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CONVEX OPTIMIZATION OF SPACE FRAME SUPPORT STRUCTURES FOR OFFSHORE WIND TURBINES

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ABSTRACT

The aim of the present project is to reduce the cost of support structures for offshore wind turbines by minimizing their total steel mass. Basic considerations for an iterative optimization approach were presented by Zwick, Muskulus and Moe (2012), and these have been improved with a convex problem formulation and faster convergence. Simplified fatigue load assessments have been studied, and computational expenses of site-specific optimization has been reduced with a factor of 66 compared to complete analysis. This has been accomplished by using load histories from the initial design to compute correction factors for each member, which enables a single load case of 10 minutes to represent 11 load cases of 60 minutes. A jacket has been optimized with this approach, and a benchmark with the full-height lattice tower concept is presented.

1. INTRODUCTION

Offshore wind turbines are mounted on costly bottom-fixed support structures such as monopiles and jackets. It is expected that significant cost reductions can be achieved by design optimization, particularly for space frame structures where members can be sized individually. Due to the large amount of vibrations that are being induced from both rotor and waves, it has been observed that fatigue is the dominant failure mode for such structures. Fatigue assessment requires comprehensive time-domain simulations, which makes optimization computationally expensive. In this paper, considerations for fast and accurate optimization of a full-height lattice tower (FLT) are presented.

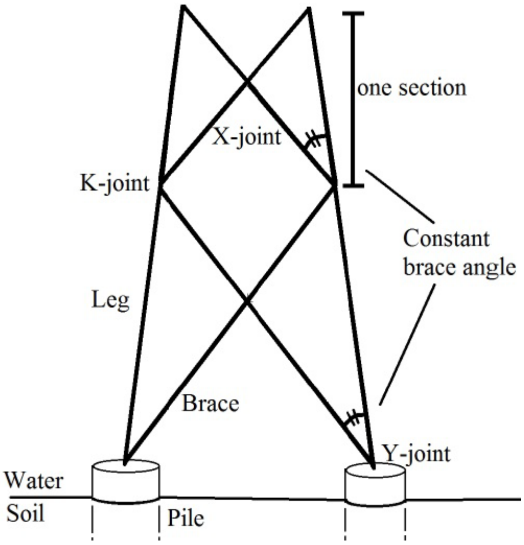

Figure 1: Illustration and terminology of space frame support structures

2. METHODOLOGY

An iterative optimization approach was presented by Zwick et al [1], with the objective of reducing weight while maintaining a fatigue life of 20 years in all parts of the structure. Welded K-, X, and Y-joints are connecting legs and braces as shown in fig.1, and though the method was developed for a FLT, it can be easily adapted to any space frame with similar structure. In this paper, a 10 MW turbine with a FLT support structure has been optimized for fatigue during power production load cases (3-25 m/s, DLC 1.2 in [6]). Fatigue damage is estimated by processing stress history from time-domain simulations with rainflow counting, SN-curve and Miners rule, which is the recommended practice [3]. An important assumption of this method is that the sections are uncoupled, meaning that the members in one section can be optimized without regard to changes in other sections. This is a bold claim, but numerical results have indicated that it works well enough to give convergence [1], [2] and [4]. Consequently, all sections can be optimized simultaneously, and the problem is split into N_{sec} (number of sections) problems, each with four variables (thickness and diameter of legs and braces).

3. PROBLEM FORMULATION

Stress concentration factors (SCFs) are used to account for the extra loading experienced in the joints, and are computed from the DNV standard *Fatigue design of offshore steel structures* [3]. SCFs are evaluated at both sides of all welds, as it is normally not the weld that fails, but the nearby material in one of the connected members. With only thickness and diameter as variables, the formulas from the standard can be simplified. Note that *D* and *T* refer to legs, while *d* and *t* refer to braces.

$$SCF_{Leg} \propto \frac{t^{0.9}D^{0.5}}{T^{1.4}}$$
$$SCF_{Brace} \propto \frac{d}{t}$$

