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Iterative optimization approach for the design of full-height lattice towers for offshore wind turbines

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Abstract

Among several possible support structure types for offshore wind turbines, a full-height lattice tower is one design option. Advantages of this design are the smaller amount of steel used for the structure compared to other concepts, and the possibility to install the whole structure in one operation. Based on the complexity of dynamic loadings on the support structure by wind and wave as well as operational loads, an initial lattice tower design with constant member dimensions over the tower height shows a large optimization potential and can be optimized section by section. This paper presents basic considerations for an iterative optimization approach and identifies sensitivities for the optimization process of a full-height lattice tower. It was found that an analysis with constant member dimensions over the tower height gives an indication about the required dimensions for an optimized design.

Keywords: offshore wind turbine, bottom-fixed support structure, full-height lattice tower

1. Introduction

Installations of bottom-fixed offshore wind farms in intermediate water depth of 20-70m are until now based on more or less the same construction idea: the support structure carrying the rotor nacelle assembly (RNA) is a combination of a multi-member (jacket, tripile, tripod), tubular (monopile) or gravity based substructure with a tubular tower [1]. A new design approach of a full-height lattice tower has been developed by the Department of Civil and Transport Engineering at NTNU [2], in which the traditional tubular tower is replaced by a space frame structure going all the way from seabed to RNA. The aims of this approach are a reduction in steel weight and a simplification of the installation, and thereby a reduction of total cost of the support structure, compared to known solutions.

An iterative method was used to optimize these designs, based on the automatic generation of tower finite element models characterized by a few parameters, the time-domain analysis of the models in FEDEM Windpower (a flexible multi-body solver developed by Fedem Technology AS, Trondheim, Norway), and post-processing of the resulting time series for the calculation of ultimate loads and fatigue properties.

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The main contribution of this paper is to show how to utilize the sensitivities for the optimization process. This helps to reduce the number of time-domain analyses necessary, thereby reducing calculation time to a manageable amount. Important design parameters are the member dimension configuration and the number of sections over the tower height. Results are presented that compare optimized designs with adapted member dimensions and different numbers of sections, with regard to the total weight of the structure. Both constant brace angle and constant section height designs were considered.

2. Full-height lattice tower design

2.1. Topology

Lattice towers are known as light weight space frame structures with a wide area of application for offshore oil and gas platform installations [3]. In the offshore wind turbine industry, lattice towers are until now only used as the sub-structure of the wind turbine installation, providing support for a traditional tubular tower. The latter is known from onshore wind turbines. A transition piece located at a certain level above the water surface is connecting the two structural parts.

The design of a full-height lattice tower presented here, as shown in Figure 1, provides directly support for the turbine nacelle, without transition to a tubular tower. The structure is characterised by leg and brace members, welded together in K- and X-joints.

The specification of a certain site location and RNA configuration gives a first indication about the structural design of the tower. The *top distance* defines the tower width at the base for the yaw mechanism. In combination with the *tower height*, these parameters are set by the turbine manufacturer due to blade tip clearance above the water surface and turbine nacelle design. Also the *bottom distance* between the legs at sea bottom is limited by the rotor design due to a minimum required blade tip clearance to the tower structure. For the design optimization process, several parameters are available:

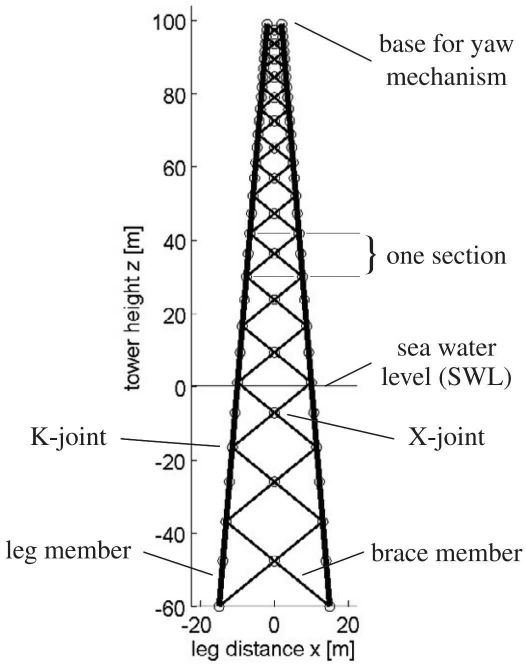


Fig. 1. Full-height lattice tower with constant brace angle

- *leg number*
- *section number*
- *leg and brace member dimensions*
- *constant brace angle or constant section height*

The described work was performed with a 4-legged lattice tower only, as the design base was chosen to be similar to common jackets combined with tubular towers used in offshore wind turbine installations today. The other mentioned parameters were used as optimization variables.

