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Research of Turbine Tower Optimization Based on Criterion Method

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Abstract: Tower cost makes up an important part in the whole wind turbine construction especially for offshore wind farms. The main method to reduce tower cost is to reduce tower weight by optimum design. This paper proposes a two-level optimization criterion method for the optimal design of steel conical tower considering different structural reliability and uncertainty, along with the discreteness of design variables such as tower thickness and bolt type. In the first level, the tower shell geometry can be obtained by section design method; in the second level, bolted connections and flanges are designed based on the results of the first level. Then, summarized analysis and iterative calculation is performed to obtain optimum tower design with constant strength and rigidness. This method will play an important role in offshore customized turbine design.

Keywords: offshore wind turbine; tower design; two-level optimization; criterion method; section design

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1. Introduction

The cost of wind power has been reduced rapidly in the past ten years. With flexible capacity size, wind farms can be constructed in a short period and easy to configure as power capacity of per turbine is moderate. Additionally, wind turbine is of high reliability, easy to operate and maintenance. Therefore, wind power has become an important alternative energy source in the future [1]. In China, wind power capacity in the Three Norths (North China, northeast China and northwest China) is gradually saturated. At present, China wind development turns to the vast offshore region. Global offshore wind industry tends to have higher power compacity, longer and more flexible towers and blades [2,3]. To reduce wind power cost, offshore wind energy requires customized turbine design in which tower design plays an important part.

As the supporting structure of the wind turbine, tower makes up 15–30% in the total cost. Reducing the cost of the tower is beneficial to reducing the cost and improving the competitiveness of wind power. The main method to reduce the cost of the tower is to reduce the weight, that is, to optimize tower design with minimum weight as the goal. On tower structure type, tubular hybrid structural system and full-height lattice tower are proposed in order to reduce weight [4–7]. A lattice tower is constructed by connecting a steel truss with bolted connection. The larger base dimensions of this system help to resist applied loads more effectively leading to a lighter structural design. The lattice tower behaves better for seismic region based on the cost of energy [4]. As all members of the lattice are assembled by bolts exposed to harsh external environment, it is hard to guarantee the structure reliability and leads to maintenance trouble later. So, the classical conical steel tower is discussed in this paper.

On the settings of tower optimization, coupled blade-tower model [8] is presented to find the optimum design considering aerodynamic and structural performances. Generally, stress, strain, deflection, vibration and buckling limits are set as constrains; tower segment thickness, length and diameter are set as variables; single objective or multi-objectives are chosen from maximum annual energy production, minimum wind turbine weight, tower top displacement, maximum first-order mode frequency and minimum system vibration [8–19]. Frequently used towers for 2.5 MW or above turbines are usually "soft", i.e., the first order frequency is less or not too much larger than the turbine rated rotational speed. Additionally, both algorithm and hardware for control strategy have made rapid progress [18], and all those lead to that vibration between tower and blade is no longer a crucial point for turbine design. Influence of tower structure on turbine load calculation and power production is mainly the tower height, so there are not many coupling factors between tower design and blade once the tower height is determined. So, tower design itself is discussed in this paper.

On the optimization method, the classical gradient-based and gradient-free method, and the modern optimization method such as non-dominated sorting genetic algorithm (NSGA) and particle swarm algorithm are used [8–17]. First, parametric modeling technique is used to construct calculation simplified models (structural and/or aerodynamic), then parameters here are selected to be optimization variables, finally a certain kind of optimization strategy is adopted. Among these, icommercial software ISIGHT is used for optimization with built-in algorithm [11,12]. A faster stochastic method which focuses on the overall dynamic behavior based on the probability of structural stresses within the tower construction is investigated for an iterative tower design [14]. A hybrid beam-shell structural finite element model is constructed for efficient analysis of metal wind turbine support towers [19]. So far, in the optimization, the bolted connections and flanges accounting for about 10% of the total weight are usually neglected which is of great importance for tower safety [20]. The tower is artificially divided into a fixed number of segments which results in the final design depending on the segment number. Segment thickness is treated as continuous variables rather than discrete variables. Details such as the door opening at the bottom are not considered, leading to bottom buckling problems later. Optimum tower design cannot be obtained with rough design variables and oversimplified calculation models.

In this paper, a two-level optimization criterion method is proposed. The first level is the tower segment design, i.e., the starting and ending height and thickness of each tower segment are optimized without considering bolted connections and flanges. The number of tower segments is determined by optimization. On the basis of the results of the first level, the second level performs bolted connections and flanges design according to the constraints of flange segment length and weight. Finally, the optimization results of these two levels are summarized and analyzed to continue iterative optimization. Section design method is adopted to solve the problem of the uncertainty of the number of tower segments. Available tower shell thickness domain is exhaustively searched in ascending order and terminates when strength and rigidity constraints are met. Thickness returned is considered to be the optimum thickness for minimum weight. This tower design method is quite easy to realize and proves efficiently in practical application.

2. Criterion Method Used in Tower Optimization

In this section, the tower optimization problem to be solved is first described, and then optimization characteristics are analyzed based on which criterion method is proposed. Afterwards, the two levels presented in criterion method are elaborated in detail. In the end, additional remarks about criterion method are listed in summary.

2.1. Tower Design Inputs and Constraints

Too much attention is paid to optimization methods, but tower design analysis itself is rarely concerned. At the beginning, the inputs and constraints of the tower design should be clarified as follows. Geometry dimensions of tower, bolted connections and flanges are shown in Figure 1.