The scaling laws above are obtained from the dominating stress contribution in the critical hot spot. Since the dominating stress contribution will scale with its respective SCF ($\sigma_i = SCF_i \cdot \sigma_0$), it can also be argued that the total stress will scale with this SCF. Stress will of course also scale with the cross sectional area ($\sigma_0 = F/A$), which for thin walled pipes scales with thickness times diameter.

$$\sigma \propto \frac{SCF}{Area}$$
$$\sigma_{Leg} \propto \frac{t^{0.9}}{T^{2.4}D^{0.5}}$$
$$\sigma_{Brace} \propto \frac{1}{t^2}$$

The SN-curve relation scales stress with maximum number of cycles, and Palmgren Miners rule scales maximum number of cycles (*N*) with fatigue damage (*U*).

$$\log N_i = \log a - m \log \Delta\sigma_i$$
$$U = \sum_i \frac{n_i}{N_i}$$
$$U \propto \sigma^m \ (m = 5)$$

Optimization problem

$$\underset{T,\,t}{minimize}: \quad f = T^2 + rt^2$$
$$subject\ to \quad g_1 = U_{Leg} - 1 \leq 0 \quad \left(U_{Leg} \propto \frac{t^{4.5}}{T^{14.5}}\right)$$
$$g_2 = U_{Brace} - 1 \leq 0 \quad \left(U_{Brace} \propto \frac{1}{t^{10}}\right)$$
$$when \quad t_{min} \leq t \leq T \leq T_{max}$$

$\frac{D}{T}$-ratio of both legs and braces should be kept fixed at a minimum value (proved in [4]), limited by the validity range of the SCF formulas ($16 < \frac{D}{T} < 64$). The objective function is then a function only of t and T, with a weighting constant $r = 2.3$ which must be included since there are more braces than legs. The problem (text box & fig.2) is convex, as the design space, the objective function and the two constraint functions are convex (their Hessians are all semi definite on the intervals described by the variable bounds). Given that fatigue damage U^j for both legs and braces have been calculated for design iteration *j*, analytical expressions for Δt and ΔT can be derived by setting $U^{j+1} = 1$.

$$\Delta t = t^j \left(\left(U^j_{Brace}\right)^{\frac{1}{10}} - 1 \right)$$
$$\Delta T = T^j \left(\left(U^j_{Leg}\right)^{\frac{1}{14.5}} \left(\frac{t^j + \Delta t}{t^j}\right)^{\frac{4.5}{14.5}} - 1 \right)$$

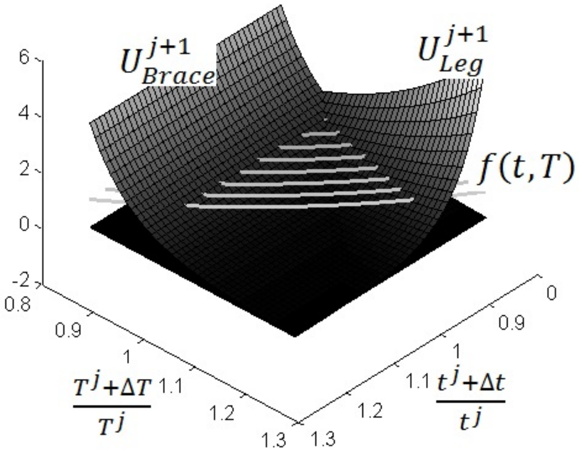

Figure 2: Convex optimization problem

4. SIMPLIFIED FATIGUE LOAD ASSESSMENT

For certification of support structures, the recommended practice is to assess the fatigue loads from simulations of a large number of load cases, each with a minimum length of one hour. For optimization purposes it is relevant to know how a fatigue load assessment can be simplified without sacrificing too much accuracy. Two assumptions were tested:

- A reduced number of load cases can represent all wind speeds.
- A reduced simulation length can represent 60 minutes.

