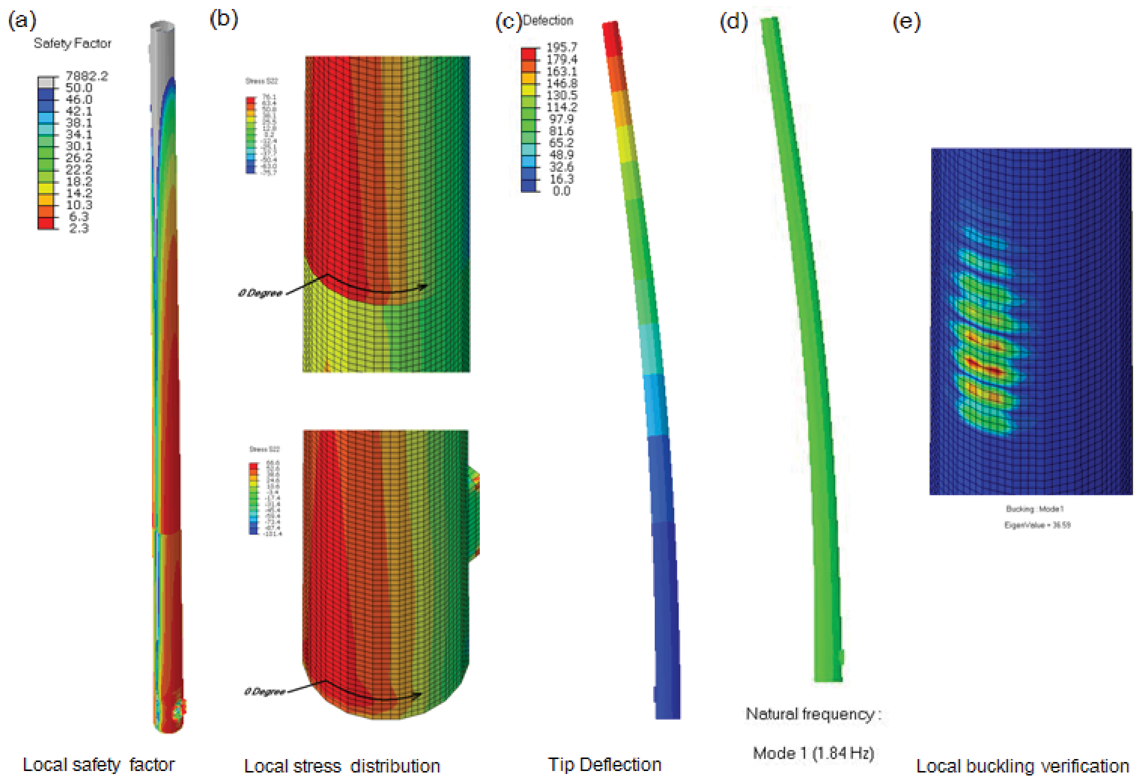

Fig. 2 Results of the static structural, the modal, and stability analyses for factored load combination.

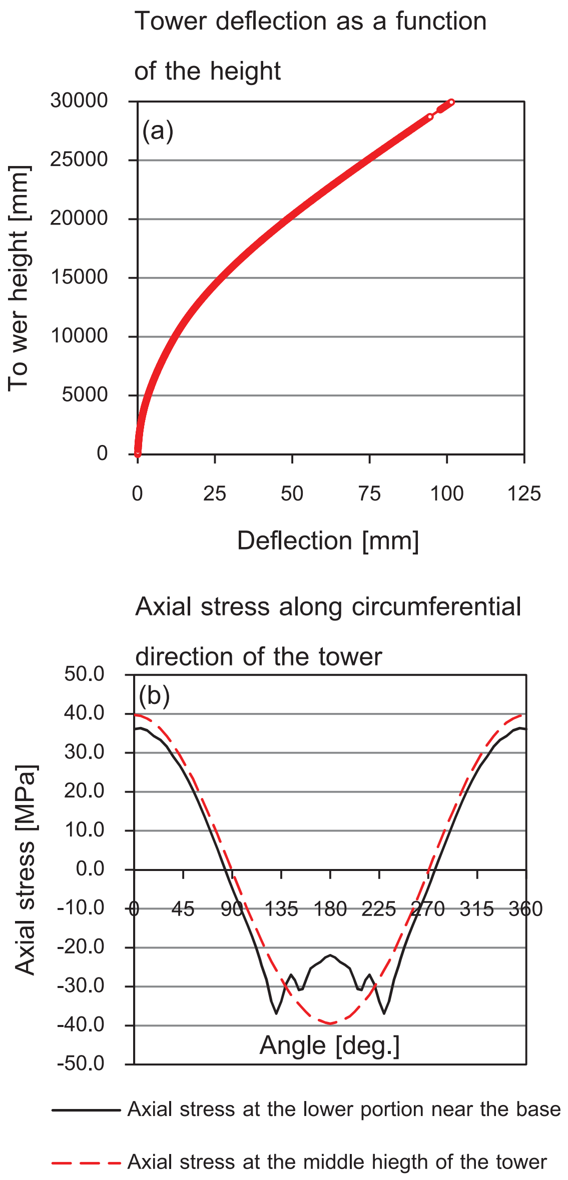

Fig. 3 Calculated tower deflection and stress distribution in the tower in the case of characteristic wind load (a) the deflection of tower vs. the height of the tower (b) the comparison of the axial stress distribution in the shell wall.

Stress associated with the buckling is the axial compressive stress in shell. Axial stress distribution at a critical position, e.g. in the lower portion near the base of the tower, and at the middle portion of the tower height is illustrated in Fig. 3b. Little difference in stress amplitude can be observed on the graph for both positions. Similar stress characteristic is that the positive axial stress can be found in the tower wall which is against the wind. On the opposite surface, shell wall is subjected to the compression as indicated as the negative stress values on the graph. A discontinuous stress distribution in the lower portion from 135 to 225 degree is occurred since this portion locates near the opening door.

Impulsive wind force due to the extreme gust is an instantaneous situation that can take place during the operation of a wind turbine power plant and it is vital to verify its effect on the structural damage.

Modal analysis yields the mode shape of the structure when the excitation frequency due to blade rotation produced by the wind stream resonates to the natural frequency of the tower structure. The suitable operating frequency range of the blade rotation is between *1P* and *3P* where *P* is the rotational frequency of the rotor. This type of structure is so called the soft tower structure [6].

5. Conclusions

The conclusion can be drawn from the study on the design of the wind turbine tower structure using the finite element method as follows:

1) Optimal design of a tower structure can be achieved by using a numerical model which provides a significant insight for the complicated behavior of the vertical structure subjected to the across wind in terms of stress distribution and deformation. Many design aspects are concerned including the global strength, the deflection, the vibration analysis, the stability which can be considered as the relevant design feature for the SWT design. Optimal base and top outer diameters are 1.30 and 0.80 m, respectively.

2) Stress distribution is significant for the lower portion locating near the base of the tower. Tensile stress in wall can be found in the tower shell against the wind. Bending moment created by the wind pressure produces the compressive stress in the opposite wall of the tower. The local buckling and associated stresses must be examined in order to avoid the structural instability, especially for the region near the base of the tower and the opening.

3) Structural optimization in terms of strength, tower dimension, and material/fabrication cost is the most important issue in the design of a wind turbine tower.

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7. References

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