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MATERIAL OPTIMISATION USE IN STEEL LATTICE WIND TURBINE TOWERS

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Abstract. *Since sustainable energy production has become essential in order to confine the Greenhouse effect consequences, the number of wind farm installation will continue to rise. In addition, since the tower of on-shore wind power generators is about one third of the initial construction cost, there is additional investigation needed to optimize the tower configuration, aiming in eliminating the initial cost and the material used. To this end, and towards taking advantage of the higher energy potential in greater heights, the wind converters' tower concept needs to be configured to be lighter and taller. Getting inspiration from telecommunication masts that are constructed as lattice towers and taking into account certain transportation restrictions of classic tubular wind tower subparts, the solution of lattice wind turbine towers is implemented aiming to achieve greater tower heights. The structural behavior of telecommunication masts has been investigated in the work of Tsitlakidou et al. and Efthymiou et al. , mainly concentrating on towers consisting of standard L shaped cross-sections fabricated in the factory and mounted on site. For wind converters, the scale of the lattice structure capable of supporting the weight and function of the nacelle is way outside the conventional industrial steel profiles. The lattice tower proposed to accommodate the wind converter has a form of a truncated cone with a square cross-section. This type of tower is a statically determinate system, composed of a certain number of discrete structural sub-systems, each with a certain function and applicability. These sub-systems are: the legs, the bracing trusses on the faces, horizontal braces and secondary bracings arranged in the plane of the face bracing trusses and outside (hip braces). All the aforementioned structural sub-systems serve for a particular role in the load transfer mechanism of the lattice tower and since the whole structure is considered a structurally determinate system, the axial stresses of the members can be determined by closed form expressions. The present paper addresses the stability performance of a lattice steel wind turbine tower, examining alternative solutions of bracings. More specifically the tower has the same height of an equivalent tubular one and bears the same loading. An algorithm has been elaborated in Mathematica software that uses an iterative procedure to design the tower members, the need of secondary and hip bracing and evaluates the total material used. The iterative procedures solves the material optimization problem and provides valuable feedback on the effect of secondary bracings on the economy of the material and the tower's structural robustness.*

1 INTRODUCTION

The fossil fuels shortage and the CO_2 that are exacerbating the greenhouse effect have led to the expansion of renewable energy sources use for energy production. To this end, the European Commission has established the European Union Renewable energy directive accepted by all member States, setting a target of 20% final energy consumption produced by renewable sources by 2020 [1]. Wind energy has been proved as one of the most promising renewable energy sources due to its great potential and infinite nature. Hence its evolution the past ten years has been remarkable. Indicatively the power capacity of wind parks installed in Europe has tripled from about 50 GW in 2005 to over 150 GW in 2016 [2]. Since investments on onshore wind structures are becoming bigger in number, there has been a higher demand for minimizing design, material and construction costs. The tower constituting more than 25% of the initial wind turbine cost [3], needs to be investigated and optimized in terms of morphology and material use. In the present work, the structural configuration of onshore wind turbine towers is investigated and analysed in terms of structural behaviour and material use. The aim of the investigation is to minimize the wind tower initial construction cost by means of limiting the material while maintaining its robustness.

The tower configurations for horizontal axis onshore wind converters are: the tubular steel tower, the lattice tower and the hybrid tower; which combines a truss structure for the lower part and a tubular one for the upper part. The dominant structural configuration is the tubular steel tower due to its robust structural detailing, easier mounting and limited labour required on site. The tubular tower consists of subsequent tubular subparts, manufactured in the factory and mounted on site by means of bolted flanges with the use of pretensioned bolts [4]. The structural detailing optimization of tubular towers has been investigated by Stavridou et al ([5], [6]) aiming to minimize the total material used while preserving the tower's robustness by inserting internal stiffeners at critical points and keeping the tower wall thickness in minimum levels.

