STRUCTURAL DESIGN OPTIMISATION FOR WIND TURBINE TOWERS USING ADVANCED FEM MODELS

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ABSTRACT

In this paper, the structural behaviour of typical steel tubular wind turbine towers is analysed. In particular, towers of various heights between 50-250m are considered and numerically investigated with three different design options being the following: (i) intermediately thick tower with internal horizontal stiffening rings, (ii) intermediately thick tower without stiffening rings and (iii) thin tower with strong stiffening rings. As the weight of the steel structure is closely related to the manufacturing cost, the weight reduction ratios are examined in relation to the displacement and stress increase ratios in order to estimate the optimal tower design with reduced manufacturing cost, whereas stiffness and strength requirements are still satisfied in line with structural codes.

1 INTRODUCTION

The use of renewable energy and in particular, wind energy, mitigates the rate of environmental deterioration as it reduces the emission of greenhouse gases. Nowadays, the wind energy has been extensively used and the underpinning technology develops very rapidly [1]. Wind turbines are energy converters that convert kinetic energy from the moving air to electrical power; they are attached to supporting towers that also support the rotor and the power transmission and control systems. One of the most common design options for the wind turbine towers is the tubular steel structure manufactured in the sections of 20-30m with flanges at both ends facilitating the bolting of these sections *in situ*.

Economic efficiency is a key parameter that needs to be considered in the design of a wind turbine tower. Amongst the total cost, the construction cost of the wind turbine takes up a considerable percentage, i.e. approximately 15 to 20%. The use of the materials and subsequently the weight of the system determine the costs incurred during transport and erection. On the other hand, the height of a tower directly determines the energy yield, and hence will be determined before the design process commences.

A successful structural design of tower should meet the design criteria of cost effectiveness, safety and functionality, and thus, the design optimization without compromising other performances becomes an important step in the wind tower construction. Maalawi and Negm considered the cross-sectional area, the radius of gyration and the height of each segment as the key design variables and suggested five design options for the design of towers [2]. Bazeos *et al*. analysed a prototype wind turbine steel tower with respect to its static and dynamic behaviour and other destabilizing effects [3]. Lavassas *et al.* analysed and presented the detailed design of a prototype of a 1-MW steel wind turbine tower of tubular shape with a variable wall thickness along the height of the tower [4, 5]. Uys *et al.* undertook a cost minimisation study for a steel tower where the cost function was formulated by including material and manufacturing cost [5]. Recently, Chou and Tu investigated the collapse mechanism of a large wind turbine tower in order to avoid similar accidents [6]. Perelmuter and Yurchenko described a parametric optimization procedure of steel conic shell towers of high-capacity wind turbines [7]. Dimopoulos and Gantes carried out the experimental and numerical study of the buckling behaviour of cantilevered shells with door openings and stiffening rings [8].

In the present paper, the wind towers of three different heights have been numerically modelled by means of advanced finite element models. In each height case, the towers have been designed as an intermediately thick shell structure with or without rings and as a thin shell structure with strong rings respectively. The weights of the shell structure and rings associated with each tower construction have also been considered. Thus, the three design options for each height case are compared in order to identify the most efficient design that can reduce the cost while retaining the strength and the serviceability performance in a satisfactory manner.

2 FE ANALYSIS OF TOWERS WITHOUT RINGS

2.1 Wind turbine towers without rings

In engineering practice, the choice of the tower height is pre-determined based on the energy yield requirement. In the present study, three different heights have been chosen to be numerically examined, with height 50m, 150m and 250m, respectively. The geometric characteristics and the relevant FEM models of the wind turbine towers are shown in Fig 1. The typical cross-section and the flange arrangement of the 50m tower are presented in Fig 2. The material properties of steel towers are displayed in Table 1, whereas the heights and widths of flanges and shell thickness are shown in Tables 2 and 3. The diameters of the towers cross-section from bottom to top vary linearly.

