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New Lattice-Tubular Tower for Onshore WEC – Part 1: Structural Optimization

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Abstract

Currently, onshore wind turbines are economical for 2.5 mega-watt inland installation [1]. One of the alternatives to achieve the higher power capacity in onshore wind turbines is to go to higher altitude, which increases the wind speed and has more uniform wind pressure, leading to higher possible annual energy production and relatively lower maintenance costs due to wind shear induced vibrations.

This paper deals with a predesign of a new type of tower that should overcome known disadvantages of steel tubular towers for heights over 150 meters. This first part of the paper addresses the viability of a hybrid support structure in respect of ultimate limit states and structural dynamics as part of the requirements in exploring the feasibility of the hybrid tower concept.

The hybrid wind turbine tower concept consists of a lattice (lower) structure and a tubular tower for the higher tower segment. The study cases found in literature were designed with maximum height of 160m and the 2.5MW wind turbine. Moreover, they used commercial "L" sections which leads to high number of connections and bolts. The project that supports the present paper aims at using optimally design hollow cross sections, to reduce the number of connections, and low maintenance type bolts. The developed study case is made for 220m tower height and using 5MW wind turbine.

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1. Introduction

Onshore wind energy is a very competitive renewable energy alternative to fossil fuels. The status of installed wind energy capacity was more than 141 GW by the end of 2015 [1]. However, technological advancement suggests refurbishing and replacement of the old facilities with new technology might increase the profits with lowering the maintenance cost and increasing the power output by increasing the height [2]. A new design approach of lattice tubular tower has been developed in this study in which the lower part of tubular part is replaced with the lattice structure and the tubular tower was connected to the lattice structure with a transition piece. The aim in this approach is to reduce the base diameter of the tubular segment used in a tower to facilitate the transportation. Although several similar lattice tubular supporting structures were proposed as an onshore wind turbine supporting structure, the objective of this study is to use new type of bolted polygonal built-up cross sections and to reduce number of the connections in the lattice tower, thereby reducing the number of the installed bolts.

An iterative process based on the numerical aeroelastic simulation of the complete tower and turbine was used in the design of the lattice structure and the tubular tower. The time series of the force and moments were obtained using ASHES (aero-servo-elastic simulation software) and post processed for the calculation of the ultimate limit state and the dynamic behavior which are explained in the companion paper.

The main contribution of this paper is the preliminary design of the high rise hybrid steel lattice tubular wind turbine tower with the optimal weight and number of connections in lattice structure. Main design parameters are the spread of the lattice structure, number of legs, brace configuration and inclination angle. The lattice topology and the brace configuration were investigated. The results are presented and compared in order to select the optimal design.

2. Lattice tubular tower design

2.1. Topology

Lattice structures are widely used in energy industries and buildings [3].The lattice structures were used as the offshore wind turbine sub-structure. Many research have been conducted to optimized different aspects of jacket structures [3–9]. A transition piece is used as a connection between the lattice structure and tubular tower.

The design of the 220 m lattice tubular tower presented here, as it is shown in Fig. 1, provides the support for tubular tower and enables reaching higher altitudes without large diameter of the tubular tower base. Moreover, the overturning moment can be resisted more effectively with larger base diameter. The site specification and RNA (rotor nacelle assembly) define the operational loads for the structural design.

Height to spread ratio, number of legs, brace's angle and the cross sections are governing parameters to be investigated in the design process and iterative optimization.

In this study, 4 and 6 legged, 1/1 to 6/1 height to base spread ratio (H/S) ratio and x and k bracing with and without horizontal bracing (HB), are investigated and the element's cross section dimensions are obtained based on the design for gravity and aeroelastic loads. The optimized structure is chosen corresponding to mass of the lattice structure and number of the required bolts in the connections.

