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Improved design of the support structure for the NOWITECH 10 MW Reference Turbine

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Submission date: June 2014
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Abstract

The aim of this thesis is to improve the support structure for the Nowitech 10 MW reference turbine (NRT) by optimizing the thickness and diameter of legs and braces section by section. This is a so called full-height lattice tower, and has been successfully optimized for a single load case in previous studies. However, these have only guaranteed local optima, as the problem formulations have been non-convex, and the algorithms gradient-based.

This thesis first derives a convex problem formulation, also providing explicit expressions for step lengths. In the next stage a study investigates the ability of various fatigue load assessments to accurately represent a lifetime of loads. These findings are used to assemble a site-specific optimization approach which can be applied to any space frame structure. Using this approach, the support structure for the NRT was optimized for typical north sea conditions with 60 meter water depth. A jacket model was also designed for the NRT, and optimized using the same approach. Finally the lattice tower was benchmarked with the jacket support structure to assess the competitiveness of the concept.

The explicit expressions for step lengths gave the optimization faster convergence, and the study of fatigue load assessments concluded that computation expenses can be reduced with at least an order magnitude while retaining good accuracy. A site-specific optimization of the NRT support structure led to a weight reduction of 40 percent compared to the previous design. Excluding the transition pieces, both the lattice tower and the jacket were optimized to approximately 700 tons. Consequently the lattice tower can be designed more than a hundred tons lighter, because the jacket TP is much heavier.

Sammendrag

Målet med denne oppgaven er å forbedre understellet til Nowitechs 10 MW referanseturbin (NRT) ved å optimere tykkelse og diameter til staver seksjon for seksjon. Dette er et såkalt fullhøydes fagverkstårn, og har med hell blitt optimert for enkeltlaster i tidligere studier. Dog, disse har kun garantert lokale optimum, siden problemformuleringen har vært ikke-konveks og algoritmene gradientbaserte.

Denne oppgaven utleder først en konveks problemformulering som også gir eksplisitte utrykk for steglengde. I det neste trinnet har et studie undersøkt ulike typer utmattingsanalyser sin evne til å nøyaktig gjengi alle laster gjennom levetiden. Dette ble så brukt til å lage en områdespesifikk optimeringsmetode som kan brukes på alle fagverksstrukturer. Ved å bruke denne metoden ble understellet til til NRT optimert for typiske nordsjø-forhold på 60 meters havdyp. Et jacket-konsept ble også designet for NRT, og optimert med den samme metoden. Tilslutt ble de to understellene sammenlignet for å vise konkurransefortrinnet til fagverkstårnet.

Det eksplisitte utrykket for steglengde gav raskere konvergens, og studiet av utmattingsanalyser konkluderte med at datakraften kunne reduseres med minst en størrelsesorden og fortsatt gid god nøyaktighet. En områdespesifikk optimering av fagverkstårnet til NRT ledet til en vektreduksjon på 40 prosent sammenlignet med det tidligere designet. Sett bort fra mellomstykket (TP) ble både jacket og fagverkstårn optimert til ca 700 tonn. Dermed kan fagverkstårnet spare over hundre tonn, ettersom jacketkonseptet krever mye tyngre TP.

Preface

The work of this thesis was carried out from January to June 2014 at NTNU. Supervisors have been associate professor Michael Muskulus, PhD candidate Daniel Zwick, and post doc Karl Merz. It has been inspiring to have such competent guidance along the way; I hope our roads will cross again.

I am thankful for the liberty I have been given in my work with this thesis. Most of it express my own ideas, but help has been given when I have asked for it. It has been exciting to solve the problems I found on my way, rather than to follow a prescribed path.

I end my education where it began, in a burning desire to create a sustainable future. I would like to thank those who believe I can do that, and those who help me do so.

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Chapter 1

Introduction

1.1 Background

The International Panel on Climate Change (IPCC) have concluded that anthropogenic forcing explains the unusual climate change in the 20th century, and most countries in the world have agreed that the emissions of carbon dioxide to the atmosphere must be reduced. Since energy is vital for peoples standard of living, the reduction of fossils in the energy mix should be compensated with renewable energies like wind and solar. In recent years the potential of offshore wind has been recognized because of its good wind conditions and huge areas in close vicinity to consumption hot spots. A merge of onshore wind industry, and offshore and maritime industries have proved capable of building large offshore wind farms($> 100MW$), but the current cost level is too high to compete with energy prices on the continent. Extended mass production will reduce costs to some extent, but there is also need for technological innovation.