2.2. Simulation model and initial load conditions

A full-height lattice tower for the installation of the proposed 10MW NOWITECH reference turbine in 60m water depth was selected. This design idea of the tower was originally presented by Long and Moe [2]. Details of the analysed design in this study can be found in Table 1. The fully-coupled model of an offshore wind turbine was build in FEDEM Windpower with a blade design based on the study of Frøyd and Dahlhaug [4]. Simulation runs with 13.5m/s turbulent wind (16% turbulence intensity) and an irregular sea state with JONSWAP spectrum (significant wave height H_s = 4m and mean wave period T_p = 9s) were performed for aligned wind and wave direction to provide initial load conditions. This load case represents a typical load on the structure at rated speed in North Sea wave conditions.

2.3. Iterative optimization approach

For the iterative optimization approach, each iteration, as shown in Figure 2, is based on two main steps. First the analysis of a specific tower design with a multi-body solver, and second the post-processing of calculated time series of forces and moments for each member and joint. Each tower model is analysed for the ultimate limit state (ULS) and the fatigue limit state (FLS). The analysis includes the calculation of stress concentration factors (SCF) to determine hot spot stresses (HSS) in the joints of the lattice tower (see Section 2.3.1).

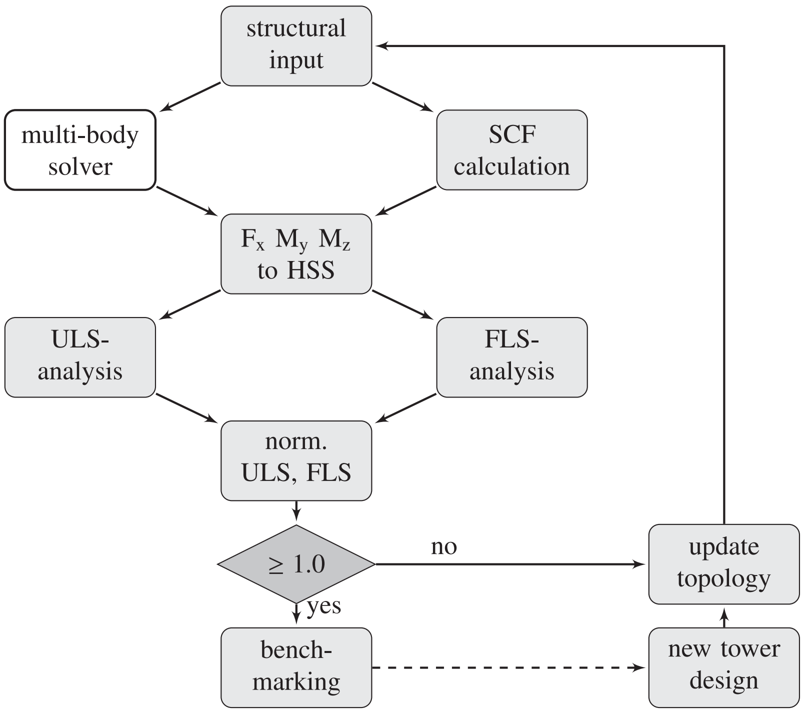


Fig. 2. Iterative optimization approach

The optimization from one iteration step to the next is based on the strategy of resizing members with lifetimes farthest away from the design lifetime. Lifetime was chosen as optimization criterion due to the fact that fatigue is one of the design drivers of support structures for offshore wind turbines [5]. During optimization, one or several members can be optimized in each iteration step at the same time. Members are resized according to their benchmark value (see Section 2.3.3) as whole numbers, from minimum 1mm to a maximum value within 10% of the benchmark result. A design is regarded as optimized when normalized lifetimes for all sections were found in an interval of 1.0 to 1.5. Limitations for the feasibility to find such designs are described in Section 4.2. As a starting point for this study, the presented optimization is based on the resizing of member thickness only, while member diameters were kept constant.