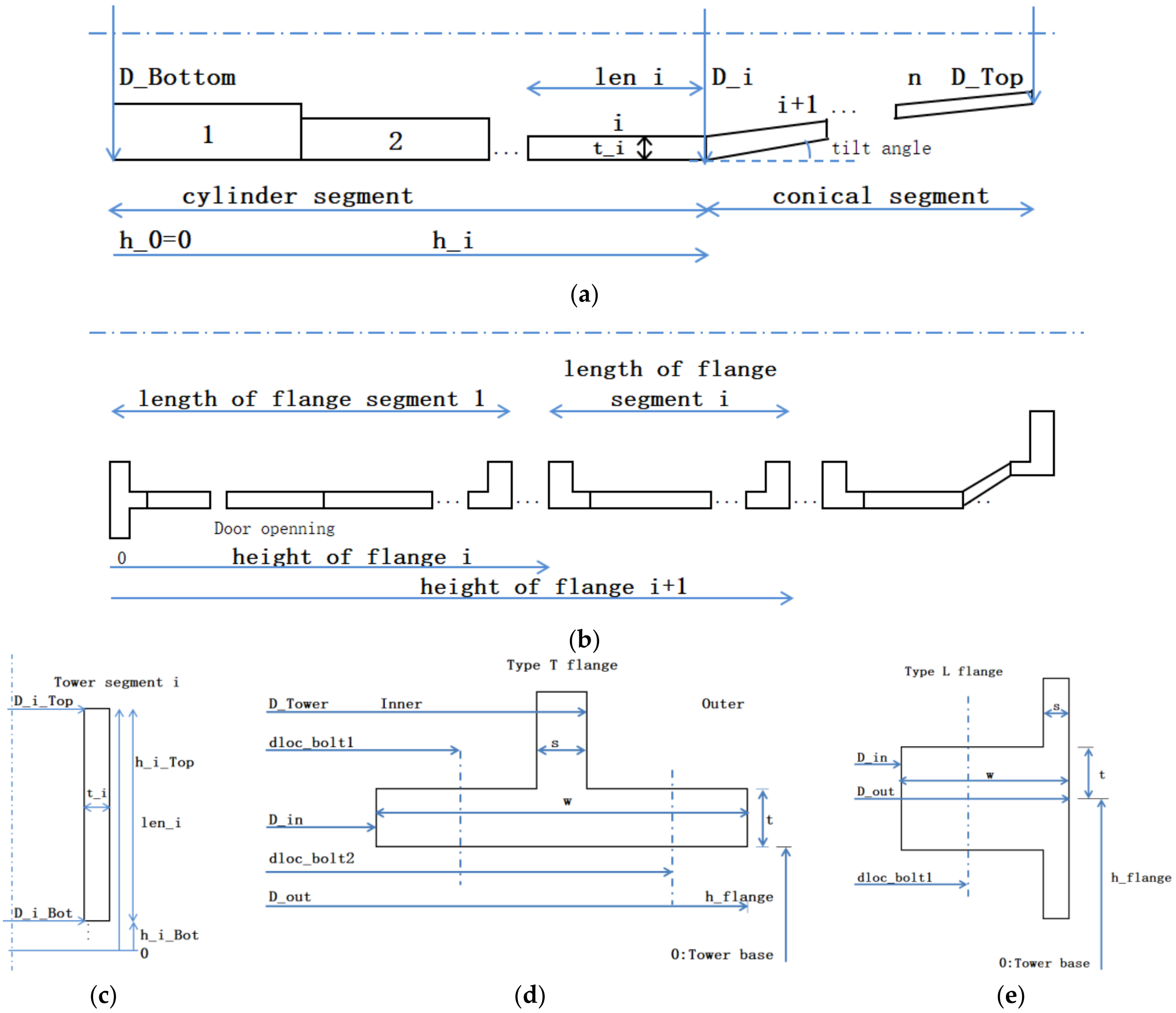

Figure 1. Geometry dimensions of tower and bolted connection (**a**) Tower segment profile (without flange); (**b**) Tower flange segment profile; (**c**) Tower segment; (**d**) Bottom flange (T Type); (**e**) Flange (L Type).

1. Available materials and corresponding material safety factors

Elastic modulus, density and yield strength (usually decreases with material thickness) of tower shell, flanges, bolts and even washes. Usually, material types are specified and do not need optimization. Material safety factors can be referred to GL2010 [21]. Available tower shell thickness can be obtained according to material supplier.

2. Available bolt types (Referred to Handbook of Mechanical Design [22])

Frequently used bolt types for turbine tower are M30, M33 M36, M39, M42, M45, M48, M52, M56, M60, M64, etc. Besides nominal diameter and stress area, bolt tightening method should be considered to obtain tightening force, torque and minimum spacing distance. Generally, bolt tightening force equals 0.7 times the production of yield strength and stress area. Different available bolt types can be set for each bolted connection, respectively.

3. Loads

Envelope loads of each available tower section should be provided. Because of tower top thrust force, section shear force (internal load) is much larger than the acting load (external load), and shear forces of adjacent sections change slowly, so loads of any middle section can be calculated by linear interpolation.

4. Geometry

As it can easily be deduced that the larger the diameter, the less the weight. So, the maximum diameter of the tower, i.e., bottom diameter should be constrained in advance. Usually, this maximum value is determined by transport constraints and process conditions. The maximum length and/or weight of per flange segment are also restricted by transport constraints. The diameter of the top section is determined by the yaw bearing, and tower height by wind resources and turbine capacity. The geometry of door opening is specified according to the installing equipment size and treated as constant inputs. Although these inputs along with tower design are finally determined by iteration analysis in turbine overall design, they are treated as constant inputs in tower design.

5. Safety constraints

Tower must satisfy strength and stability requirements. Additionally, the specified minimum safety factors can vary with section height. Safety factor configuration will be discussed in Section 3.3. Safety factors of bolted connections and flanges can be set, respectively, to each item (flange contact, flange strength and bolt strength) of each flange.

6. Control parameters for optimization

The thickness variousness range of adjacent tower segments basically determines the number of tower segments. Maximum thickness variousness of adjacent segments is specified according to eccentricity requirements, typically 6 or 4 mm. This value mainly affects the thickness of the tower bottom and the second segment. As tower thickness generally decreases with tower height, minimum thickness variousness can vary with tower height, larger in bottom part, less in top part.

Minimum tower segment length is also specified, typically min_len = 2000 mm. Iteration length used in section design is typically min_dlin = 200 mm, which is wide enough. As can be seen from Figure 1a, tower segment can be divided into cylinder segment with a constant diameter (tower bottom diameter) and conical segment with linear variation diameter (vary from tower bottom diameter to tower top diameter). Tower section stress can be calculated approximatively as $\sigma = M/W = M/(\pi D2t/4) = 4M/(AD)$, where M is section moment, D section diameter, t section thickness, $A = \pi Dt$ section area, so on the condition that allowable stress and section moment is definite, section area decreases with section diameter, i.e., tower weight decreases with section diameter, the longer the cylinder segment is, the less the tower weight is [23]. Tower tilt angle is specified to determine the maximum cylinder segment length. Or cylinder segment length can be directly specified. Original length of flange segments is specified at the beginning which is used to calculate section buckling factors. It is also the transfer parameters between Level 1 and Level 2.

These parameters will be discussed in Section 3.3.

2.2. Tower Optimization Analysis

Characters of tower optimization problem are analyzed as below.

1. Number of design variables is uncertain, and some design variables are discrete: tower can be divided into any unknown number of segments, and each segment has its independent unknown length and thickness. Tower shell thickness is restricted in available thickness region.
2. Constraints and objective are generally monotonous with design variables. According to mechanical analysis, safety factor of tower strength and stability increases with shell thickness; tower weight increases with shell thickness and decreases with section diameter. The closer the flange is to the tower bottom, the larger the bearing flange load is, and so the larger the flange weight is.
3. Coupling of design variables is weak. The strength and stability of tower segment i is basically determined by its own thickness but barely relevant with other segments. Design of bolted connections is closely related to flanges but seldom influences the overall strength and stability of tower.

Based on the above analysis, a two-level optimization criterion method is proposed. In the first level, bolted connections and flanges are neglected. The number of tower segments and geometry of each segment can be obtained given thickness variousness range of adjacent segments by section design method. This level mainly concerns strength and stability constraints and designs tower segments with minimum weight; in the second level, bolted connections and flanges are designed based on the results of the first level. This level mainly concerns maximum length and/or weight of per flange segment. Then, summarized analysis and iterative calculation is performed.

Tower optimization flow chart is shown in Figure 2.