Support structures comprise about 17 percent of total capital cost, and partly because current structures are adopted from the conservative and high cost oil and gas industry, this is an area with high potential for cost reduction. An alternative support structure concept for large offshore wind turbines have been studied at the Norwegian Research Centre for Offshore Wind Technology(NOWITECH). This is a full-height lattice tower, where a continuous jacket structure from sea bed to nacelle replaces the heavy transition piece at sea level with a lighter one at the yaw mechanism.

1.2 Problem

The task is to improve the design of the support structure for the NOWITECH 10 MW Reference Turbine (NRT). The design of the piles shall be considered, and the structure shall be checked with a more complete and realistic set of load cases, including extreme wind and sea states and emergency shutdown.

This text was written after a specialization project [16] found the model to have severe performance issues, leading to fatigue failure in less than 12 months. A hypothesis of pile effects was tested and rejected, and faults related to nacelle weight and load path definitions were found to have caused the bad performance. In light of this, the pile study was dismissed, and soil profile from the reference site was used. A complete check of the current design showed that fatigue was driving the design in all sections, and that safety factors for yield was above 2 for all legs, and above 5 for all braces. This indicates that fatigue damage during power production is the leading design criterion, and extreme weather events were also dismissed in favour of an in-depth study of the optimization approach. Convexity of the optimization problem have been considered, and the optimization method have been improved with respect to convergence and accuracy. The improved design has been benchmarked with a conventional design optimized for the same site and turbine.

1.3 Guide to Reader

This master thesis is split in two, such that theory and background required to understand the thesis is systematically presented in *Background*, while my own work is presented in 4 different chapters. These chapters are divided into similar subsections to give a methodical representation of the work, and can be understood alone. Chapter 3 study the optimization of member dimensions, chapter 4 study the computational expenses of optimizations, chapter 5 presents the improved support structure for NRT, and chapter 6 benchmarks the lattice tower with a jacket concept. The *Conclusion* at the end is for the whole thesis, and discuss the implications of the results and give recommendations for further research.

Chapter 2

Background

This chapter will establish the scientific basis for the thesis. Relevant theory to understand the findings in chapter 3 to 6 is presented in a systematic manner. Starting broad with existing support structures, and narrowing down towards the mathematical properties of continuous optimization.

2.1 Offshore Wind Turbine Support Structures

This section presents the motivation for harvesting offshore wind energy, and gives an overview of existing concepts for support structures.

Energy Demand

Climate change has become a serious crisis in many parts of the world, and there is a global consensus that emissions must be reduced. Nothing suggests that energy consumption will decline, which implies that renewable energies should satisfy a greater part of the demand. Wind energy, solar and hydro-power are competitive on price in many countries, but there are still challenges:

- Power production is variable and difficult to predict, and good solutions for energy storage is still missing.
- Large scale renewable energy often requires substantial areas, which can intervene with ecosystems or create conflicts with neighbours.

Offshore Wind

Wind turbines have traditionally been built onshore, but due to

- stronger and more stable wind conditions,
- large available areas in close proximity to consumption hot spots,
- less NIMBY(Not In My Back Yard) conflicts,

offshore wind have emerged as a new industry. Experience with offshore operations from the oil and gas sector, as well as other marine industries is vital when the wind turbines take the step into the oceans. An important difference between onshore and offshore wind turbines is the availability for installation, operations and maintenance. Offshore operations are far more challenging than onshore, and this have triggered a drive towards bigger turbines. In a 100 MW wind farm its more convenient to manage 10 units than 100. Installation is also a large cost driver, and when a structure is installed to withstand the hostile conditions of the sea, its preferable that it generates as much money as possible. The size of wind turbines have increased substantially the past years, and 6 MW turbines have been planned for several wind farms. At the moment, the worlds largest(in MW) turbine is a 8 MW from Vestas.