There is a constant increase observed in the height of contemporary wind energy structures and their energy production capacity since there is higher energy potential available at greater heights away from the earth's surface. The tubular tower configuration functions as a simple cantilever structure; hence as the tower increases in height there is a parallel increase in the bottom diameter required. Certain transportation limitations (eg. Bridge span at highways etc.) prevent the towers from having greater diameters and longer subparts. In cases where transportation limitations apply, lattice towers appear as an appealing solution for wind turbine towers. These type of structures had been implemented on telecommunication masts and their structural performance has been investigated explicitly by Tsitlakidou et al.[7] and Efthymiou et al.[8]. The implementation of lattice towers on off-shore and on-shore wind turbines has just been investigated the past years by various research groups like: Zwick et al. [9]; Long et al. [10]; Long and Geir [11]; Gencturk et al. [12] and still their optimal design has not yet been studied. Therefore, there is room for development and optimization of such structures. Telecommunication masts are constructed mostly with the use of standard L shaped cross sections fabricated in the factory and mounted on site. The rotor of a wind converter though is of great weight and produces great loads due to the operation of the blades. This fact leads in the case of wind turbine towers, to cross sections that are well outside the range of standard industrial profiles. A lattice tower that is capable of accommodating the nacelle has the form of a truncated cone with a square cross-section. The tower is a statically determinate lattice structure composed of a number of discrete structural sub-systems; the legs, the bracing trusses on the faces, horizontal braces and secondary bracings arranged inside the plane of the face bracing trusses. These structural subsystems have a particular role in the load transfer mechanism that develops inside a lattice tower and since the tower is a statically determinate structure, the axial stresses of the legs and the bracings can be determined by closed form expressions. The present paper investigates the structural performance of a lattice wind turbine tower of a certain height and examines various alternative configurations in order to achieve structural robustness along with minimum tower weight.

2 TOWER OPTIMIZATION CONCEPT

The lattice tower investigated in the present study and is capable of accommodating the nacelle at the top has the form of a truncated cone with a square base. The structure is statically determinate and composes of discrete structural sub-systems; the legs, the bracing trusses on the faces and the horizontal braces as they are presented in Figure 1. Each of the aforesaid structural sub-systems have distinct roles in the load transfer mechanism of the tower, therefore each sub-system is investigated and optimized separately.

The legs transfer the axial load caused by the horizontal shear and top-moment imported to the lattice structure at it's top by the nacelle. The face bracing truss undertakes the transfer of the horizontal shear and the horizontal braces take the out-of-plane buckling of the face bracing truss (FBT) elements. Being a structurally determinate system means that the axial stresses of the tower legs and the FBT elements can be determined by closed form expressions.

The problem of the design of a cross section in a certain member calls for the choice of a cylindrical cross-section that will result to a $N_{b,Rd}$ equal to the design axial force N_{Ed} according to Eurocode EN1993-1-1 [13]. The problem of determining the diameter (D) and the thickness (t) of the most economical cross section can be solved by keeping the D/t ratio to the limiting value of Class-III cross sections i.e. 90 ε^2 where ε is given by Equation 1.

$$\varepsilon = \left(235 + f_y)^{0.5}\right) \tag{1}$$

The whole issue of structural optimization of the given problem is treated by developing a specialized script in Mathematica software [14], which finds the diameter of the tubular cross-section that fulfils the buckling resistance and minimizes the tower weight.

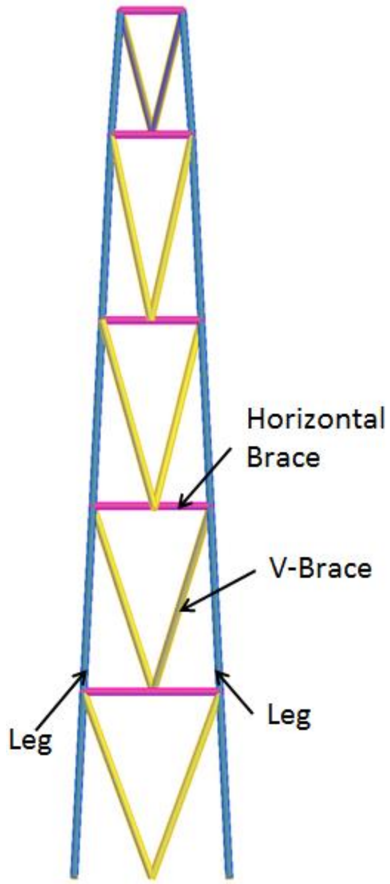

Figure 1. Tower subsystems.

