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Tubular, lattice and hybrid steel turbine towers for offshore wind energy. A numerical investigation.

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Abstract. The increasing world power demand combined with the need of environment protection and sustainable energy production, has led recently to the use of alternative means of energy production minimizing CO2 emissions including wind energy harvesting. The new trend to expand to offshore wind power installations in order to increase the amount of world sustainable energy production has led to the development of multiple structural solutions both for the foundations and the upper structure of wind power generators. Research on the structural optimization of wind turbine towers is of great interest and importance due to their high manufacturing and erection costs and certain transportation limitations that prevent them from reaching greater heights. The present work addresses the comparison of a classic tapered steel wind turbine tower configuration with a hybrid lattice tower of the same height and energy production potential. Aiming to contribute to better understanding of the structural behaviour of both types of wind turbine towers, the present research work focuses on the development of reliable numerical models along with the use of analytical equations in order to predict accurately and interpret the aforementioned structural response of the two tower configurations by conducting a comparative study between them.

Keywords: Off-shore Wind Turbine Towers, Numerical Analysis, Structural Design, Steel Structures.

1 Introduction

Since sustainable energy production has become essential in order to confine the Greenhouse effect consequences, the European Commission has set a target of 20% final energy consumption from renewable sources by 2020 [1]. Wind energy due to its infinite nature and due to its great potential has shown remarkable expansion in Europe the last ten years. Indicatively the power capacity of wind parks installed in Europe has tripled from about 50GW in 2005 to over 150GW in 2016 according to the European annual statistics [2]. Given wind energy's great applicability impressive structural applications have been observed lately, like large scale on-shore wind turbines, off-shore ones, small scale wind turbines in urban environments, floating structures, flying structures, etc. Taking advantage of the great wind energy potential combined with the distance of the turbulent urban environment, off-shore wind turbines show great expansion and efficiency, therefore research towards that direction is beneficial to the overall energy production. The optimized design of a wind turbine tower, being the basic structural part of a wind converter is of great importance in order to achieve more robust structures and more economic design. The commonest wind energy converters' upper structure type is the cylindrical steel tower. Since the construction of the upper structure of the tower and the foundation covers almost 70% of the initial construction cost in off-shore structures, research on their structural optimization is of great interest and importance.

As far as the cylindrical steel wind turbine tower is concerned, the tower modules are manufactured in the factory as cylindrical or conical subparts, transported to the site and mounted subsequently to their final position [3]. The structural analysis of the main supporting structure of wind generators is considered of high importance since failure in such projects has great economical, structural and safety losses. The governing loads acting on the tower are the wind pressure up the tower height, the moment and the lateral load due to the rotor operation and the vertical load that is equal to the rotor weight. The transition piece connecting the tower with the foundation has to be additionally designed in order to resist to wave loads too. The classic tubular wind turbine tower is a simple structure, which due to its geometry can carry great loads with small shell thickness. The investigation of the buckling behavior of cylindrical shells has been founded by the research work, both numerical and experimental, conducted in the past by Timoshenko and Gere [4], Bazant and Cedolin [5], Teng and Rotter [6] and a plethora of other researchers. Tubular steel wind turbine towers belong to the area of cylindrical shells under combined loading and special research work has been devoted to the behavioral analysis of those structures and the explanation of their main structural problems [7]. Lee and Bang [8] elaborated a finite element model to simulate the collapse of an actual wind turbine tower which was matching the actual findings on site. Classic cylindrical structures, despite thoroughly being investigated, continue having high manufacturing and erection costs and certain transportation limitations that prevent them from reaching greater heights where higher wind speeds provide higher energy potential for harvesting.

In order to increase the wind energy harvesting, the construction of taller structures and the improvement of their structural detailing is critical towards achieving greater energy production along with economy in material use and structural robustness. Since installation of off-shore wind power converters is complicated in matters of module transportation and installation, there is a need for solutions that permit the construction of lighter structures that are easy to carry on site and facilitate on-site mounting. As an alternative to classic cylindrical wind turbine towers, lattice or hybrid tower configurations are investigated. The solution of lattice towers has been till now implemented on telecommunication masts mostly and its structural behavior has been investigated by Tsitlakidou *et al.* [9] and Efthymiou *et al.* [10]. Conventional lattice towers are constructed mostly with the use of standard L shaped cross sections fabricated in the factory and mounted on site. The scale of the lattice towers which are able to support the rotor of a wind converter leads to cross sections that are well outside the range of standard industrial profiles. A lattice tower that is capable of accommodating the nacelle or a cylindrical transformation element has the form of a truncated cone with a polygon or 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. The aforementioned 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 addresses the stability performance comparison of a tubular steel wind turbine tower and a lattice wind turbine tower of the same height and with the same loading applied at the hub height. It examines the performance of each tower while attempting to minimize the total material used maintaining its endurance and robustness.

2 Numerical Modelling

2.1 Cylindrical Steel Wind Turbine Tower

In the present study a cylindrical steel wind turbine tower is compared with a lattice one of the same height and same bearing capacity. The cylindrical tower has a hub height above sea level of 76.15 meters. The modules that constitute the total tower are 3 in total with 21.8 m, 26.6 m and 27.8 m length respectively going from the sea level to the top. The tubular subparts are manufactured in the factory and transported to the platform of the site and finally mounted to their final position with the use of cranes. The numerical investigation of the tower is conducted with the use of Abaqus software [11] and more specifically the tower shell is modelled with reduced integration shell elements S4R as described in detail in the software manual. The tubular tower diameter ranges from 4.3 meters at the bottom to 3 meters at the top of the tower and the shell thickness is gradually increasing from 12mm at the top to 30mm at the sea level.