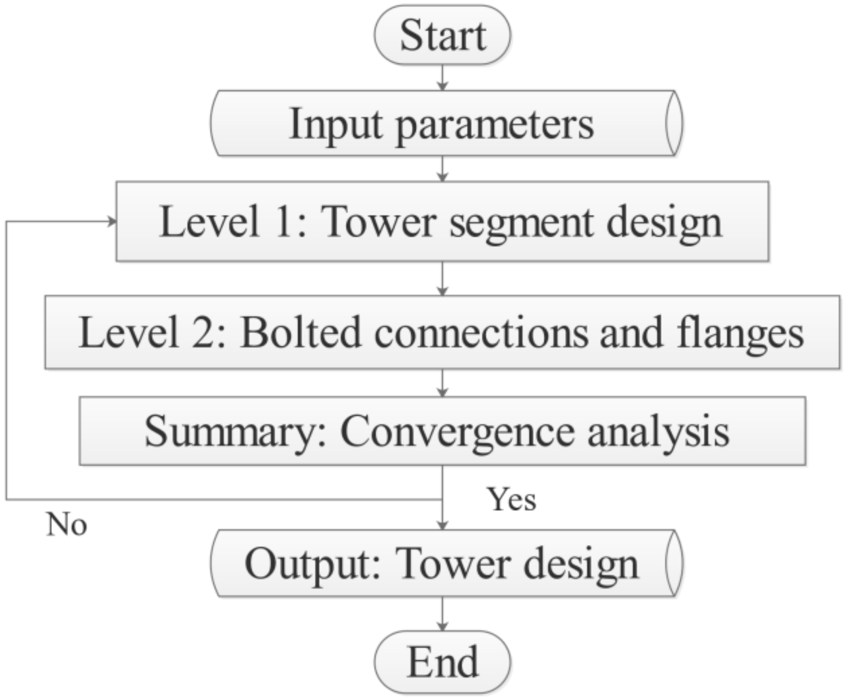

Figure 2. Tower optimization flow.

2.3. Level 1: Tower Segment Design

Section design method is used in the tower segment design. Strength calculation is referred to DIN18800-1 [24], and stability calculation is referred to DIN18800-4 [25]. Available tower shell thickness domain is exhaustively searched in ascending order, i.e., all thickness in the discrete thickness domain is iterated in order from smallest to largest to calculate constraint values such as thickness variousness, strength and stability requirements; the iteration is stopped once all constraints are met, and the corresponding thickness is considered to be the optimum thickness for minimum weight. As available thickness constitutes a limited discrete region, the calculation will consume a very short period of time. If it exists, the section design returns a minimum thickness or else returns null.

For stability calculation, boundary type of tower bottom is treated as RB1 (Fixed) and connected flanges is treated as RB2 (pin support). Calculation length is the corresponding flange segment length. Shell defect sensitivity is HIGH for axial buckling, NORMAL for shear buckling. Section buckling factor is the minimum value of axial, shear and combined buckling factors for conservation. In general, stability constraint is the compact constraint.

As tower weight decreases with tower diameter, the longer the cylinder segment length is, the less the tower weight is. So, cylinder segment length is first specified by the user or calculated from the maximum tilt angle. The diameter of any tower section is definite based on section height, bottom section diameter, top section diameter and cylinder segment length. The load of any tower section can be calculated by linear interpolation from input section loads.

Section design starts from tower bottom (h = h_1_Bot = 0) where door opening is located. The buckling factor should be reduced at this section based on door opening geometry. Thickness returned from section design of h = h_0 is the thickness of tower segment 1.

Thickness of tower segment 2 is that returned from section design of (h = h_2_Bot = h_1_Top specified in door opening geometry). Then, section design of height h = h_2_Bot + min_lin to tower height step by min_dlin is iterated until minimum thickness is returned. The top height of segment 2 is h_2_Top = h where loop terminates, and thickness of segment 3 is the returned thickness. This method is also used for subsequent sections.

Flow chart is shown in Figure 3.

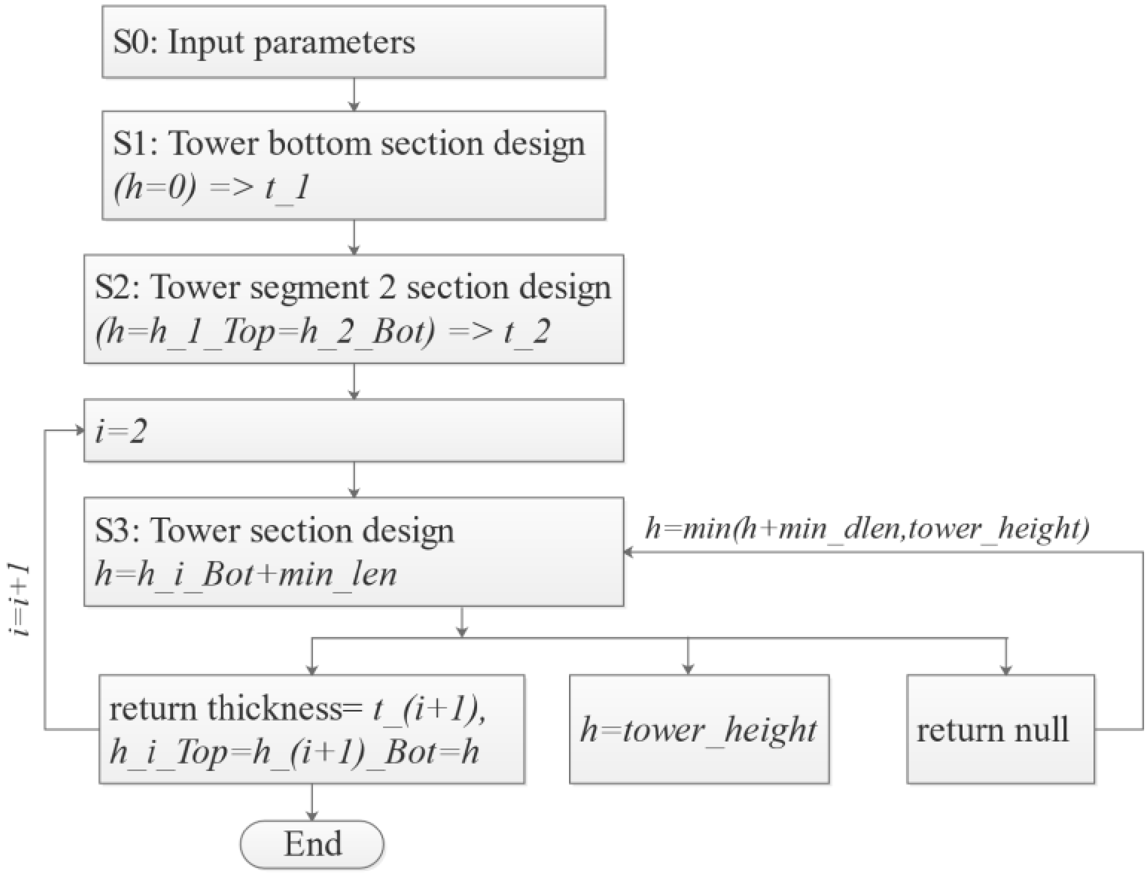

Figure 3. Level 1-Tower segment design flow.

Level 1 optimization returns the number of tower segments, starting and ending heights and thickness of each tower segment. So, the tower weight distribution with tower height can be calculated.

2.4. Level 2: Design of Bolted Connections and Flanges

Number of flange segments can be easily determined upon tower height, tower weight from Level 1 and transport length and/or weight constraints. Peterson algorithm [26] is used to calculate strength of bolted connections and flanges.

Then, the height of each mid flange is determined based on the following principles. Or the user can specify flange heights instead upon other considerations.