As stated above the different subsystems are optimized separately and certain geometrical parameters have to be taken into consideration for the design of the legs and face bracing trusses (FBTs). The form of the tower is like a truncated cone and among the most popular bracing geometries, the V shaped FBT appears more advantageous since it keeps the total length of the diagonals less than the X brace and the inverted V brace. In order to the determine the V brace angle that leads to the minimization of the total FBT weight, a special investigation is being conducted at the beginning of the script. The angle of the V braces that has been proved in all the cases the most favourable was the one of 45 degrees and this angle determines also the buckling length of the tower legs as this length is the length of the segments that the tower is split to by the braces. The normal force that develops in the legs of a tower with a square base is derived from closed form equations and the governing situation for the legs appears when the top shear acts in the direction of the diagonal of the tower. Hence, the axial force is given by Equation 2:

$$N_{45}(z)=\frac{M(z)}{b(z)\sqrt{2}}\times\frac{1}{cos(\pi/2-\phi_d)} \tag{2}$$

Where $M(z)=M_{top}+(H-z)\times F_{top}$ is the bending moment of a vertical cantilever acted upon by a moment M_{top} and a horizontal force F_{top} at the tower's top, and b(z) is given by equation 3:

$$b(z)=\frac{B_{top}-B_{base}}{2}\times\frac{z}{H}+B_{base} \tag{3}$$

and ϕ_d is the angle of the leg to the horizontal plane and is given by equation 4:

$$\phi_d = tan^{-1} \frac{\sqrt{2} \times H}{B_{base} - B_{top}} \tag{4}$$

Using as a reference case the one with constant leg cross-section from bottom to top and therefore constant axial force, there is a characteristic base width given by Equation 5 that keeps the axial force constant.

$$B_{base}^{ch} = B_{top} \frac{M_{top} + H \times F_{top}^{H}}{M_{top}} \tag{5}$$

Where B_{top} is the top width, M_{top} is the moment at the top of the tower, H is the tower height and F_{top}^{H} is the horizontal force acting at the top of the tower

Taking all the above into account, the optimization problem of the lattice tower is confined to the search space defined by the two independent variables: B_{top} and μ. The variable μ is a non-dimensional parameter that determines the deviation of the base width from the characteristic and is given by Equation 6.

$$\mu = \frac{B_{base}}{B_{base}^{ch}} \tag{6}$$

The total weight of the tower is determined by the buckling checks described in Eurocode EN1993-1-1 [13]. Working on equation 5 does not guarantee that the result of the design will indeed be of minimal weight as the cross-section of the legs is determined by the buckling checks of Eurocode which is a highly non-linear procedure. In addition the result of the buckling check is up to a point controlled by the buckling length which is controlled by the introduction of secondary braces. Therefore the optimal weight does not come as a result of deriving equation 5, but needs an iterative procedure to take into account and counterbalance the two antagonistic factors that determine the optimal tower design; (a) the parallel increase of the leg axial force along with the reduction of the face bracing weight, when closing the distance between the legs and (b) the parallel reduction of the leg axial force along with the total length and slenderness increase of the V braces, when increasing the distance between the legs

3 RESULTS

As explained in the introduction, the tower subparts are designed and optimized separately. The optimal design of the legs and the braces separately is presented in figure 2 and figure 3 respectively. From all the cases investigated the optimum tower configuration is selected in order to minimize the total material used along with maintaining the tower load bearing capacity. The loads used for the lattice tower design are the same as a real constructed tubular structure of the same height. The total number of lattice tower configuration cases investigated in order to optimize tower weight, are 126. The total weight for the optimal lattice tower solution is 77.47 tn and is given for base width equal to 800mm and μ parameter equal to 0.6.