2.3.1. SCF and HSS calculation

The calculation of SCF and HSS is based on DNV-RP-C203, *Fatigue design of offshore steel structures* [6]. As shown in Figure 3, in total eight stresses are calculated at hot spots around the circumference at the intersection of brace and leg members, as well as at brace to brace connections in X-joints. HSS at these points are derived by summation of single stress components from axial, in-plane and out-of-plane action.

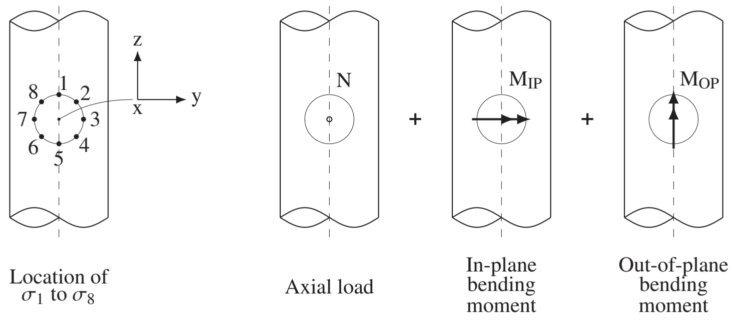


Fig. 3. Superposition of stresses for tubular joints (adapted from DNV-RP-C203 [6])

2.3.2. *ULS and FLS analysis*

In the ULS-analysis, extreme values for each HSS variation $\sigma_{1..8}$ are calculated. The minimum and maximum values of the time series characterize the ultimate load applied on the structure during simulation time. For the calculation of fatigue properties in the FLS-analysis, a rainflow counting process is performed [7], followed by a fatigue analysis based on the Palmgren-Miner approach [8]. Results from rainflow counting of each time series and HSS $\sigma_{1..8}$ are used to estimate the lifetime of the structure according to S-N curves for tubular joints in DNV-RP-C203.

2.3.3. *Normalization and benchmarking of different tower designs*

To be able to compare different tower designs in terms of their ULS- and FLS-performance as well as material weight, a normalization approach was proposed for benchmarking. Results from ULS-analysis are normalized by the yield strength for steel, while results from FLS-analysis are normalized by the requirement of 20 years lifetime [9]. These normalized values have to be ≥ 1.0 to characterize a stable design. As shown in Figure 2, values < 1.0 will require an update of the tower topology and a re-run of the simulation. These benchmark values can be regarded as additional safety factors.

3. Optimization results

3.1. *Constant member dimensions over tower height*

Due to simplicity in the design process, first studies of the full-height lattice tower concept were performed with constant member dimensions over tower height only [2]. The application of such a design is a rather unrealistic case due to heavily oversized members in several tower sections. However, this case also shows quite clearly where and in which order the highest potential for optimization can be found for the support structure, where both wind and wave loads are acting on different parts of the structure.

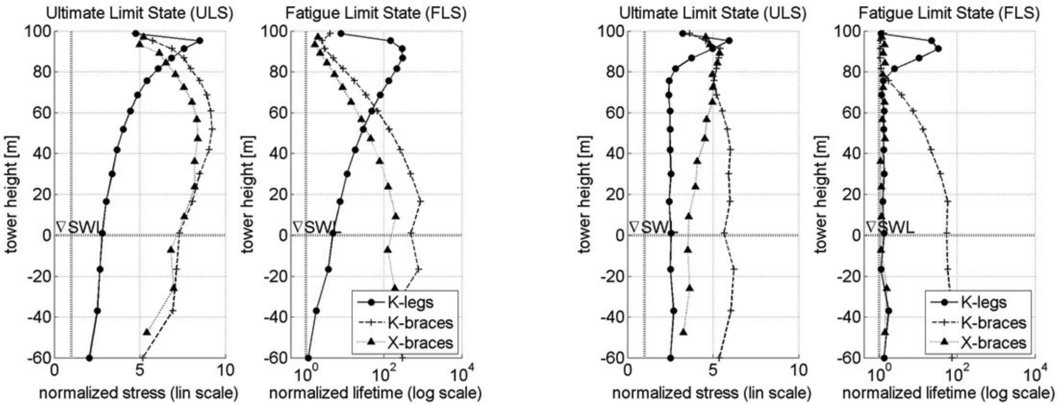
Figure 4(a) shows a typical distribution of minimum normalized HSS in each tower section over tower height for a design with constant member dimensions. For the ultimate limit state, the behavior of the main legs seems not to be dominated by wave loads, but suffers high loadings at the tower top from the transition between lattice tower and yaw mechanism. Brace members are affected by wave loading as seen in the fluctuation of the curves for K- and X-brace joints below and above sea water level (SWL). This has been checked by comparison with a simulation without wave loading. The lifetime of the braces is decreasing towards the tower top and bottom, and is higher in the middle part of the structure.