1. Weight and length of each flange segment should meet transport constraints.
2. Flange height equals to certain tower segment height, so that flange connects tower segments with different thickness. Or else length between flange and the bottom/top of the tower segment which flange locates at should not be less than min_h, i.e.,

h_i_flange = h_j_Top, or else
h_j_Bot < h_i_flange < h_j_Top,h_i_flange-h_j_Bot >= min_h,h_j_Top–h_i_flange >= min_h.
(*i* for flange ID, *j* for tower segment ID)

3. To reduce flange weight, flange height should be set as large as possible.

Weight of flange W is calculated as the following formula, where D is the flange out diameter in Figure 1, t is flange thickness and w is flange wideness, shown in Figure 1.

$$\begin{array}{c} W = \rho\pi D t w \\ \frac{\partial W}{\partial t} = \rho\pi D w, \frac{\partial W}{\partial w} = \rho\pi D t \end{array} \text{ Generally, } w > t \Rightarrow \frac{\partial W}{\partial t} > \frac{\partial W}{\partial w} \quad (1)$$

So the exhaustively searched method is adopted here and the design points are listed in the following sequence, where dt denotes flange thickness increment, and dw flange wideness increment. Design flow of of bolted connections and flanges is shown in Figure 4.

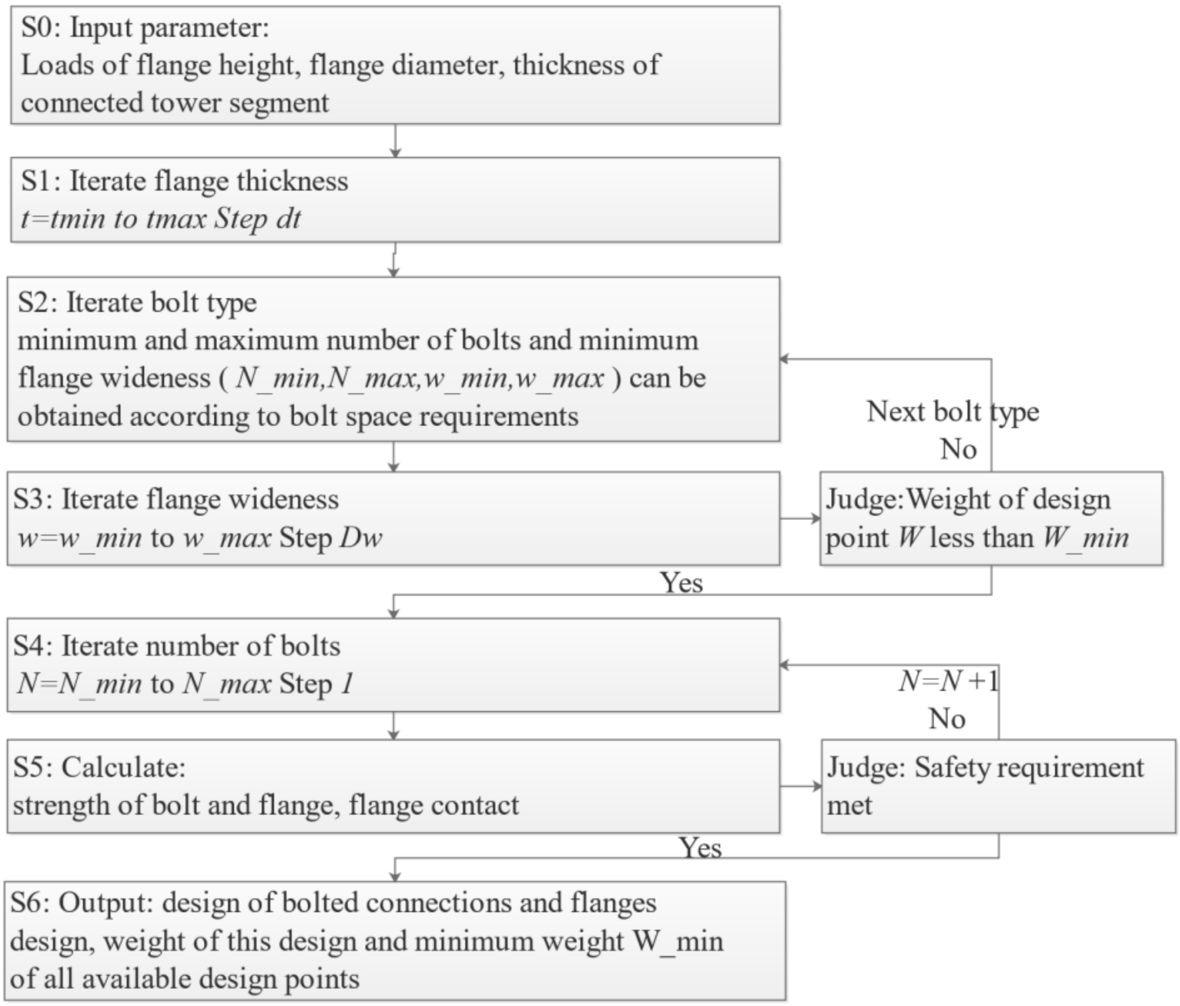

Figure 4. Bolted connections and flange design flow.

Bolted connections and flange design with minimum weight can be obtained by this method. Meanwhile, other available design points can be considered upon other considerations other than minimum weight. As Peterson algorithm is a simplified engineering fast method, it will not consume much time even using exhaustive method. Meanwhile, local optimum design can be avoided.

2.5. Summary

Transfer parameters between 2 levels are length of flange segments. After Level 2 is completed, update the transfer parameters and recalculate buckling factors in Level 1. If safety requirements are still met, no iteration is needed. Or else perform Level 1 and iterate.

As flange length has little effect on buckling factor in a certain range, convergence is quickly achieved in 0–2 iterations. As the specified minimum safety factors can vary with section height, constant strength/rigidness structure design can be obtained based on this criterion method.

3. Results

First, a 3 MW tower typically used in recently built onshore wind farms is optimized and compared with the original design to verify the method proposed in this paper. Then, a 10 MW+ offshore tower is designed with the criterion method. Optimum design is a compromise proposal between weight and safety factors. To reduce weight while keeping the same safety level is basically impossible. Tower design is not independent of turbine design, so a certain safety level of optimum design must be achieved considering different structural reliability and uncertainty.

3.1. Optimum for 3 MW Tower

The basic property of the 3 MW tower is shown in Table 1. As safety factors for original design is close to 1.0 or less than 1.0, the reduced percent of tower weight is less than 3%.

Table 1. Basic property of the original 3 MW tower.