As the tower is symmetric and the wind load can come from any direction, in each tower subpart the same type of elements are selected to have the same cross-sections. In our case circular hollow cross-sections are used and the optimal tower design is presented in Table 1. It is observed from figure 4 that the tower weight for values of μ equal to 0.8 and lower, the lattice tower is lighter than the tubular one. When μ takes values greater than 0.8 the total tower weight increases radically with the increase of the top width of the tower.

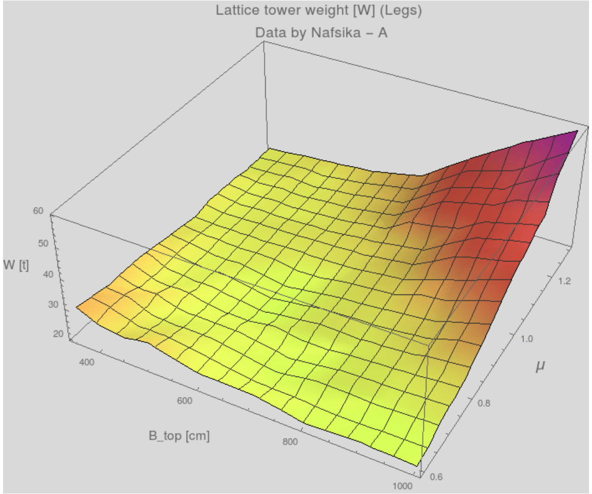

Figure 2. Tower leg weight in comparison to the top tower width and μ.

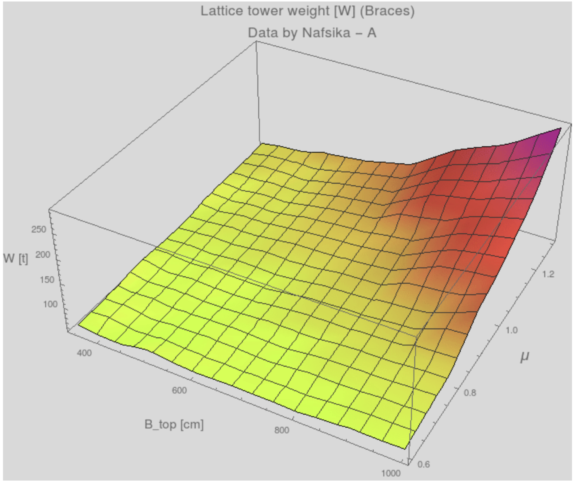

Figure 3. Braces' weight in comparison to the top tower width and μ.

Diameter and thickness of tower cross-sections (mm)					
Legs	P-1	P-2	P-3	P-4	P-5
Diameter	411	371	352	340	286
Thickness	8	8	7	7	5
V-Brace Diagonals	P-1	P-2	P-3	P-4	P-5
Diameter	413	385	375	363	253
Thickness	7	7	7	7	5
V-Brace Horizontals	P-1	P-2	P-3	P-4	P-5
Diameter	342	282	240	216	214
Thickness	6	5	5	4	4

Table 1 : Example of how to set a table

The tower is almost 30 % of the initial construction cost of a wind turbine. Therefore, the reduction of the material used is of great importance in the economical aspect. When using the lattice solution the total material used is reduced by almost 40 %. Taking also into account the fact that in terms of transportation and in-situ construction, the lattice solution is advantageous in regards to flexibility in transportation and easiness in mounting, the lattice solution should be taken into consideration for the construction of contemporary wind turbines.

