Orthogonal experiment optimum design for GFRP wind turbine tower

Fei Zhao[1, a], Haihao Guo[2], Weihua Chen[3] and Donghai Li[1]

[1]*College of Civil Engineering and Architecture, Hainan University, Haikou 570228, China*
[2]*College of Civil and Hydraulic Engineering, Hefei University of Technology, Hefei 230000, China*
[3]*School of Civil Engineering and Architecture, Changsha University of Science & Technology, Changsha 410114, China*

Abstract. In recent decades, Fiber Reinforced Polymer/Plastic (FRP) has been successfully applied in varieties of structures due to its lightweight, high strength and corrosion resistance properties. In this paper, we developed a finite element model to predict the behaviour of a 1.5 MW GFRP wind turbine tower by using the SAP2000 software program, then applied the orthogonal experiment optimum design methodology in the tower. The minimum self-weight of tower was selected as the performance target and the diameters and the wall thicknesses at the top and base of tower were selected as the four main factors in orthogonal experiment. EXCEL software was also applied to gain the linear regression equation and to establish the mathematical model of the tower. Finally, we obtained the optimal solution of the tower through the MATLAB software.

Keywords: GFRP; wind turbine tower; orthogonal experimental design; finite element analysis; optimization design.

1 Introduction

With the development of wind power technology, various types of wind turbine towers have been applied in practical engineering. The construction materials commonly used in the towers include reinforced concrete, prestressed reinforced concrete and steel. However, some disadvantages existed in such towers, such as large weight, poor corrosion resistance and high maintenance. Fiber Reinforced Polymer/Plastic (FRP), as a new type of material, has a lightweight, high strength, corrosion resistance, good elastic properties and design flexibility [1,2]. Nowadays, FRP has been successfully applied in varieties of structures. In China, many researches on wind turbine tower mainly focus on reinforced concrete tower, prestressed reinforced concrete tower and steel tower [3-7], and the research on FRP wind turbine tower is rarely reported [8].

In this present work, a finite element model was developed using the SAP2000 software program to predict the behavior of a 1.5 MW GFRP wind turbine tower, such as static strength and modal. Then the orthogonal experiment optimum design methodology was applied in the tower. The minimum self-weight of tower was selected as the performance target and the diameters and the wall thicknesses at the top and base of the tower were selected as the four main factors in orthogonal experiment. EXCEL software was also applied to gain the linear regression equation and to establish

[a]Corresponding author : zfhw2006@163.com

the mathematical model of the tower. Finally, the optimal solution of the tower was obtained by MATLAB. Furthermore, the comparison between the GFRP wind turbine tower and the galvanized steel wind turbine tower on the overall cost was made.

2 Material properties

The material properties of GFRP were shown in table 1. For the convenience of analysis, it can be assumed that GFRP was isotropic material.

Table 1. Properties of GFRP[8]

Parameter	Value
Tensile strength [Mpa]	900
Compressive strength [Mpa]	586
Elastic modulus [Gpa]	45.105
Density[kg/m3]	1800

3 Design loads

The wind turbine tower should resist two types of loads: loads acting on the tower and loads transferred from the wind turbine to the top of the tower, as shown in Fig. 1. The former include: dead load due to the self-weight of the tower and live load due to snow, ice, rain, wind and earthquake; the latter include: dead load due to the self-weight of the wind turbine, normal operating loads, extreme operating loads, wind, gust, generator short circuit and rotor eccentricity. For the limitation of space, only parts of loads were given in table 2 where, FXH1 is the horizontal force due to the mean pressure which is dependent on the rated wind speed under normal operation condition, FXH2 is the horizontal force due to the wind pressure which is determined by the gust wind speed under extreme operating condition, G is the self-weight of the wind turbine, and MXH is the resisting moment caused by the rotation of the rotor.

Table 2. Loads at the top of the tower

FXH1	FXH2 [kN]	G [kN]	MXH
627.93	1021.5	580	75

Wind load acting on the tower can be calculated from the formula which is provided by Load Code for the Design Building Structures (GB50009-2012).

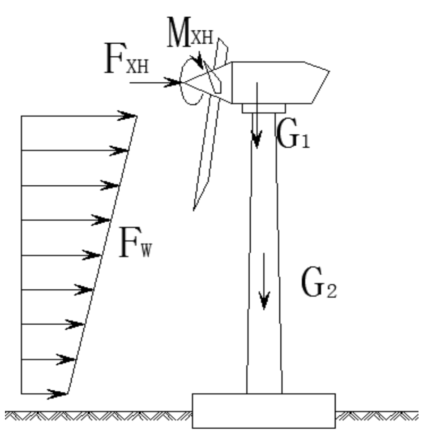

Figure 1. Force diagram of the tower

4 Finite element modeling

Modeling of the GFRP wind turbine tower was carried out using the SAP2000 finite element software. The tower analyzed in this study has the following characteristics parameters: a height of 60m, a diameter at the base of 7m, and a diameter at the top of 4.5m. A total of one thousand nine hundred and twenty eight-node quadrilateral shell elements were used to model the tower. To accurately evaluate the stress and deformation of each element, the aspect ratio should be no more than 3. Finite element model of the tower is shown in Fig. 2.