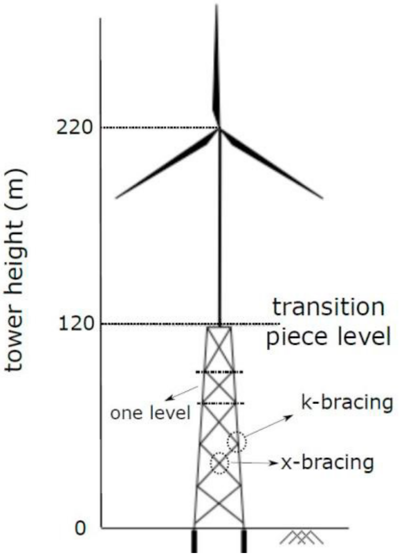


Fig. 1. Lattice tubular tower illustration

2.2. Simulation model and initial load conditions

The NREL 5MW wind turbine [11] is used in this study. The controller, power electronics, generator, blades and other parts properties are NREL baseline turbine. The full model is built in ASHES [12] and the loads are obtained for the specific load case from IEC61400-1 [13] which are explained in the companion paper in detail [14]. The design load envelopes are used in the structural verification. Loads are applied on the top of the lattice part, while in the final design in which the tubular part is included, the loads are applied at the top of tubular part. As the lattice structure is double symmetrical for both case (4 legged and 6 legged structures) the wind loads were applied in two direction, acting in the direction of the pylon and on the face of the lattice structure.

2.3. Iterative approach

The iterative design approach [3] is used with coupling the ASHES and SAP2000 as an aeroelastic and structural analysis software respectively. The iterative approach is depicted in Fig. 2. The cross section properties are derived based on the applied loads and the selected geometry configuration.

First steps are carried out by ASHES software. The columns, braces, tubular tower and blades are modeled by using flexible linear beam elements and Rayleigh damping for steel material while the transition piece is considered as a rigid body. The design load cases are used to create load table. In the step 3, the lattice structure cross sections are calculated to obtain the dimensions and then verified by ultimate limit state and buckling checks. Furthermore, the transition piece and tubular part are added to the selected models to finalize the dimensioning and integration of the hybrid tower.

The structure is finalized when all the structural checks and structural integrity are fulfilled. These criterions include natural frequencies to avoid near-resonance behavior, tower blade tip clearance and top displacement.

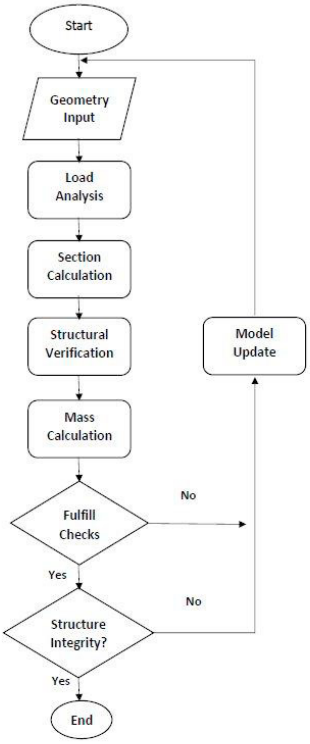


Fig. 2. The iterative design methodology

2.4. Structural verification checks

Design verifications of the members are carried out in SAP2000 according to EN1993: 1-1 and number of the bolts in the connections are calculated according to EN1993:1-8.

Loads acting on the structure are self-weight of the structure and the wind load. Buckling length of the brace members is considered as the length of the brace member, while the buckling length of columns is the distance between connected brace members on columns. Open polygonal sections buckling curve (curve D) is adopted for the verification. At present stage no fatigue verifications are performed, since the preliminary design governing criterion is assumed to be members' stability.

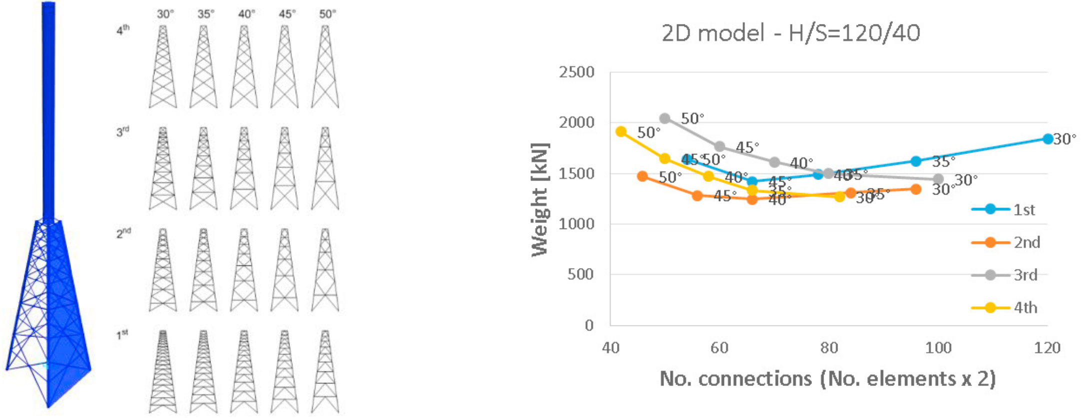
3. Geometry optimization

The 2D analysis of the different bracing configurations (Fig. 3a) are carried out on a face of 4-legged lattice structure. Weight and number of the connections for each typology is determined and compared. The number of the connections in the structure is considered number of the bracing elements multiplied by two. All the cross sections of columns and braces are considered the same along the height.