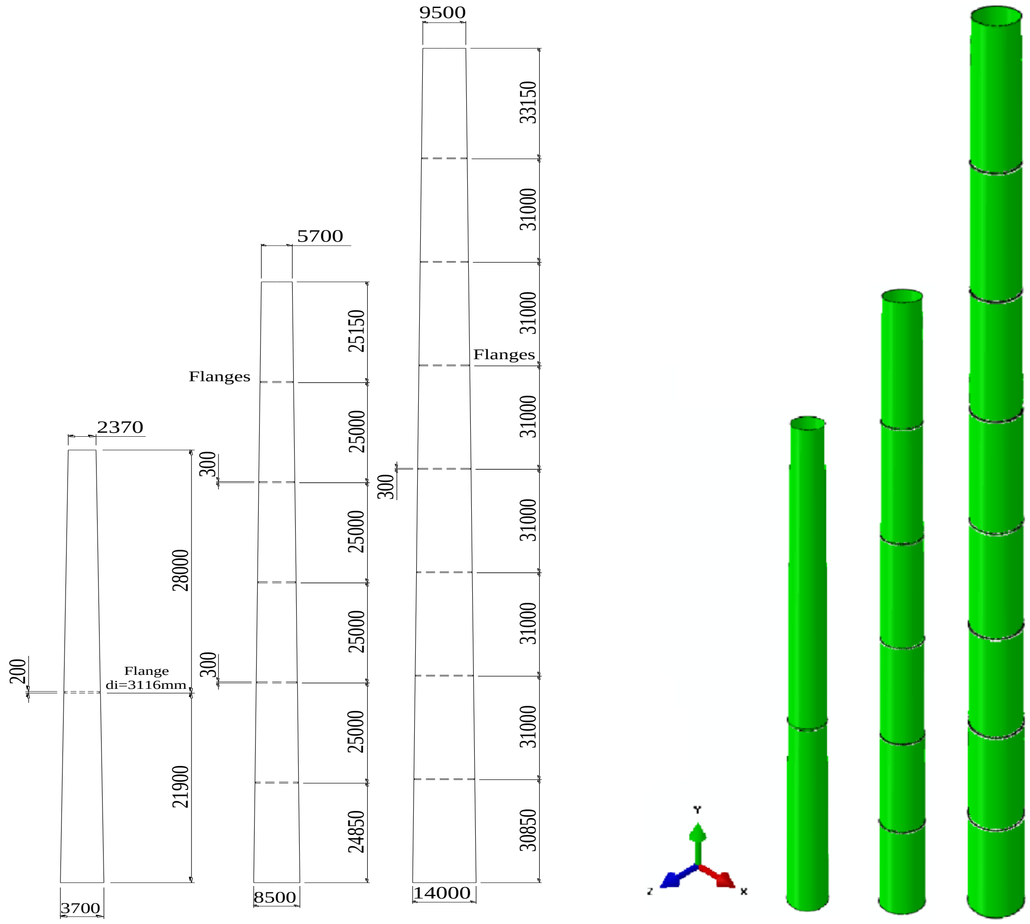

Fig 1. Tower designs of 3 different heights: geometrical dimension and FEM models

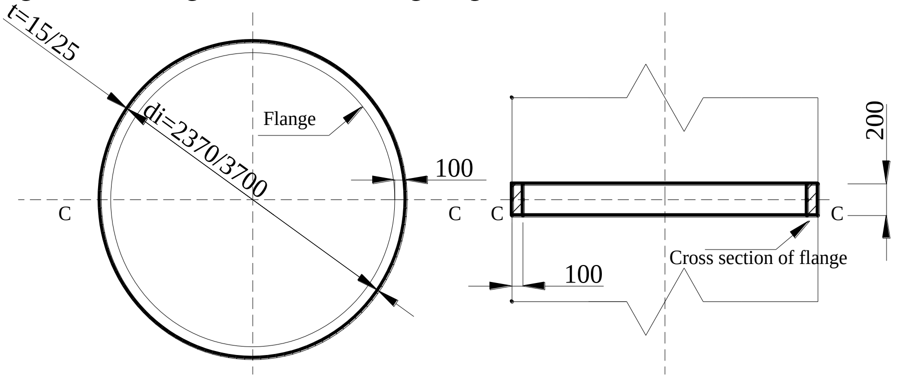

Fig 2. Typical cross-section of the 50m height tower (in mm)

Table 1 Material properties of the wind turbine tower structural steel

Material property	Elastic modulus	Density	Poisson’s ratio
Steel	205GPa	7.85g/cm^3	0.3

Table 2 Flange dimensions of the wind turbine towers

Height of towers	Thickness of flanges	Central spacing of flanges
50m	200mm	100mm
150m	300mm	150mm
250m	300mm	150mm