Property	Unit	3 MW
Mass	[ton]	446.28
Height	[m]	137.5
Material	[-]	Q355D
Bottom Diameter	[mm]	4500
Top Diameter	[mm]	3780
Height of Cylinder	[m]	107
Height of Door Section	[m]	5.2
Min SF of tower segment	[-]	1.08
Number of flange segments	[-]	5
Flange Mass	[ton]	44.21
Flange Mass Ratio	[-]	9.91%
Remark	[-]	flange 1 contact danger

Constraints related to engineering reality is used in the optimization: minimum tower segment length is min_len = 2000 mm, and iteration length is min_dlin = 200 mm. As can be seen from the original tower shell thickness distribution, thickness variousness is generally no greater than 0.5 mm for adjacent segments with thickness less than 30 mm, and no less than 1mm for adjacent segments with thickness greater than 30 mm. In order to better estimate the tower optimization method, inputs should be as consistent as possible. So, tower segment thickness region is set as [16:0.5:30 31:1:56], which means discrete arithmetic sequence thicknesses region with minimum 16 mm, step 0.5 mm, maximum 30 mm, and minimum 31 mm, step 1.0 mm, maximum 56 mm. Minimum thickness variousness of adjacent segments is set 1 mm under 15 m height, 0.5 mm above 15 m height. The influence of the door opening at the bottom on the tower's strength is considered. Optimization is performed based on the approximate safety levels, shown in Equation (2).

$$sf_{\min} = \begin{cases} 1.1 & \text{height} < 40 \\ 1.05 & \text{height} \geq 40 \end{cases} \tag{2}$$

In addition to the tower segment design, bolted connections and flanges are also considered. For bolted connection construction, more bolts of smaller diameter are preferred than less bolts of larger diameter. According to original bolt type, the optimum bolt type is set as two grades upwards maximum (Referred to 2.1 Available bolt types). For example, if the original bolt type is M36, then the optimum bolt type is no greater than M42.

The uncertain number of design variables caused by the uncertain number of tower segments is perfectly solved by introducing section design method. As the optimization is divided into two levels, the overall calculation amount is small. The optimization can be completed in a few minutes run in an ordinary computer (RAM = 8 GB, CPU = 2.8 GHz).

After optimization, the weight of 3 MW tower reduces to 440.28 ton by 6.00 ton and 1.34%, weight of flanges is 36.48 ton, 8.29% of the total weight, shown in Table 2. Original and optimum tower segment thickness is shown in Table 3. Thickness and safety factors of original and optimum towers are shown in Figure 5.

Table 2. Optimization weight results summary of 3 MW tower [ton].

Item	Org	Opt	Reduced	Percent
Tower	446.28	440.28	6.00	1.34%
Flange	44.21	36.48	7.73	17.48%
Shell	402.07	403.80	−1.73	−0.43%
Flange Ratio	9.91%	8.29%	-	-

Table 3. Original and optimum tower segment thickness of 3 MW tower.

Original Design			Optimum Design		
t [mm]	FromH [m]	ToH [m]	t [mm]	FromH [m]	ToH [m]
50	0	5.15	48	0	5.2
44	5.15	7.738	43	5.2	7.2
42	7.738	10.538	41	7.2	9.2
40	10.538	15.738	39	9.2	11.2
38	15.738	19.95	38	11.2	14.2
37	19.95	22.75	37	14.2	18.2
36	22.75	25.55	36	18.2	23.4
35	25.55	28.35	35	23.4	28.6
34.4	28.35	31.15	34	28.6	33.6
32.6	31.15	33.95	33	33.6	38.8
31.2	33.95	36.75	32	38.8	40.8
30.7	36.75	39.55	31	40.8	44.8
30.2	39.55	42.35	30	44.8	47.6
29.7	42.35	45.15	29.5	47.6	50.4
29.2	45.15	47.425	29	50.4	53.2
28.8	47.425	49.905	28.5	53.2	56
28.4	49.905	52.705	28	56	58.8
27.9	52.705	55.505	27.5	58.8	61.6
27.4	55.505	58.305	27	61.6	64.4
26.9	58.305	61.105	26.5	64.4	67.2
26.5	61.105	63.905	26	67.2	70
26	63.905	66.705	25.5	70	72.8
25.5	66.705	69.505	25	72.8	75.8
25	69.505	72.305	24.5	75.8	78.6
24.6	72.305	75.105	24	78.6	81.6
24.1	75.105	77.405	23.5	81.6	84.6
23.6	77.405	79.865	23	84.6	86.6
23.3	79.865	82.665	22.5	86.6	88.6
22.8	82.665	85.465	22	88.6	91.4
22.1	85.465	88.265	21.5	91.4	94.2
21.6	88.265	91.065	21	94.2	97.2

Table 3. *Cont.*

	Original Design			Optimum Design	
t [mm]	FromH [m]	ToH [m]	t [mm]	FromH [m]	ToH [m]
21.1	91.065	93.865	20.5	97.2	100
20.6	93.865	96.665	20	100	103
20.2	96.665	99.465	19.5	103	105.8
19.7	99.465	102.265	19	105.8	107.6
19.2	102.265	105.065	19	107.6	110.2
18.8	105.065	107.395	18.5	110.2	117.8
19.1	107.395	107.675	18	117.8	124.8
18.3	107.675	109.857	17.5	124.8	131.6
18.2	109.857	112.657	17	131.6	137.5
18	112.657	115.457			
17.8	115.457	118.257			
17.6	118.257	121.057			
17.4	121.057	123.857			
17.3	123.857	126.657			
17.1	126.657	132.257			
17.5	132.257	135.057			
30	135.057	137.5			

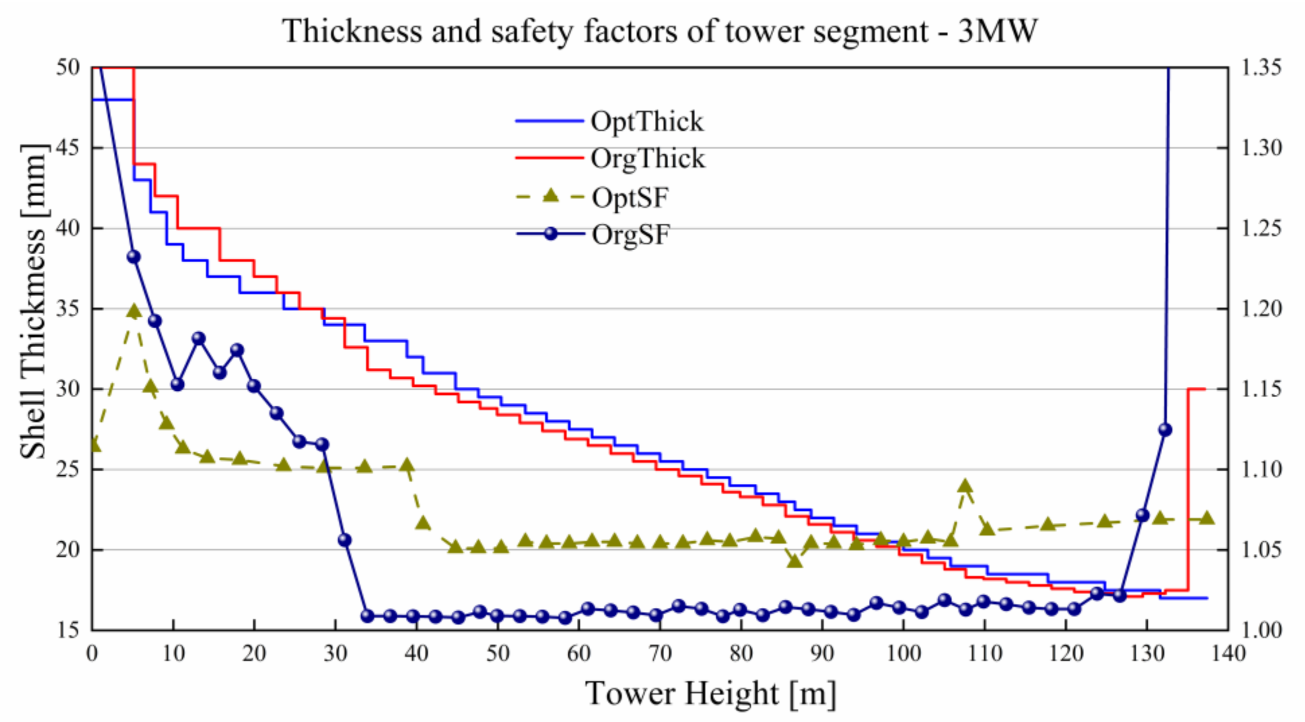

Figure 5. Thickness and safety factors of original and optimum 3 MW tower segments.