The optimum solution regarding the ratio between the weight and the number of connections of the structure seems to be obtained with the X braces and horizontals at the level of the interception of the braces. The brace angles between 30° to 50° are considered to improve assembling feasibility.

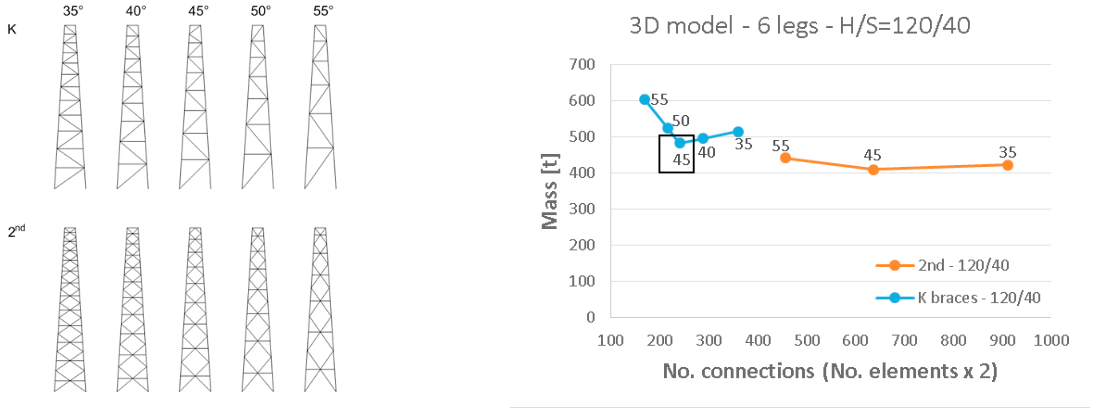
This solution has the lowest number of connection for 4-legged lattice structures, however, it leads to too many connections if the 6-legged lattice structure is considered. Therefore, K-bracing was investigated besides the X-bracing for the 6-legged lattice structures.

In Fig. 4 the comparison of 3D model of the 6-legged structure with K-bracing and X-bracing is depicted. K-bracing comparing to X-bracing has significantly lower number of connections. Inclination angle of 45° has the lowest mass to number of connection ratio, therefore this angle is adopted for further analysis.



(a) (b)

Fig. 3. (a) Different bracing configuration, (b) The weight to No. Connections ratio for the corresponding models



(a) (b)

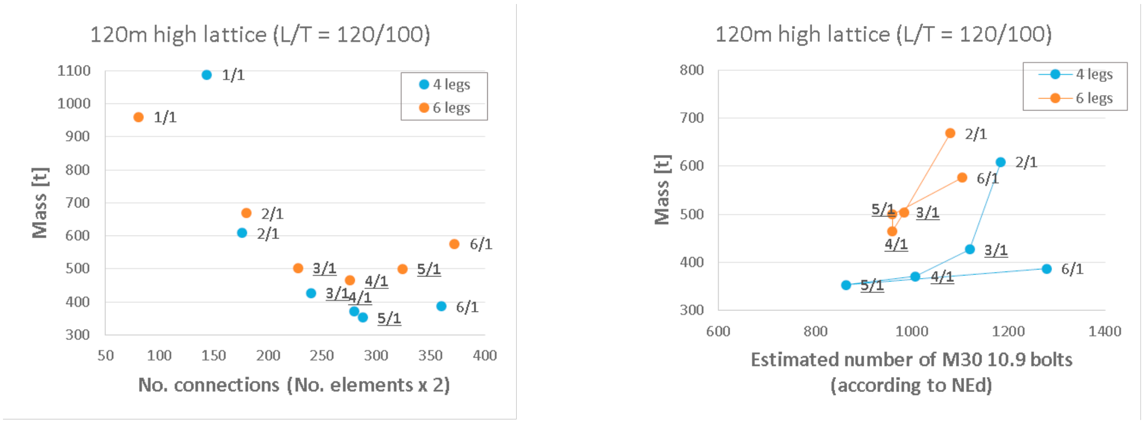
Fig. 4. (a) 6-legged bracing system, (b) braces inclination angle