Table 3 Shell thicknesses of the wind turbine towers

50m	Height	0-21.9m	21.9m-50m	
	Shell thickness	25mm	15mm	
150m	Height	0-49.85m	49.85m-99.85m	99.85m-150m
	Shell thickness	40mm	30mm	25mm
250m	Height	0-92.85m	92.85m-185.85m	185.85m-250m
	Shell thickness	60mm	50mm	45mm

2.2 Wind loading

In the structural model, the self-weight of the towers is calculated directly by the FE analysis software by considering the dimensions of the tower and the material density. The contribution of the platforms and the ancillary equipments (ladders, cable racks etc.) to the total weight of the tower are neglected. On the top of the tower, the weight of the nacelle including the blades and the rotor will induce vertical force and moment that acts on the top of the tower. Moreover, there is a horizontal wind load applied on the blades of the towers with the data provided by the rotor manufacturer [9, 10].

According to BS EN 1991-1-4, the wind loads over the tower stem are calculated based on the specific dynamic characteristics and geometry of the tower structure. The distribution function of basic wind load along the height z of the 50m tower stem is related to the diameter D as given by Eqs. (1, 2) (z, D in m; f_b in kN/m):

$$z \leq 2.00\text{m}: f_b = 0.51 \cdot D \quad (1)$$

$$z > 2.00\text{m}: f_b = 0.013 \cdot \ln(20 \cdot z) \cdot [\ln(20 \cdot z) + 7] \cdot D \quad (2)$$

where D= -0.0266·z+3.7 (variation of tower diameter along the height). Fig 3 shows the distribution of wind loads along the tower height and circumferential circle.

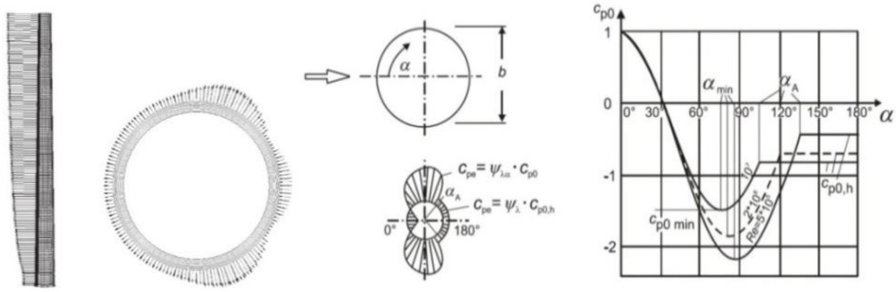

Fig 3. Distribution of wind loads along the tower height and around the circumference

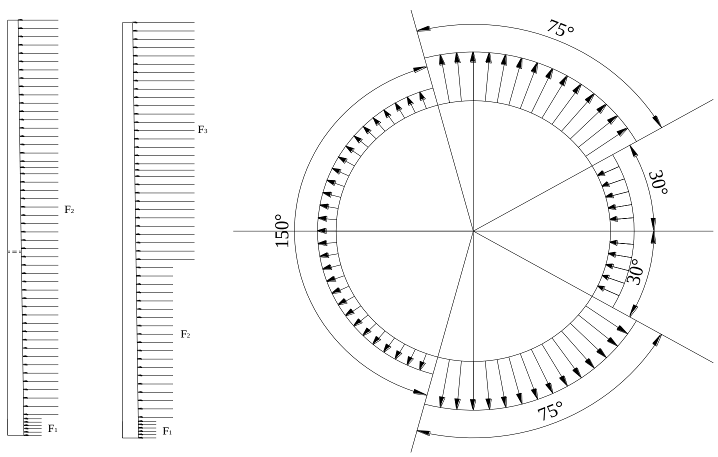

Fig 4. Simplified distribution pattern of wind load along the tower height and around the circumference

Simplified distributions pattern of the wind load used in the present analysis are presented in Fig 4 in accordance to BS EN 1991-1-4. As shown in Fig 4, the wind load distribution profile of 50m and 150m tower is divided into two parts, and the profile of 250m tower is separated into three parts where the wind pressure of each part are equal to the maximum value within the corresponding zone. Similarly, the distributions of wind load coefficients around the circumference are divided into four parts as is shown in Fig 4.