The loading conditions that the tower is designed to bear consist of the gravity loads that are directly calculated through the material density within the software, the loads due to the rotation of the blades and the wind loading distributed along the tower height. The analysis conducted in the software is material non-linear analysis for steel grade S355, where Poisson’s ratio coefficient is 0.3, Young’s modulus is 210 GPa, the yield stress is taken as 350 MPa and the ultimate strength as 510 MPa. In order to introduce plasticity data in the software the material properties have to be considered in terms of plastic true stress and true strain.

2.2 Lattice Steel Wind Turbine Tower

As far as the lattice tower is concerned, it shares the same height as the tubular one explained in detail in the previous paragraph and the loading condition that it is designed for are the same also. As already referred, the structural subsystems that the tower consists of have distinct roles in the load transfer mechanism of the tower. Since the lattice structure is a statically determinate system, the axial stresses of the legs and the bracings can be determined by closed form expressions. For this purpose a script in Mathematica software [12] is developed.

The tower has a square base with four face bracing trusses. The optimal face bracing truss is the V shaped and in order to minimize the total weight of the structure while maintaining its load bearing capacity, the angle of the diagonals needs to be determined. For the present investigation, the angle is set to 45 degrees and secondary braces are also used.

In the script, each sub-system; legs, horizontal V-braces, diagonal V-braces and secondary bracing are investigated and optimized separately using different subroutines. After having selected the optimal diagonal angle of the V-braces, the only parameters that need to be additionally selected for the design of the tower are the bottom and top width of the tower's face. The two factors that influence the optimal tower design at this stage are: (a) the parallel increase of the leg's axial force and the reduction of the face bracing weight when lowering the distance between the tower legs and (b) the parallel reduction of the leg's axial force and the increase of the total length and slenderness of the V-braces when increasing the distance between the legs. These two factors are obviously antagonistic. The determination of the optimal tower weight therefore is dependent on the width of the tower at the top and the buckling checks of all the components. Since the buckling check is a highly non-linear procedure, a two-dimensional search is demanded in order to assess the variation of the two independent parameters; the width at the top and the non-dimensional parameter of the top width over the bottom width of the tower. The script used for the optimal design of the tower uses a successive iterations scheme in order to converge to a final solution when total weight is minimum.

3 Results

3.1 Cylindrical Steel Wind Turbine Tower

The tubular tower mass is 127.215 tn, with the tower modules having 54.54 tn, 44.817 tn and 27.858 tn respectively going from bottom to top. The tower thicknesses are optimized in order to achieve minimum weight along with fulfilling the structural criteria as shown in Fig. 1.

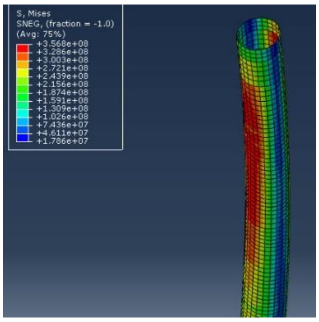

Fig. 1. Tubular tower Material Non-linear Analysis results

3.2 Lattice Steel Wind Turbine Tower

The lattice tower face consists of 5 subparts. All the subparts are designed and the optimum tower configuration is selected in order to minimize the total material used along with maintaining the tower load bearing capacity. The total number of cases investigated in order to achieve the minimum weight are 126. The total tower weight for the optimal lattice tower solution is 77.47 tn and critical assumptions can be made towards wind turbine tower optimal design based on the results presented in Fig.2.

As the tower is symmetric and the wind load can come from a random direction, in each tower subpart the same type of elements are selected to have the same cross-sections. In the present study, circular hollow cross-sections are used.

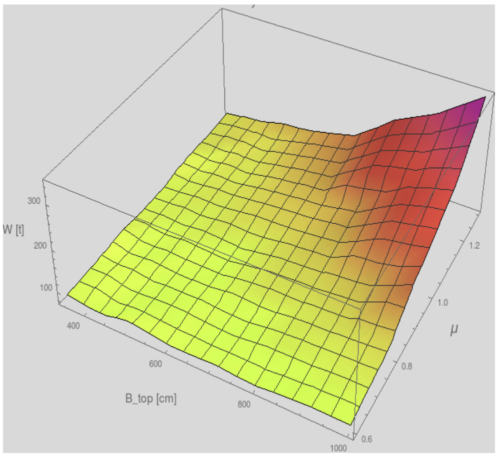

Fig. 2. Total lattice tower weight in comparison to the top tower width and μ

Constituting a great part of the initial construction cost, the material used for the construction of the tower is of great importance in the economical aspect. As it can be seen from the comparison of the two tower cases investigated in the present study, the total material used in the lattice solution is almost 40 % less than the tubular one. Taking also into account the fact that in terms of transportation and mounting, lattice towers are more advantageous and flexible, the lattice solution should be taken into consideration for future implementation in wind turbine tower construction

4 Conclusions

The present work constitutes a primary investigation of a potential substitution of tubular wind turbine towers with lattice ones. The initial goal is the minimization of the total steel weight used for construction while maintaining the structure load bearing capacity. The lattice tower, along with the lower initial material cost, benefits from easier mounting and minimum use of large scale cranes. Aiming to the construction of taller off-shore towers, the minimization of the total material use along with the transportation and mounting advantages that truss structures exhibit is of great importance in terms of structural configuration solution. Cylindrical shells have been proven to be robust enough, offering higher capacity to the structure, but substantially greater amounts of material use. After a comparative study, lattice structures when optimized in terms of cross-sections used, are proved to be able to sustain great loads with minimum initial material weight. In terms of total weight, in a tower of about 76 meters tall the lattice solution is 40% lighter compared to the tubular one. The additional advantages that the lattice solution may potentially offer may lead to great and advantageous changes in the configuration concept in wind turbine tower design.

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