4. 3D structural design

4.1. Parametric optimization

The previous geometry optimization has shown that the X-bracing with 45° for 4-legged lattice and K-bracing with 45° for 6-legged lead to better mass to number of connection ratio. Therefore, 4-legged and 6-legged lattice structures using same bracing systems and different H/S ratio of 1/1 to 6/1 are comprehensively considered. Fig 5 shows the mass to number of connection and the estimated number of bolts in the connections for different lattice structures.

The H/S ratio of 5/1 for 4-legged and 4/1 for 6-legged lead to lower mass and number of connections which means lower number of estimated bolts. 6-legged lattice structures showed more mass than 4-legged. In order to investigate possible mass reduction in 6-legged lattice structures the horizontal braces are omitted. The H/S ratios of 1/1, 2/1 and 6/1 lead to extreme mass or number of connections, thereby, they would not be desirable case studies for further detail design.



(a) (b)

Fig. 5. (a) The mass and the number of connections, (b) the mass and the estimated number of bolts

Table 1 compares the behavior of 4-legged and 6-legged lattice structure. It is clear that the structural mass and the maximum tensile force in the foundation for 6-legged structures are less than 4-legged structures. Moreover, removing the horizontal braces in 6-legged structure does not influence the structural responses and the mass reduction happens due to omitting the horizontal braces, although the pylon cross-section increases.

Table 1. Mass, dynamic response and ground support reactions comparison for 4-legged and 6-legged towers

	H/S	Mass[t]	R3†[kN]
4 legs	3/1	1060	9281
	4/1	1050	15423
	5/1	812	22847
6 legs With HB	3/1	1088	12424
	4/1	1021	16429
	5/1	1008	22873
6 legs Without HB	3/1	1073	12433
	4/1	990	16484
	5/1	976	22944

The 4 and 6-legged lattice structures with H/S ratio of 3/1, 4/1 and 5/1 and using the tubular tower and considering two light (50 tonnes) and heavy (250 tonnes) transition piece are simulated and the cross sections are calculated. Table 2 shows the fore-aft displacement at the transition piece level and tower top.

Table 2. Displacement of the supporting structure with light and heavy transition piece

			L4-120-24	L4-120-30	L4-120-40	L6-120-24	L6-120-30	L6-120-40
With 50 tonnes Transition	**Tower top**	u_x **[mm]**	4032	3530	3364	4193	3935	3646
	Transition piece	u_x **[mm]**	383	198	127	412	300	184
With 250 tonnes Transition	**Tower top**	u_x **[mm]**	3984	3520	3354	4184	3925	3636
	Transition piece	u_x **[mm]**	382	197	126	411	299	183

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† Maximum tensile force in the foundation

Table 3 presents the cross section dimensions for two optimal lattice structures. 4-legged lattice with H/S=5/1 with mass to number of bolts equal to 0.61 and 6-legged lattice without horizontal braces and with H/S=5/1 having mass to number of bolts equal to 0.98 were selected as the most favourable structures.

Table 3: Maximum and minimum dimensions of columns, diagonals and braces

	Column Diameter and Thickness [mm]	**Max. Diagonal Diameter and Thickness [mm]**	**Min. Diagonal Diameter and Thickness [mm]**	**Max. Brace Diameter and Thickness [mm]**	**Min. Brace Diameter and Thickness [mm]**
6-legged, H/S =4/1	1350-35	530-14	440-6	---	---
4-legged H/S = 5/1	1500-35	390-14	330-14	310-14	250-14

5. Conclusions

Future investments in onshore wind turbine installations are highly required in order to decrease the cost for repowering and new installation based on new supporting structure. Therefore, the analysis of several support structure types is an important step to identify the potential in cost reduction by an optimized design. The presented hybrid lattice/tubular tower is an alternative design solution. Since several factors influence the lattice structure design, a comprehensive parametric study is planned. The parametric study presented in this paper shows optimal solutions based on the realistic optimization criteria. The paper presents a first stage of a complete analysis of the hybrid lattice/tubular tower concept. Further work will focus on the improvement of parameter studies and the cost assessment of the concept in future wind park installations.

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