For wind pressure, according to Equations (1) and (2), the applied wind pressure on the surface of the tower shell can be obtained based on the assumption of the wind load distribution along the height in Eqs. (1-2). The formula can be given by equation (3):

$$p = f_b / [\theta \cdot (D/2)] \tag{3}$$

where θ is equal to π/3. So the wind pressure can be calculated by equations (4) and (5):

$$z \leq 2.00\text{m}: p = 0.975\times10^{-3}\text{N/mm}^2 \tag{4}$$

$$z > 2.00\text{m}: p = 0.025\cdot\ln(20\cdot z)\cdot[\ln(20\cdot z) + 7] \tag{5}$$

Obviously, the function $p = 0.025\cdot\ln(20\cdot z)\cdot[\ln(20\cdot z) + 7]$ is increasing when z>2.00m. According to BS EN 1991-1-4, equations (4) and (5), as for the 50m tower, the distribution of maximum wind pressure of the lower 2m tower is (in N/mm^2): $0^\circ<\alpha_A\leq30^\circ$, $p_1=0.975\times10^{-3}$N/mm^2; $30^\circ<\alpha_A\leq105^\circ$, $p_1=-1.455\times10^{-3}$N/mm^2; $105^\circ<\alpha_A\leq180^\circ$, $p_1=-0.768\times10^{-3}$N/mm^2. Similarly, the distribution of maximum wind pressure of the upper 48m tower is (in N/mm^2): $0^\circ<\alpha_A\leq30^\circ$, $p_1=2.39\times10^{-3}$N/mm^2; $30^\circ<\alpha_A\leq105^\circ$, $p_1=-3.585\times10^{-3}$N/mm^2; $105^\circ<\alpha_A\leq180^\circ$, $p_1=-1.893\times10^{-3}$N/mm^2, where α_A is the position of the flow separation. The simplified distribution pattern of wind load around the circumference is described in Fig 4. According to the calculation process of 50m tower wind load, the wind load of 150m and 250m towers can also be calculated in a similar way.

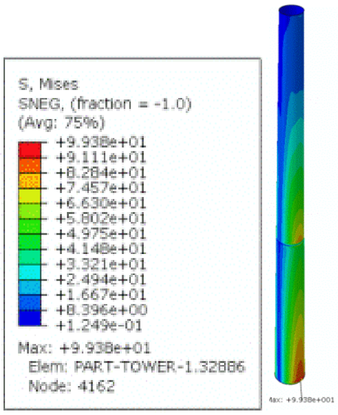

Fig 5. Shell stress in the 50m FEM tower

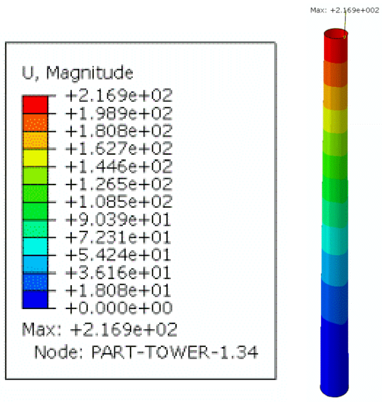

Fig 6. Deformation of the 50m FEM tower

Drawn from the modelling results, the stress distribution of the shell structure of the 50m tower without rings is depicted in Fig 5, where there is stress concentration near the bottom of the tower is observed. The maximum stress of the tower under vibrational wind loads is 99.38Mpa. The deformation of the 50m tower is presented in Fig 6 where the maximum displacement at the top is 216.9mm.

3 FE ANALYSIS OF TOWERS WITH STIFFENING RINGS

Steel shells are regularly stiffened by means of stiffening rings. Thus, in order to improve the structural response of the tower, stiffening rings are added at the inner side of the shell. The dimensions and FE models of towers with stiffening rings are depicted in Figs 7 and 8. The flanges and stiffening rings are tied in the numerical model. Specifically, all stiffening rings of 50m tower are of 100mm thickness and 50mm central spacing. The other dimensions are identical with the ones of the 50m tower without stiffening rings, so are loads. As for the 150m and 250m towers, the thickness and central spacing of stiffening rings of 150m and 250m towers are respectively 300mm and 150mm. The interaction between rings and shell, element types and boundary condition as well as the loads situation and shell thickness are considered to be similar to those of 150m and 250m towers without rings. The heights of parts 1 and 36 of 150m tower are respectively 4050mm and 3850mm. In addition, the height of parts 6, 12, 18, 24 and 30 are 3700mm, and the remaining parts of the tower are all 3900mm. As for 250m tower, the height of part 1 is 5000mm; the heights of parts 6, 12, 18, 24, 30, 36 and 42 are 4950mm; the heights of parts 48 and 49 are 3400mm and the heights of the other parts in tower are 4850mm. The thickness details of shells are the same with the towers without rings.