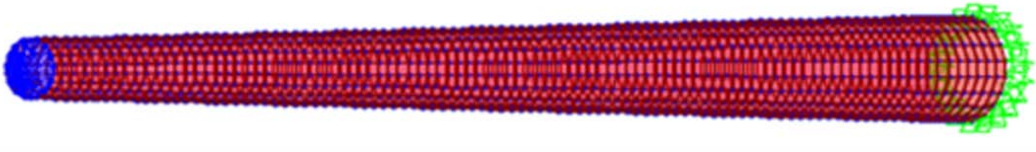

Figure 2. Finite element model of the tower

All degrees of freedom were restrained at the end of the composite sleeve to simulate the fixed end condition. A massless rigid body was added at the top of the tower to keep the deformation compatibility when applying the concentrated load to the location.

5 Orthogonal experiment

5.1 Factors, levels and experimental indices

In the optimization design of the tower, the tip deflection, the first mode and the second mode of the tower were chosen as orthogonal experimental index, and the diameters and the wall thicknesses at the top and base of the tower were selected as the factors which influence the design of tower structure after neglecting of the doorway of tower.

The current orthogonal experiment involves four factors and three levels (shown in table 3), expressed as $L_9(3^4)$ in orthogonal experimental table where, factor A and B are the diameter at the base and top of the tower, respectively; factor C and D are the wall thickness at the base and top of the tower, respectively. A total of eighty-one groups of tests should be needed if using the comprehensive comparative experimental method, while only nine groups of tests if using the orthogonal experimental method. According to the orthogonal experimental table, nine models of tower were established using SAP2000, and then three experimental indices involving the tip deflection, the first order and the second order natural frequency of the tower were obtained for each model.

Table 3. The factors and levels of the orthogonal experiment on tower

Factors / Levels	A[m]	B[m]	C[mm]	D[mm]
1	7	4	91.5	53.0
2	6.52	3.52	86.0	47.5
3	7.48	4.48	97.0	58.5

5.2 Orthogonal experimental result

The combination schemes and results of the orthogonal experiment were shown in table 4 where, x1, x2, x3 and x4 were represented as the experimental design variables of four factors A, B, C and D, Δ was represented as the tip deflection of tower, f1 and f2 were respectively represented as the first order and the second order natural frequency for the tower, and G was represented as the self-weight of the tower body, which can be automatically calculated by the SAP2000 software.

Table 4. The combination schemes and results of the orthogonal experiment

NO.	x1[m]	x2[m]	x3[mm]	x4[mm]	Δ [m]	f1[Hz]	f2[Hz]	G[t]
1	7.00	4.00	91.5	53.0	0.4748	2.25400	2.29844	135.2188
2	7.00	3.52	86.0	47.5	0.5529	2.30820	2.37119	120.4425
3	7.00	4.48	97.0	58.5	0.4209	2.20245	2.23539	150.8696
4	6.52	4.00	86.0	58.5	0.5704	2.00027	2.03581	128.0747
5	6.52	3.52	97.0	53.0	0.5739	2.15597	2.20722	128.7910
6	6.52	4.48	91.5	47.5	0.5382	2.12815	2.16647	129.4119
7	7.48	4.00	97.0	47.5	0.4079	2.52503	2.58074	142.6825
8	7.48	3.52	91.5	58.5	0.4308	2.38768	2.44027	140.7201
9	7.48	4.48	86.0	53.0	0.4090	2.34143	2.38061	140.7712

6 Optimization analysis of the experimental results

6.1 Liner regression analysis

Four target variables were made multiple linear regression analysis using EXCEL software and the results were shown in table 5. The P value of each independent variable is less than 0.05, which means all the independent variables have high correlation with the dependent variables.

Table 5. Regressive coefficient table

	Coefficient	Standard error	T-statistic	P value
Constant	2.289385	0.07524	30.42781	6.95E-06
x1	-0.150972	0.006137	-24.6009	1.62E-05
x2	-0.065799	0.006137	-10.7219	0.000429
x3	-0.003927	0.000536	-7.33275	0.001841
x4	-0.002330	0.000536	-4.35099	0.012148

According to the coefficient in table 5, the linear regression equation of the tip deflection Δ at the top of tower on variable xi can be taken as follows:

$$\Delta = 2.289385 - 0.150972x_1 - 0.065799x_2 - 0.003927x_3 - 0.00233x_4 \quad (1)$$

The regressive equations of other dependent variables such as the first order natural frequency f1, the second order frequency f2 and the self-weight G for the tower can be also obtained using the above method.