As can be seen from Table 3, the thickness of the initial tower design changes rather slowly, which leads to a great many segments. After optimization, the number of segments is reduced. According to Figure 5, the designed safety factor level of tower segment is higher than that of the original, so the optimum mass of tower shell is larger relative to the original. As door opening undermines the stability of tower segment and tower thickness cannot reduce rapidly, sections except tower bottom and the minimum safety turning region are generally designed with constant strength and rigidity.

Parameters and safety factors of bolted connections and flanges are shown in Figure 6.

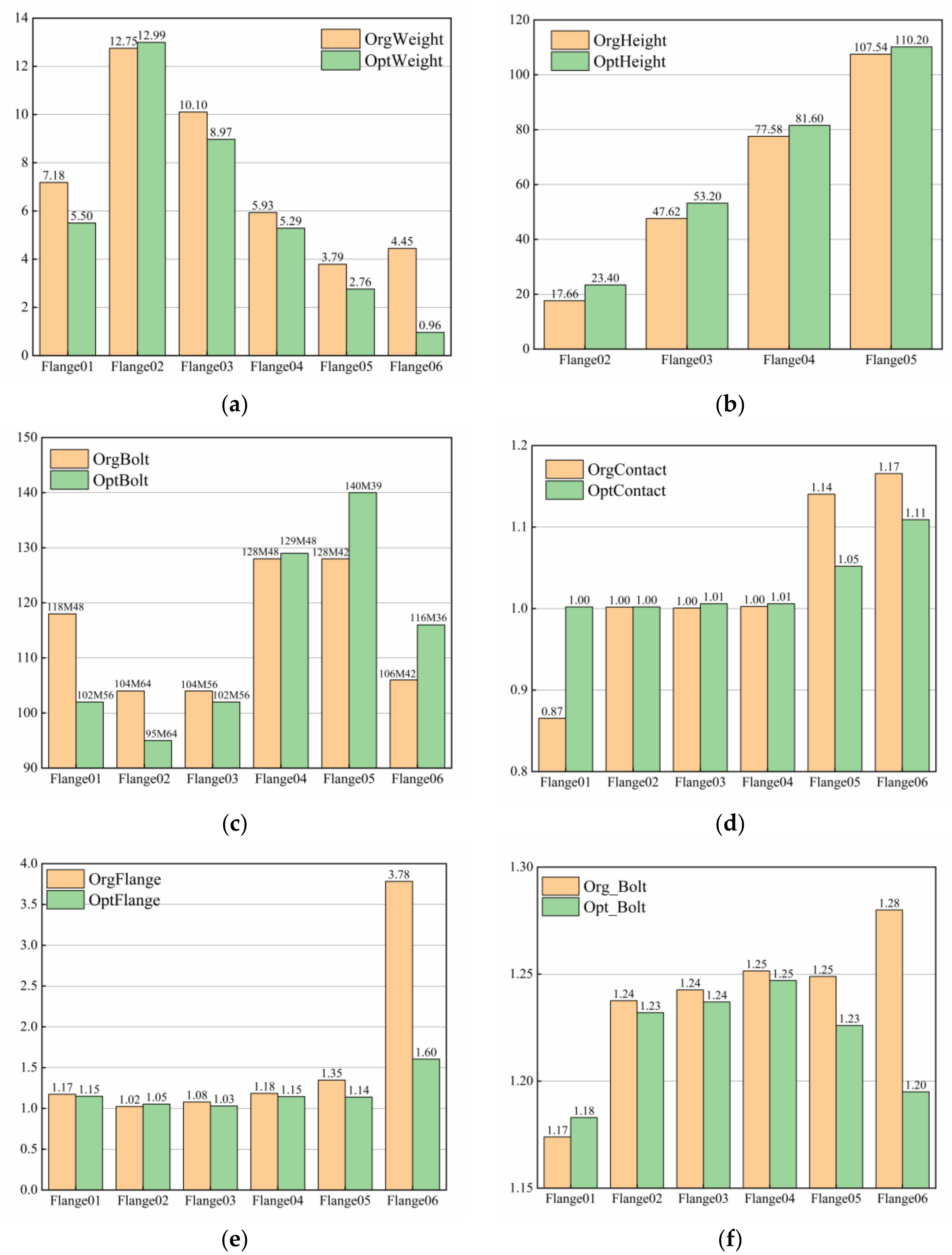

Figure 6. Property and safety factors of original and optimum 2MW bolted connections and flanges. (**a**) Weight of flanges; (**b**) Height of flanges; (**c**) Bolt settings; (**d**) Safety factors of contact; (**e**) Safety factors of flange strength; (**f**) Descrip Safety factors of bolted connection.

As can be seen from Figure 6, the optimization improves strength of bolted connections and flanges. Safety factors of contact, flange strength and bolted connection are distributed more reasonably.

Reduction weight of the 3MW tower mainly depends on bolted connections and flanges. So, optimization of bolted connections and flanges in tower design cannot be neglected, especially for original tower design with low safety level for which reduction weight of tower shell is seldom feasible.

3.2. Design of Certain 10 MW+ Offshore Wind Turbine Tower

Basic requirement of the 10 MW+ offshore wind turbine tower is shown in Table 4.

Table 4. Basic requirement of 10 MW+ offshore wind turbine tower.

Property	Unit	10 MW+
Mass	[ton]	<670
Height	[m]	105
Material	[-]	Q345D
Bottom Diameter	[mm]	7500
Top Diameter	[mm]	5000
Height of Cylinder	[m]	0
Height of Door Section	[m]	5.2
Min SF of tower segment	[-]	1.2
Number of flange segments	[-]	5
Moment of tower top	[Nm]	4.10×10^7
Thrust of tower top	[N]	2.30×10^7
Moment of tower bottom	[Nm]	3.50×10^7

Constraints used in the optimization is: minimum tower segment length is min_len = 2000 mm, and iteration length is min_dlin = 200 mm. Tower segment thickness is considered as discrete and selected from available thickness region [25:56]; minimum thickness variousness of adjacent segments is set 1 mm, the maximum thickness variousness 4 mm. Optimum tower design can be obtained based on the criterion method. Segment thickness is shown in Table 5. Thickness and safety factors of optimum tower are shown in Figure 7.