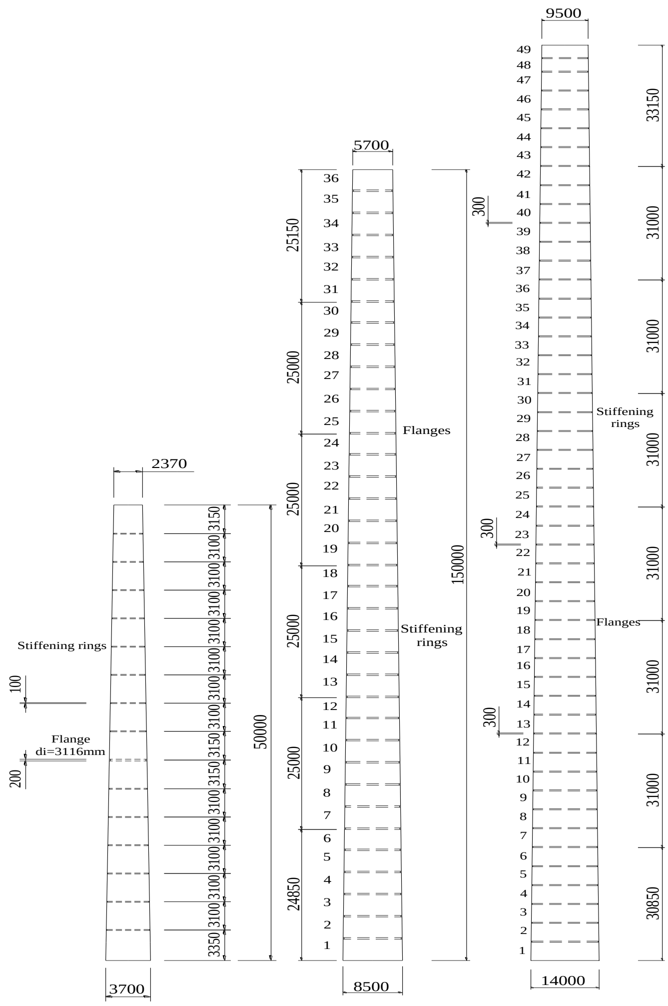

Fig 7. Geometry of tower prototypes (in mm)

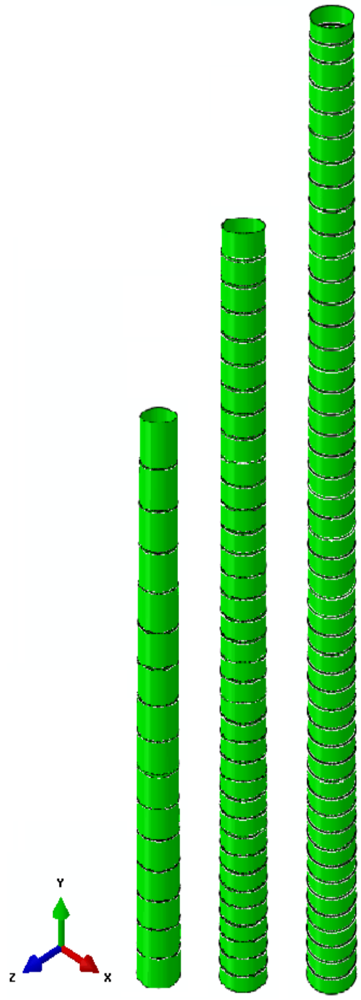

Fig 8. FE models of the towers with rings

The shell stress state of the 50m tower with rings is shown in Fig 9. The stress distribution in a wind turbine tower under wind loads is obviously very different from its counterpart without rings. The maximum shell stress is only 19.78MPa, which is far less than the stress 99.38MPa in the 50m tower model. The deformation of the 50m tower with rings is presented in Fig 10. The maximum deflection of this tower is 10.2mm at the top of the tower.