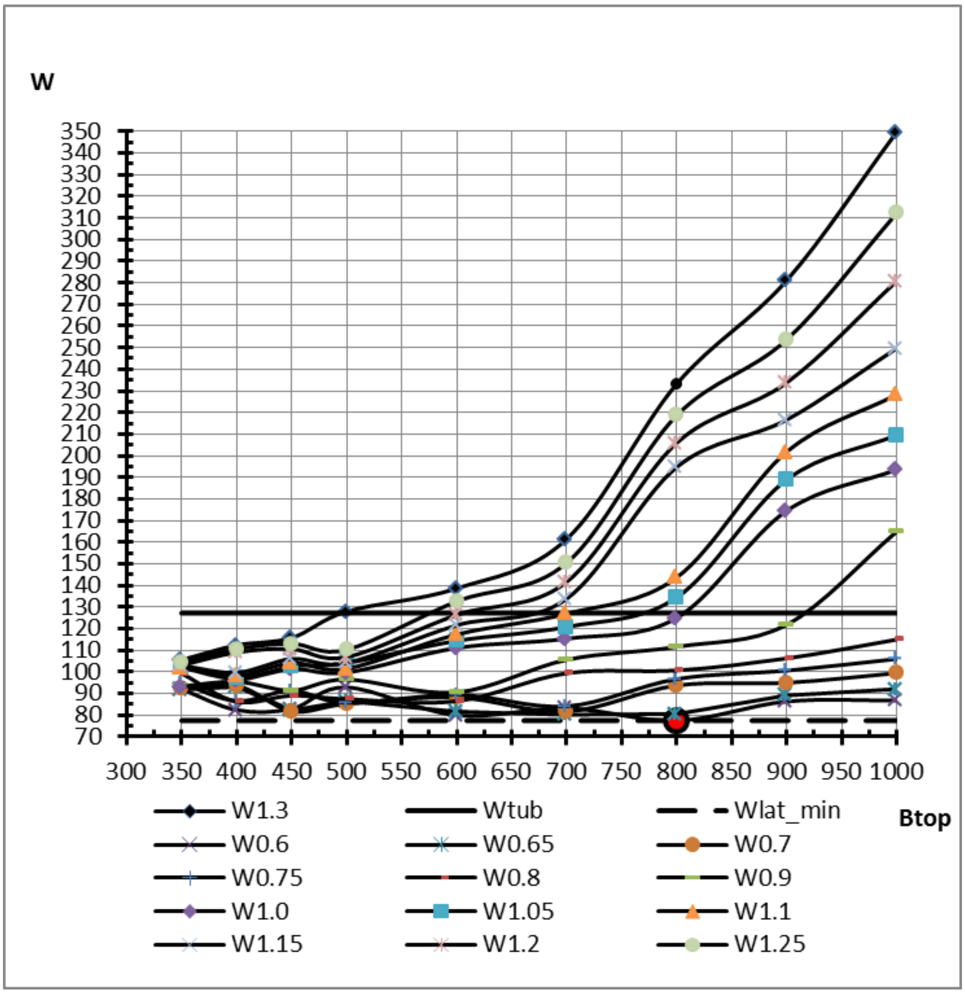

Figure 4 : Total tower weight with regards to top width for given values of μ.

4 CONCLUSIONS

The present study investigates the potential of using lattice wind turbine towers with the prospect of minimizing the total structure weight while preserving its liability and robustness. When constructing taller structures, the minimization of the total material use is of great importance along with the transportation advantages that truss structures exhibit over the tubular ones. Lattice structures when using the appropriate cross-sections for construction of tall structures are proved to be able to sustain great loads with minimum initial material weight. An additional advantage that lattice structures offer is the lower bending moment transferred to the foundation, which facilitates the concrete foundation design and minimizes its construction cost. In the present investigation, a lattice wind turbine of 76.15 meters height has been optimized using a dedicated Mathematica code. The iterative procedure adopted, examines the alternatives of 126 cases and gives back the optimal lattice tower configuration, which minimizes the total tower weight while preserving the structural robustness. The design loads are taken from a real tubular structure and all the alternative lattice solutions are compared in terms of total weight to the tubular one. The optimal lattice tower is 40% lighter than the lattice one, minimizing by almost 15% the total initial construction cost. The advantages that the lattice solution offers in terms of transportation and fabrication, along with the flexibility of its configuration may lead to great and advantageous changes in the configuration concept in wind turbine tower design.

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