Table 5. Optimum tower segment thickness of 10 MW+ offshore wind turbine tower.

t [mm]	FromH [m]	ToH [m]
56	0	5.2
52	5.2	7.2
48	7.2	9.2
44	9.2	11.2
42	11.2	13.2
41	13.2	15.2
40	15.2	17.2
39	17.2	19.2
38	19.2	25.8
37	25.8	33.8
36	33.8	36
34	36	43.2
33	43.2	49.8
32	49.8	55.6
31	55.6	61
30	61	66
29	66	70.4
28	70.4	74.6
27	74.6	78.6
26	78.6	82.2
25	82.2	105

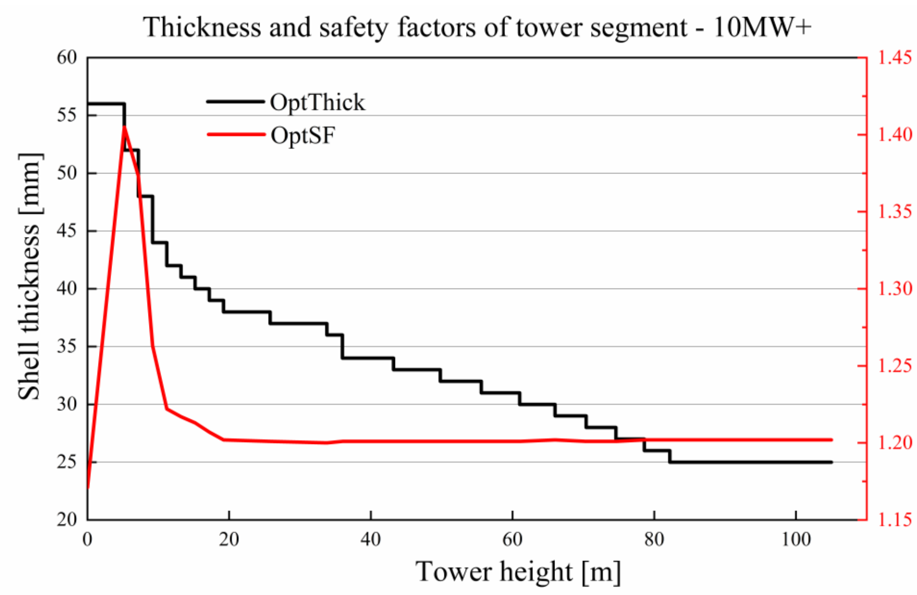

Figure 7. Thickness and safety factors of 10MW+ tower segment.

As can be seen from Figure 7, sections except for tower bottom are generally designed with constant strength and rigidity. For the tower bottom, door opening undermines the stability of tower segment and tower thickness cannot reduce rapidly.

Parameters and safety factors of bolted connections and flanges are shown in Table 6.

Table 6. Parameters and safety factors of bolted connections.

Item	Unit	1	2	3	4	5	6
h_flange	[m]	0	13.2	31.1	52.8	78.6	105
D_In	[mm]	6446	6235.7	6107.5	5638.9	5236.6	4730
t	[mm]	210	180	165	155	135	100
D_Out	[mm]	7500	7185.7	6759.5	6242.9	5628.6	5000
dloc_bolt	[mm]	7232	6959.7	6541.5	6048.9	5446.6	4850
Bolt	[-]	168 × M60	168 × M56	156 × M56	180 × M48	159 × M48	164 × M36
flange mass	[ton]	19.595	29.105	17.727	14.243	7.4751	1.7776
bolt strength safety factor	[-]	1.18	1.243	1.234	1.249	1.235	1.177
bolt load safety factor	[-]	1.989	2.749	2.612	2.855	2.629	1.963
flange strength safety factor	[-]	1.122	1.129	1.109	1.115	1.122	1.588
flange contact safety factor	[-]	1.051	1.052	1.052	1.054	1.051	1.112

In conclusion, Total mass of tower is 631.0 ton, less than the 670 ton required. The safety requirements are generally met. This tower design can be used in initial offshore turbine structures and be updated with the turbine design.

3.3. Discussion of Control Parameters in Optimization

The influence of safety factors, thickness variousness range and minimum tower segment length on tower weight is discussed in this chapter. The 10 MW+ offshore tower in Section 3.2 is taken as an example.

➢ Safety factors

Safety factors can be used to identify the uncertainty of design constraints and reliability of the tower structure. For example, if the tower is designed for a certain type of wind class and power level, the safety factors can be higher; for a specified wind farm, safety factors can be medium; for customized turbine design, safety factors can be just above one.

Tower segment design according to different safety factor level (flanges and bolted connection neglected) is shown in Figure 8. Tower segment weight VS. safety level is shown in Figure 9.

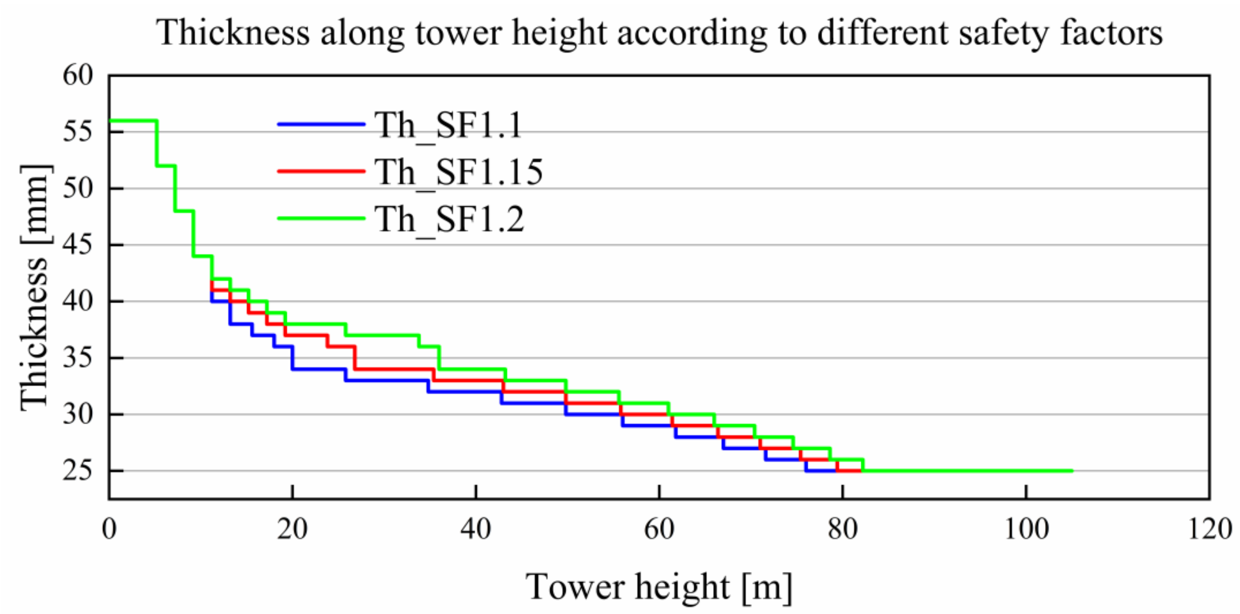

Figure 8. Thickness along tower height according to different safety factors.