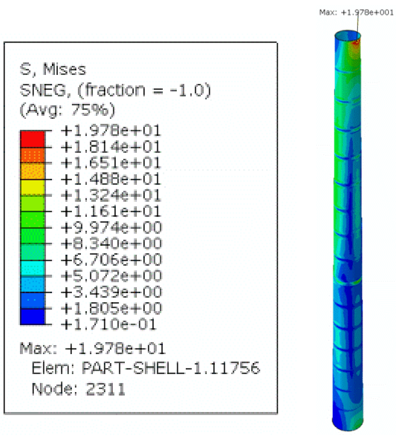

Fig 9 Shell stress of the 50m tower with rings

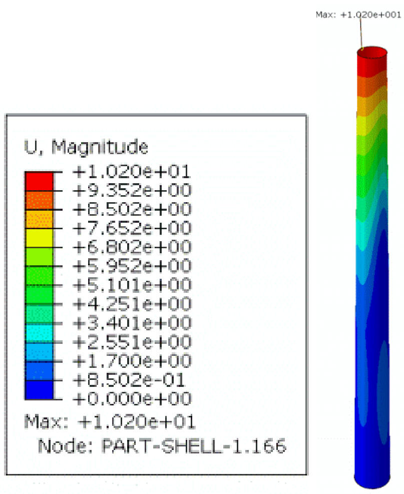

Fig 10 Deformation of the 50m tower with rings

In the case of thin tower with stiffening rings, the thickness of the shells is reduced properly taking into account strength, stiffness and stability constraints. The shell thickness of these three types of towers is considered to be reduced in some range. The shell thickness of thin towers is shown in Table 4. The other parameters are identical with the thick shell towers. Moreover, the distribution of stiffening rings are also the same as in the case of the thick shell towers.

Table 4 Shell thickness in thin towers

50m	Height range of tower	0-21.9m	21.9m-50m	
	Shell thickness	20mm	10mm	
150m	Height range of tower	0-49.85m	49.85m-99.85m	99.85m-150m
	Shell thickness	35mm	25mm	20mm
250m	Height range of tower	0-92.85m	92.85m-185.85m	185.85m-250m
	Shell thickness	55mm	45mm	40mm

4 RESULTS AND DISCUSSION

The cases of three wind turbine towers of different heights and with or without stiffening rings have been modelled by means of finite element method. Specifically, the results of numerical simulation are displayed in Table 5 involving the maximum stress of shell and deformation.

Table 5 Maximum deformation and stress of 50m, 150m and 250m towers under wind loads

Height of towers	Variables	Tower with rings	Tower without rings	Thin tower with rings
50m	Max. deformation	10.2mm	216.9mm	14.63mm
	Max. stress	19.78MPa	99.38MPa	29.67MPa
150m	Max. deformation	430.8mm	434.4mm	508.9mm
	Max. stress	64.43MPa	95.75MPa	84.60MPa
250m	Max. deformation	136.6mm	193.3mm	152.1mm
	Max. stress	49.83MPa	83.96MPa	62.42MPa

As is well known, the weight of the tower is related to cost. So, in order to reduce the cost, material weight can be reduced as much as possible while still meeting the stiffness and strength requirements. From the dimensions and density, the weight of the towers can be calculated. The masses of three different towers are shown in Table 6.

Table 6 Wind turbine tower mass characteristics

Height of tower	m_1 (t)	m_2 (t)	m_3 (t)	Δm_S	Δm_R
50m	81.09	76.02	62.38	23.07%	6.25%
150m	1118.50	887.17	987.17	11.74%	20.68%
250m	4460.52	3934.29	4098.28	8.12%	11.8%

where m_1 is the mass of towers with rings, m_2 is the mass of towers without rings, m_3 is the mass of thin towers with rings, Δm_S is the mass reduction ratio between m_1 and m_3, and Δm_R is the mass reduction ratio between m_1 and m_2.

The numerical results for all the three towers are analysed and listed in Table 7 where the deformation and stress variation ratios are calculated in accordance with the data in Table 5. In order to estimate marginal increase/decrease, the differential deformation and stress are divided by the corresponding differential mass.