$$f_1 = 0.096874 + 0.336719x_1 - 0.062438x_2 + 0.007077x_3 - 0.011242x_4 \quad (2)$$

$$f_2 = 0.218372 + 0.344486x_1 - 0.082017x_2 + 0.007144x_3 - 0.012331x_4 \quad (3)$$

$$G = -135.3018 + 13.1584x_1 + 10.7983x_2 + 1.0017x_3 + 0.822x_4 \quad (4)$$

6.2 Mathematical model

Without considering the cost of tower's maintenance and installation in the analysis of the tower, only the weight of the tower was chosen as the optimization goal function. The tip deflection of the tower should be 0.5%-0.8% of the tower's height according to the practical engineering[9]. In this paper, 0.8% of the tower's height was taken as the limitation of the tip deflection, so the tip deflection should be less than 0.48 m. The diameter at the top of the tower was usually taken as 0.8m to 3.5m according to the requirements in tower design[10]. In this paper, the range of the diameter at the top of tower was taken as 2.7m to 3.5m for the models, thus the constraint function was obtained. The mathematical model can be expressed as:

$$\min(G) = -135.3018 + 13.1584x_1 + 10.7983x_2 + 1.0017x_3 + 0.822x_4 \quad (5)$$

$$-0.150972x_1 - 0.065799x_2 - 0.003927x_3 - 0.00233x_4 \le -1.797705 \quad (6)$$

$$-0.336719x_1 + 0.062438x_2 - 0.007077x_3 + 0.011242x_4 \le -2.003126 \quad (7)$$

$$-0.344486x_1 + 0.082017x_2 - 0.007144x_3 + 0.012331x_4 \le -1.881628 \quad (8)$$

$$6.52 \le x_1 \le 7.48 \quad (9)$$

$$2.7 \le x_2 \le 3.5 \quad (10)$$

$$86 \le x_3 \le 97 \quad (11)$$

$$40 \le x_4 \le 58.5 \quad (12)$$

Among the above expressions, Eq.(7) and Eq.(8) can be Substituted by Eq. (13) and Eq.(14) shown as below when the first order frequency is less than 1.9Hz and the second order frequency is greater than 2.1 Hz or by Eq.(15) and Eq.(16) whenboth of two frequencies are less than 1.9Hz:

$$0.336719x_1 - 0.062438x_2 + 0.007077x_3 - 0.011242x_4 \le 1.803126 \quad (13)$$

$$-0.344486x_1 + 0.082017x_2 - 0.007144x_3 + 0.012331x_4 \le -1.881628 \quad (14)$$

$$0.336719x_1 - 0.062438x_2 + 0.007077x_3 - 0.011242x_4 \le 1.803126 \quad (15)$$

$$0.344486x_1 - 0.082017x_2 + 0.007144x_3 - 0.012331x_4 \le 1.681628 \quad (16)$$

Thus the other two new mathematical models can be obtained. The optimum solution is the best among the three mathematical models.

7 Results and discussion

Three mathematical models were put into the linprog function in MATLAB software, then each model's optimum solution can be obtained as follows:

$$x = [7.48 \;\; 3.5 \;\; 87.8375 \;\; 40]\mathrm{T} \quad (17)$$

Two substituted items could not get the optimum solution due to the constraint of the frequency of tower, so they can be ignored.

For the convenience of establishing model and fabricating, the optimum result was adjusted to x=[7.48 3.5 88.4 40] T. Then the result was used to establish a model in SAP2000, and tip deflection at the top of tower is 0.493m, the first order frequency is 2.59733Hz, the second order frequency is 2.6848Hz, and the self-weight of tower is 122.6625t. Due to the linear regressive error, this model's parameters can be taken as the optimum parameters of the mathematical model.

In 2012, the market price of galvanized steel tube and GFRP was respectively 10000 RMB/t and 13000 RMB/t. So the weight of Steel wind turbine tower and GFRP wind turbine tower which have the same dimensions was respectively about 130t and 122.6625t, and the total price of them were respectively 1300000 RMB and 1594600 RMB, so the latter was about 300000RMB higher than the former.

8 Conclusions

1.5 MW wind turbine tower model was established using SAP2000 software, then the orthogonal experiment optimum design methodology was applied in the tower. The minimum self-weight of tower was selected as the performance target and the diameters and the wall thicknesses at the top and base of tower were selected as the four main factors in orthogonal experiment. EXCEL software was also applied to gain the linear regression equation in order to establish mathematical model. The range of the design variables was determined according to practical engineering experience, after that the mathematical model of the tower was established. Finally, the optimal solution of the tower was obtained by MATLAB.

The service life of steel tower is usually 20-30 years, while the GFRP tower is at least 50 years. The maintenance cost for GFRP tower is much less than steel tower due to the high corrosion resistance for GFRP. So it is possible that the steel tower would be replaced by GFRP tower in offshore area.

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