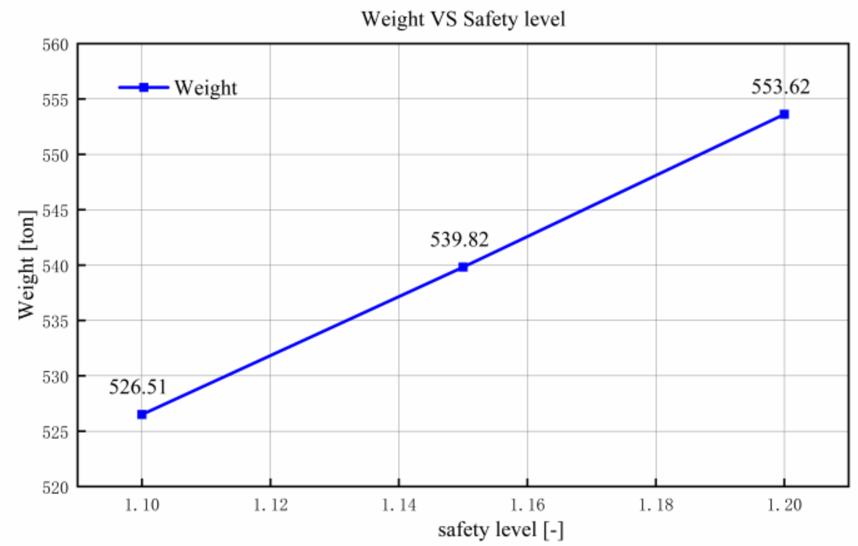

Figure 9. Tower segment weight VS. safety level.

As can be seen from Figures 8 and 9, tower weight increases with the safety level. So, if the uncertainty of design constraints and reliability of the tower structure can be evaluated more precisely, tower weight will be reduced by a considerable amount.

- Thickness variousness range and minimum tower segment length

Generally, if constraints for thickness variousness of adjacent tower segments is relaxed, i.e., thickness along tower height can change very slowly, the total weight will be reduced. However, it will bring manufacturing troubles. So does the minimum tower segment length. The tower cost with respect to the tower weight and manufacture can be optimized as the objective in further research.

Tower segment design according to different thickness variousness level (flanges and bolted connection neglected) is shown in Figure 10. Tower segment weight and the number of segments of different thickness VS. thickness variousness is shown in Figure 11.

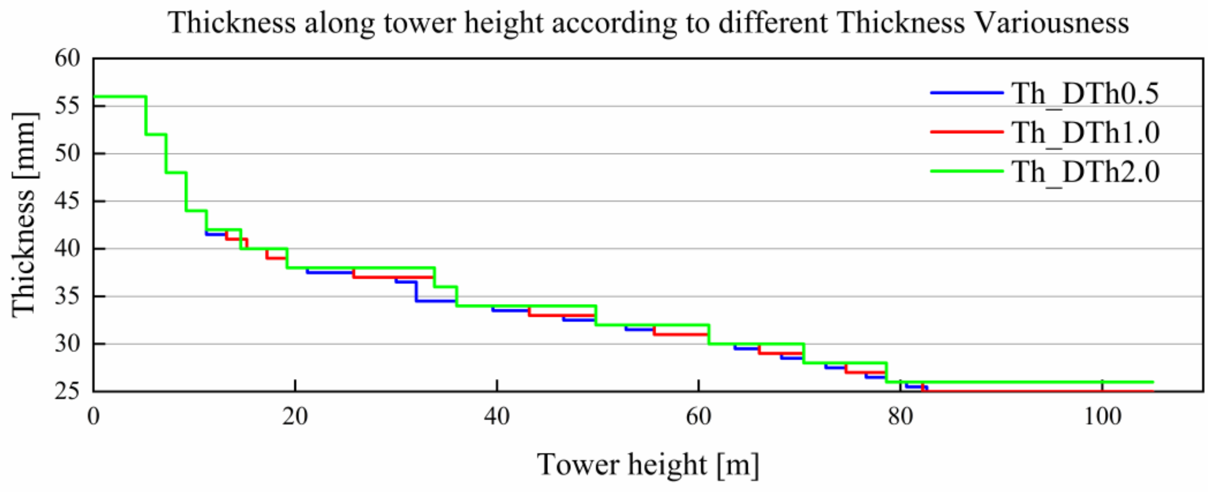

Figure 10. Thickness along tower height according to different thickness variousness.

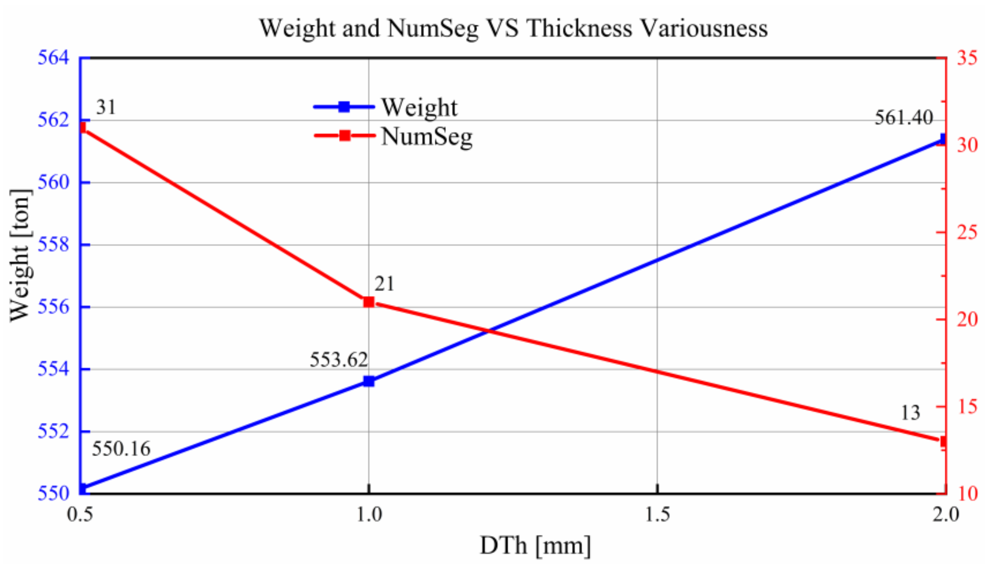

Figure 11. Weight and number of segments of different thickness VS. thickness variousness.

As can be seen from Figures 10 and 11, when the minimum thickness variousness increases, tower weight increases and the number of tower segments decreases. This can be considered with the manufacture cost function for further research.

4. Discussion

Two-level criterion method for turbine tower optimization is presented in this paper, in which the discreteness of design variables such as tower thickness and bolt type is considered, and the problem of the uncertainty of the number of tower segments is perfectly solved by the section method proposed. This optimization method is quite easy to realize and shows efficient performance. Based on this method, the number of tower segments can be obtained rather than previously designated. Segment thickness is treated as discrete variables in available tower shell thickness region. Bolted connections and flanges are included in the optimization to assure connection reliability. With minimum sectional safety factor assigned as constraints, tower design with constant strength and rigidness can be achieved.

This optimization method can be used in blade-tower coupled models for refined tower design. Sectional safety factors can be quantified considering structural reliability and the uncertainty evaluation with strict mathematical analysis for further study.

5. Summary

Engineering reality is sufficiently considered in the two-level criterion method presented in this paper, so it can be directly used in the offshore turbine tower design with a few modifications. Configuration of different safety levels can ensure extensive applied range considering different structural reliability and uncertainty. It will play an important role in customized offshore turbine design through concept, initial, and detailed design stages.

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