Table 7 Wind turbine tower deformation and stress variation

Height of tower	Variables	Δa_1	Δa_2	$\Delta a_1/\Delta m_S$	$\Delta a_2/\Delta m_R$
50m	Deformation	43.43%	2026%	1.88	324.16
	Stress	50%	402.4%	2.17	64.38
150m	Deformation	18.13%	0.84%	1.54	0.04
	Stress	31.3%	48.61%	2.67	2.35
250m	Deformation	11.35%	41.51%	1.4	3.52
	Stress	25.27%	68.49%	3.11	5.8

Δa_1 is the deformation and stress augmentation percentage of tower I with regards to tower III; Δa_2 is the deformation and stress augmentation percentage of tower I with regards to tower II. Additionally, tower I means the tower with stiffening rings, tower II stands for the tower without stiffening rings, and tower III represents thin tower with stiffening rings.

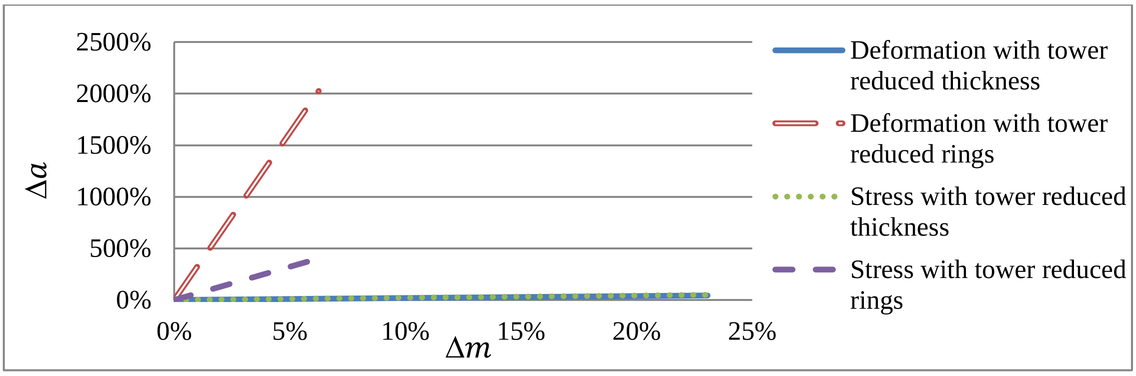

Fig 11 50m tower deformation and stress variation ratios of tower I to tower II and tower I to tower III

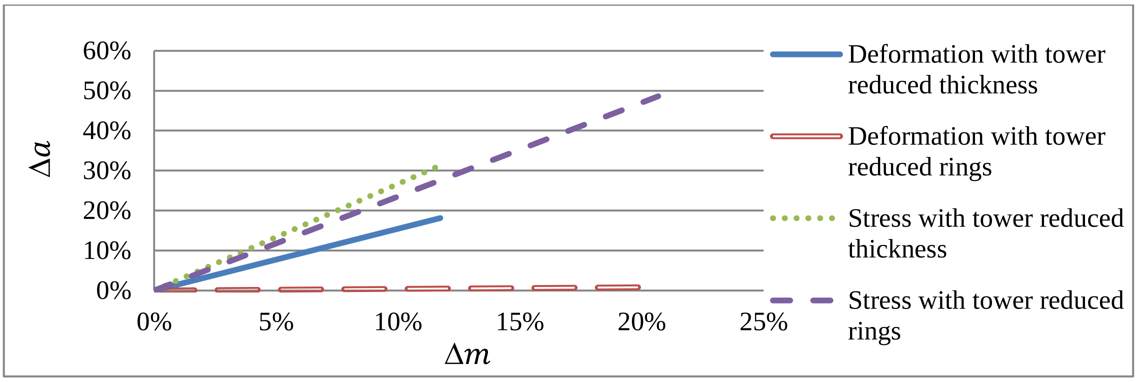

Fig 12 150m tower deformation and stress variation ratios of tower I to tower II and tower I to tower III