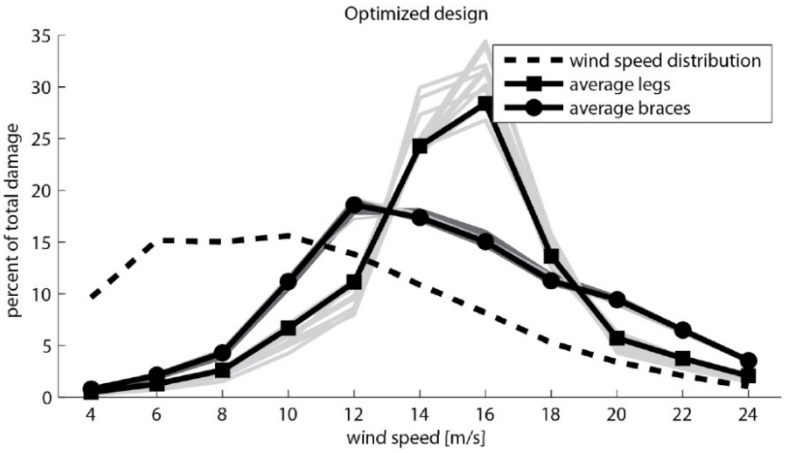

Figure 3: Distribution of normalized damage accumulation is plotted for all members (grey). Qualitatively different distributions are observed for legs and braces (black). This distribution remains relatively unchanged during large design modifications.

The problem formulation presented in section 3 was used, where fatigue damage U was evaluated with various simplified fatigue load assessments. An initial design with constant member dimensions was analyzed with a *complete* fatigue load assessment (11 load cases of 60 minutes), and the results of this was used to “adjust” the *simplified* assessments. During the optimization it was observed that the normalized damage accumulation from different wind speeds kept a more or less constant distribution (fig.3), even with large modifications to the design. The consequence is that one load case effectively can represent all wind speeds, and it was also demonstrated that simulation length down to about 10 minutes gives acceptable accuracy [4]. By reducing simulation length with a factor of 6, and the number of load cases with a factor of 11, it has been demonstrated that a conceptual design can be optimized ~66 times faster than the recommended practice. Optimization with simplified and complete fatigue load assessment achieved the same optimal design within a few percent, though statistical investigations should be performed to gain more knowledge about the accuracy.

5. JACKET VERSUS FULL-HEIGHT LATTICE TOWER

A jacket was designed with the topology from the bottom 4 sections of the FLT (fig.4), and connected to the turbine through a rigid transition piece and a scaled version of the tubular tower from the OC4 project [5]. The tubular tower was then further modified to obtain satisfying eigenmodes. When the models were optimized for the same conditions, both converged to about 700 tons (excluding transition pieces). While the FLT has the advantage of a significantly lighter transition piece than the jacket, it also has a more intricate structure (many welded joints). Thus, a fair comparison is difficult to do without a complete cost model.

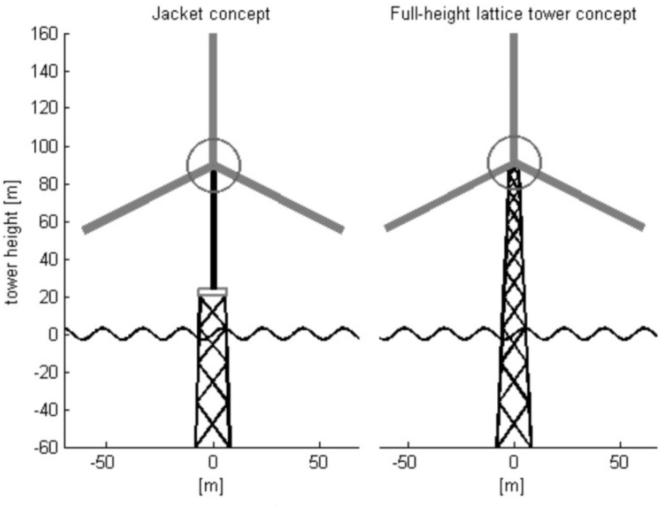

Figure 4: Two space frame support structure concepts that have been optimized with the presented method.