The lifetime distribution for the fatigue limit state shows a somehow different picture. It has to be noticed, that the scale of the x axis in Figure 4(a) (right) is logarithmic and so, a large optimization potential is offered by both leg and brace members. At the same time, the FLS profile shown here for a design with

Table 1. Details of the proposed 10MW NOWITECH reference turbine in this study

	Constant member dimensions	Optimized design
tower height [m]	158.70	158.70
leg/brace diameter [m]	1.6/0.8	1.6/0.8
leg/brace thickness [mm]	73/34	49..63/20..34
number of sections	15	15
tower weight [t]	3082	2283

constant member dimensions is optimized for the most critical section in terms of a lifetime close to, but above the required 20 years. While leg members show a large potential between water surface and the second last tower section below the yaw mechanism, brace members are significantly oversized in the lower half of the structure.



(a) constant member dimensions over tower height (b) optimized member dimensions according to loads

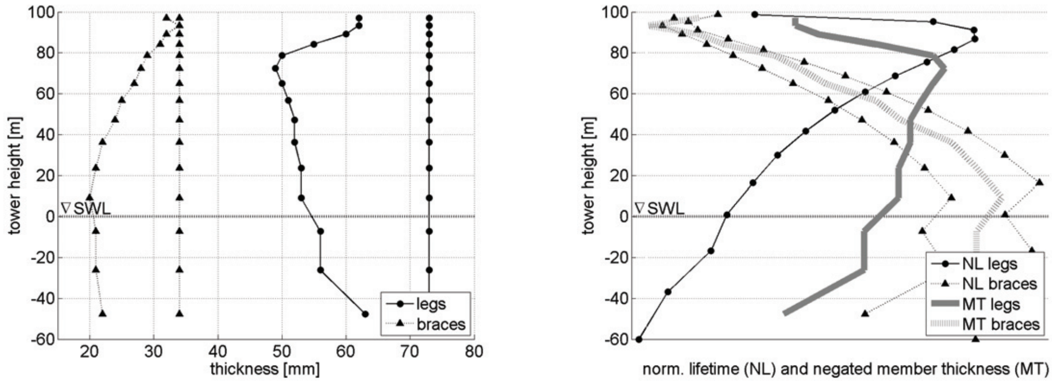
Fig. 4. Distribution of minimum normalized HSS and lifetime over tower height

3.2. *Varying member dimensions over tower height*

As expected, the possibility of introducing varying member dimensions over the tower height reduces total tower weight, while structural performance keeps ensured. Figure 4(b) shows an optimized distribution of normalized stress and lifetime over the tower height. It is interesting to see that leg-profiles are approximately the same in ULS and FLS, while those for braces are following a different trend. Since fatigue loading is the dominating design case, optimized profiles for legs and braces are close to the normalization value of 1.0 where applicable. The optimization shown in Figure 4 is based on varying member thickness, while keeping diameters constant. Figure 5(a) gives an overview over the thickness reduction during the optimization process from a constant design (straight line) to the optimized design (curved line).

4. Structural behavior of optimized designs

The responsivity of the design to changes in member dimensions (constant in each tower section) was studied with respect to fatigue lifetime estimates of joints. In addition to the fatigue properties, also ultimate loads were checked for each tower generated in the process. Based on the results presented in Section 3, ULS and FLS behaviors show different characteristics over the tower height and are discussed separately in the following. Another finding is the responsivity of the design to changes in tower parameters, which can help to narrow down the number of necessary simulation runs during the optimization needed in order to find a light-weight design fulfilling the stability and fatigue requirements.