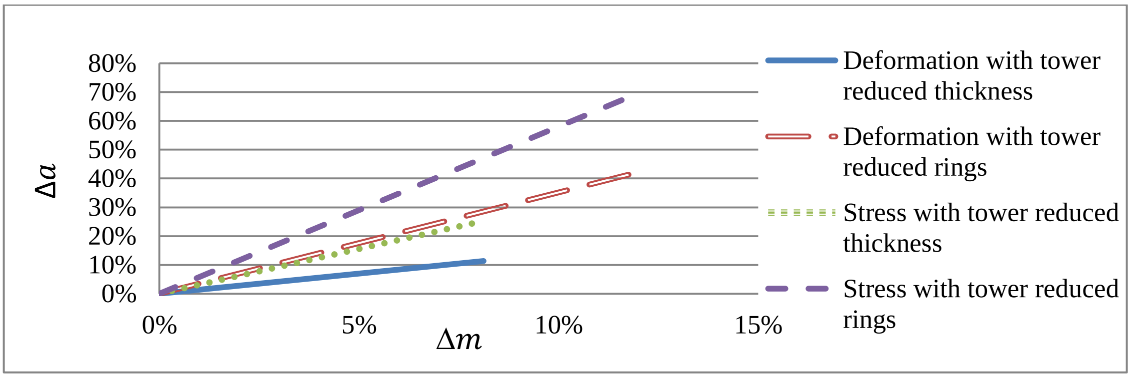

Fig 13 250m tower deformation and stress variation ratios of tower I to tower II and tower I to tower III

Furthermore, according to Figs 11-13, graphs present deformation and stress augmentation ratios of three types of towers when thickness and rings of these towers are reduced. As the $\Delta a_1/\Delta m_S$ and $\Delta a_2/\Delta m_R$ are positive with reference to the slopes of the function curves in Figs 11-13, the slope magnitudes of function curves reflect the variation velocity of deformation and stress augmentation ratios in the case that the weight reduction ratio are increased. Specifically, if slope magnitudes of function curves are bigger, this indicates that the variation velocity of deformation and stress augmentation ratios with weight reduction ratios grew is higher, thus, which is a more effective and sensitive way to change the strength of tower structure. In other words, bigger the slope magnitudes of function curves are, more efficiently the cost can be saved.

In 50m height level, the mass reduction ratio of tower I to tower III is 23.07% more than that of tower I to tower II, 6.25%. However, the magnitudes of deformation and stress augment ratios of tower I to tower III is 43.43% and 50% respectively, which are both far less than these of tower I to tower II, 2026% and 402.4%. Additionally, the magnitudes of maximum deformation and stress of tower I and tower III are also far less than those of tower II. So it illustrates that the dense rings distribution should be avoided by properly reducing the rings quantity. Relatively, the $\Delta a_2/\Delta m_R$ is equal to 324.16 and 64.38 more than $\Delta a_1/\Delta m_S$ that is 1.88 and 2.17 respectively, which indicates that the method to reduce the rings is more sensitive to the strength variation of the tower structure than that to decrease the thickness. As for the 50m height level, reducing the rings is a better way to save cost than reducing thickness.

In 150m height level, the deformation reduction ratio of tower I to tower II is rather little, only 0.84% far less than that of tower I to tower III, and 18.13%. The mass reduction ratio of tower I to tower III is 11.74%, and that of tower I to tower II is 20.86%. Deeply, the deformation and stress variation velocity of tower I to tower III $\Delta a_1/\Delta m_S$ is 1.54 and 2.67 respectively which both are greater than those of tower I to tower II $\Delta a_2/\Delta m_R$, 0.04and 2.35 respectively. Notably, the variation velocity to deformation of tower I to tower II is rather slight, only 0.04. Taking the economic efficiency into consideration, it indicates that reducing the thickness is more efficient way to control the strength of tower structure and save cost.

In 250m height level, the mass reduction ratio of tower I to tower III is 8.12% less than that of tower I to tower II. Also, the deformation and stress variation ratios of tower I to tower III are respectively 11.35% and 25.27% which are both smaller than those of tower I to tower II, respectively 41.51% and 68.49%. Moreover, the deformation and stress variation velocity of tower I to tower II $\Delta a_2/\Delta m_R$, 3.52 and 5.8 respectively, greater than that of tower I to tower III $\Delta a_1/\Delta m_S$, 1.4 and 3.11 respectively. Obviously, reducing the rings is more efficient method to manage the strength of tower structure.

5 CONCLUSIONS

The present research work concerns the investigation of the behaviour of wind turbine towers under wind loads and their deformation and stress variation ratios when tower thickness and stiffening ring numbers are reduced. Three types of tower structures have been examined using the cost as the optimisation criterion when the requirements of strength and serviceability are met. In the 50m height tower, it is found that the dense distribution of stiffening rings of tower I and tower III can be avoided in the case that the rings quantity of tower I and tower III can be properly reduced. Furthermore, in towers of 50m and 250m height, reducing the rings of towers is better and more efficient way to save cost, whereas in 150m height level, reducing the thickness of tower shell is more efficient way to economise cost.

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