6. OPTIMIZATION RESULTS

The problem formulation presented in section 3, together with the simplified fatigue load assessment from section 4 was used to optimize both of the structures presented in section 5. Only the results of the FLT are presented here, as the jacket produced almost identical results. It can be observed in fig.4 (left) that the optimized design (black) is significantly modified compared to the initial design with constant dimensions (grey). In fig.5 (middle and right) the fatigue and ultimate limit state for the optimized design is presented, and it can be observed that fatigue is the design driver (for this DLC).

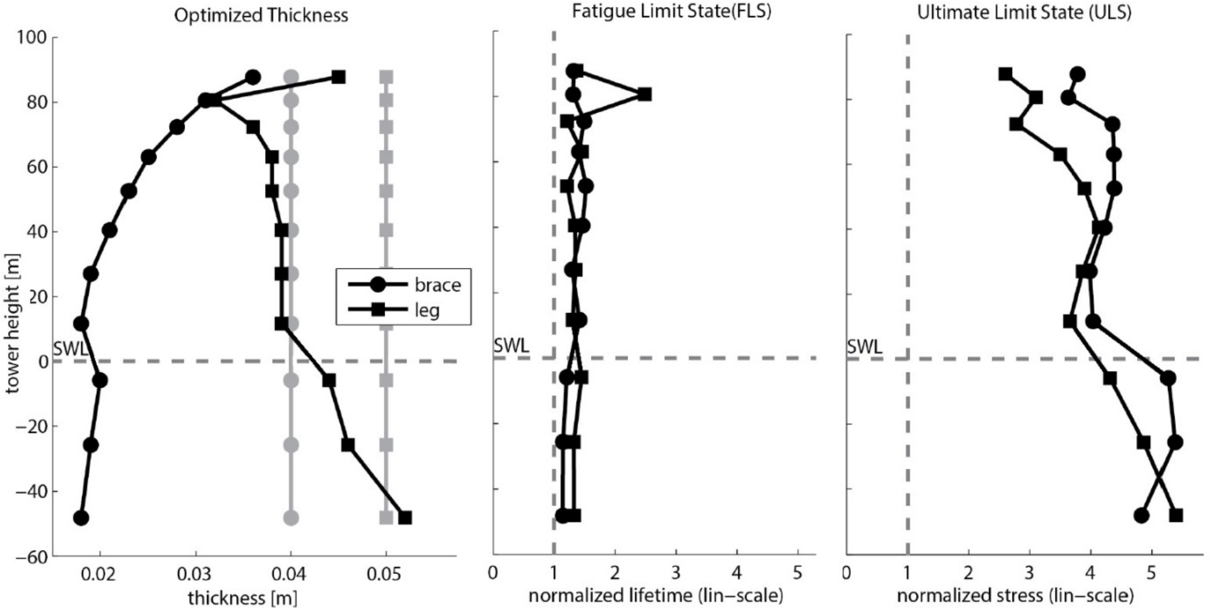

Figure 5: Results of the full-height lattice tower optimization. *Left*: Dimensions of the optimized design (diameter is 16 times thickness). *Middle*: Fatigue life normalized by 20 years. *Right*: Maximum stress normalized with yield stress (security factors shown). Below sea water level (SWL) the structure is also subjected to hydrodynamic loads.

7. DISCUSSION

Two different initial designs with masses of 450 and 1800 tons both converge to the same optimized design of about 700 tons. All sections have an acceptable fatigue lifetime close to the design limit (fig.5-middle), which means that the simplified fatigue load assessment has sufficient accuracy for optimization purposes. Legs are constrained to be thicker than braces, and this is the reason behind the high fatigue life for legs in the second uppermost section. Ultimate limit state (ULS) has not been included in this optimization, though the maximum stresses have been recorded, and it can be observed that all sections are far from yield. However, the simulations in this analysis only cover power production load cases, and extreme events should be studied to confirm the design.

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