(a) thickness profiles over tower height with constant diameter

(b) comparing lifetime and thickness profiles

Fig. 5. Member thickness profiles and their proposed use for the optimization approach (see Section 4.3.1)

4.1. ULS

For the ultimate limit state of a design with constant member dimensions, gravitational loads due to the weight of the structure and RNA are dominating the stress distribution in the legs. As shown in Figure 4(a), the normalized stress increases with the tower height until the tower top is reached. Close to the base for the yaw mechanism, thrust forces from the rotor are more dominating and lead to a reduction of total normalized stresses in the legs. The same behavior can be observed in the uppermost part for the optimized design with varying member dimensions. However, the lower part of the structure shows an equal stress distribution due to adapted member dimensions.

Effects of the optimization process on the ULS stress distribution of brace elements are smaller compared to leg elements. Comparing Figure 4(a) and 4(b), the optimized profile shows mainly an improvement in the middle part of the structure with reduced member thickness, where oversizing was reduced in X-joints.

4.2. FLS

The analysis of both constant and optimized designs confirmed that the fatigue lifetime is the design driver. By adjusting member dimensions to the minimum fatigue lifetime of 20 years, normalized values of the ultimate loads are still above 2.0. While the lifetime for brace connections in both K- and X-joints for a constant design follows a similar trend as in the ULS case, the optimized design gives the possibility to optimize the lifetime of X-joints over the whole tower height. However, due to the relation of legs and braces in K-joints, braces are oversized in these connections. The opposite behavior can be found at the tower top, where leg members are oversized to keep braces in K-joints above the required lifetime. The background for these dependencies lies in the basic design with constant brace member dimensions within the same section, which is explained further in the following section.

4.3. Responsivity to changes in tower characteristics

4.3.1. Member dimensions

Important relations for changes of member dimensions were observed. Members were changed section-wise with constant leg and brace dimension in each section. This leads to responsivities in the optimization process since legs and braces are physically connected in K-joints and the variation of one of these members results in a changed behavior for the connected member, too. Variations in member performance affecting neighboring members were mainly found to be a local phenomenon, however, global variations could be observed in some optimization steps and will be in the focus of further research. On the other hand, adjusting brace dimensions leads to changes in both K- and X-joints for brace elements. This limits the possibility to optimize leg and brace members for both K- and X-joints at the same time. By introducing stubs for the brace connections in K-joints, this relation can be broken and a deeper optimized design can be realized.

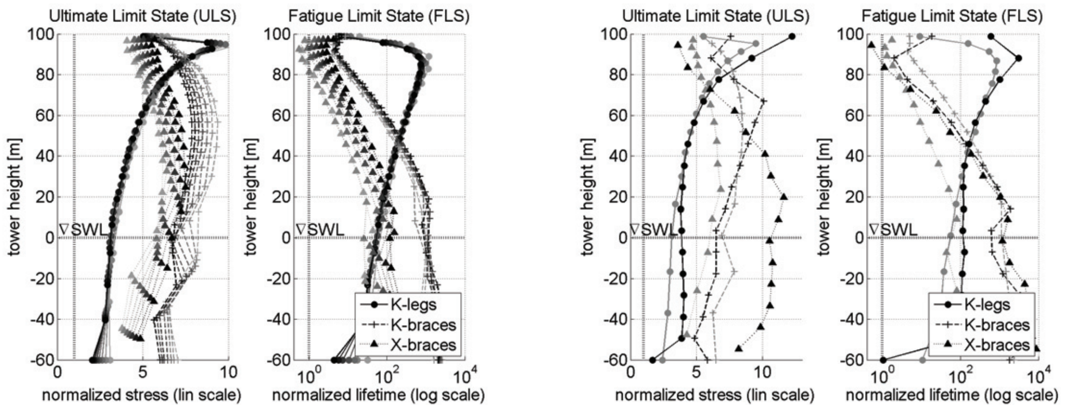
There is also the possibility to decouple the performance of K- and X-joints by use of cast nodes for X-joints. However, introducing stubs or cast nodes will at the same time increase the number of members and welds needed during fabrication of the structure.

An interesting correlation was found between the FLS result for a design with constant dimensions (Figure 4(a) to the right) and the thickness profile of an optimized design (Figure 5(a)). By mirroring the thickness profiles on a vertical axis, the curves for legs and braces respectively show significant similarity to the FLS profiles over the tower height. This observation is illustrated in Figure 5(b) and delivers a useful basis for the optimization approach. While the FLS profile for legs only gives an indication about the required optimization trend, the thickness profile for braces follows almost exactly the FLS profile over the tower height. By running a simulation with constant member dimensions first, the shape of the FLS profile result can be analysed and translated into required changes to the member thickness. The second attempt can so be further optimized in detail. Following this approach, the number of time-domain analyses necessary can be reduced.

4.3.2. Number of sections

Another design parameter for the tower topology is the number of sections, which defines how many X-braces are used over the tower height. This parameter has a significant influence on the behavior of the braces at, or close to the SWL, since it is changing their relative position to the waves. Naturally, the interest is to keep the number of sections small, since this will lead to a smaller number of members and a lighter tower structure. Figure 6(a) gives an overview over seven different tower designs with the number of sections varying from 12 to 18 (curves indicated in light grey to black).

The influence of this parameter on the legs is as expected small, both in ULS and FLS. For the braces, wave force interaction close to SWL can be observed in the ULS. Furthermore, trends in K- and X-joints show opposite behavior. While the K-joint performance for the braces is decreasing with increasing number of sections, values for the X-joints are increasing. This behavior can be explained by the fact that an increasing number of sections shares the applied load on several braces. However, variations in tower topology also lead to changes of the brace angles, and by this result in higher SCF for the K-joints.



(a) varying number of sections (b) constant brace angle versus constant section height

Fig. 6. Responsivity of several towers to changes in section design

The responsivity to the number of sections in the FLS is mainly noticeable by changes of lifetime for X-joints. A reason for that can be found in a stiffer structure when the number of sections is increased, and so increased lifetime values due to less vibrations in the plane between the legs. K-joints are less affected by this variation and show only a slight improvement in lifetime for a larger number of sections.

4.3.3. Constant brace angle versus constant section height

As shown in Figure 6(b), the change of tower characteristics from constant brace angle (light grey) to constant section height (black) results in significant variations for the X-joints in both ULS and FLS. Due to the slender topology of the tower, section heights for a constant brace angle design are two times larger than those of a constant section height design at the bottom section, while they are only one third at the top section. These changes lead to the varying behavior of loads on X-joints for the two cases. At the same time, legs and braces in K-joints are not affected in the same order as the X-joints. It can be noticed that the ULS and FLS performance of braces in X-joints becomes larger for the constant section height design for most of the tower joints. However, at the tower top, where brace lengths are increasing for the constant section height design compared to the constant brace angle design, the latter delivers better performance.

Based on fabrication aspects of the structure, it is expected to be an advantage to select the constant brace angle design. This will avoid small angles between braces and legs, as they occur close to the tower top for a constant section height design. By keeping the same brace angle configuration at all K-joints, also prefabrication of geometrically similar joints will be a possibility.

5. Conclusion

Future investments in offshore wind turbine installations are highly based on the expectation that the price level for installations will decrease. Therefore, the analysis of several support structure types is an important step to be able to identify the potential in cost reduction by an optimized design. The presented full-height lattice tower is one possible design solution and should be further developed in this consideration.

Since several design parameters lead to significant changes in the tower topology of a full-height lattice tower and time-domain analyses are time consuming and expensive, an effective optimization approach is needed to be able to reduce the number of necessary simulation runs. An approach is presented in this paper, where results from the analysis of a design with constant member dimensions over tower height are analysed and translated into an expectation of the member dimension profile over tower height for an optimized design. This approach saves a significant number of iteration steps during optimization. Further detailed optimization of the design is achieved by changing member dimensions in one or several sections stepwise in each iteration step.

The paper presents a first stage of a complete analysis of the full-height lattice tower concept. Further work will focus on the improvement of the mentioned iterative optimization approach, the extension of several parameter studies and the assessment of suitability of the concept in future wind park installations. In addition, the concept has to be analysed and proven using more extensive load case simulations according to the standard [9].

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