Existing Concepts for Support Structures

The most common support structure for offshore wind turbines built to date is the driven monopile, as seen to the left in figure 2.1. As turbine size and sea depth increases, the overturning bending moment at the sea bed becomes large, and greater diameter and thickness is required. This is expensive, and makes the monopile less advantageous. Multi-member hybrid concepts such as the jacket and the tripod have been introduced as solutions to this, but the transition assembly in these solutions impose strict requirements for strength and stiffness, that finally increase the total cost[18].

Scaling of Tower Mass for Tubular Towers

The cubic rule is a phenomenon in design, meaning that if length or thickness in one dimension is increased, so must the two others, causing the volume and thus the mass to scale with the cube of the initial increase. This is usually applied to rotors, where an increase in length must be accompanied by increase in cross section. However, the height of a tower does not always need to be increased as

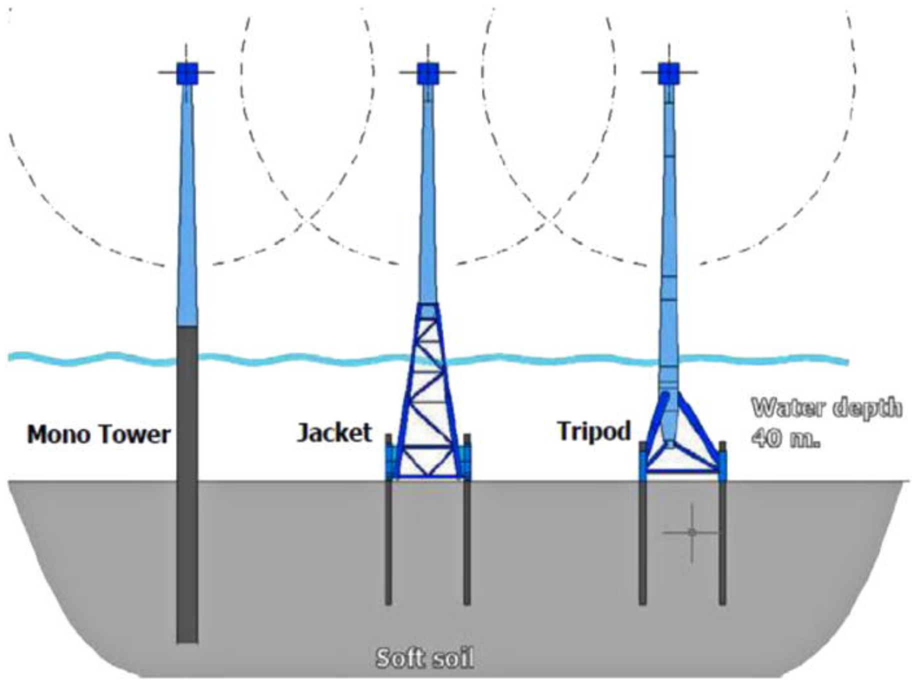


Figure 2.1: Three support structure concepts for offshore wind turbines.

much as the length of the rotor, and so this scaling law have been proposed by NREL [17]:

$$m_{Tower} \propto r_{rotor}^2 h_{hub} \tag{2.1}$$

The scaling does not take into account the power output from the turbine, which makes it less accurate for comparison of turbines with different P/A ratio(Power per swept Area).

2.2 The Full-Height Lattice Tower

It was the group of Geir Moe at the Department of Civil and Transport Engineering at NTNU that first got the idea, during the time when the first jacket support structures were installed for the Beatrice wind farm demonstrator project.

The full-height lattice tower is an alternative support structure for bottom-fixed wind turbines. In contrast to the hybrid designs, this concept has abandoned the tubular tower, and is a continuous space frame from bottom to top. This gives a more effective design, and replaces the expensive transition piece with a much smaller one at the top of the tower. In the early age of large onshore wind turbines, lattice towers were actually the predominant style. They were then replaced with tubular towers in the 1980s partly because of aesthetic concerns. Far offshore where nobody can see them, aesthetic concerns are less important, and other pros and cons have been identified:

Advantages

- Easy to tune eigenfrequency and avoid global vibrations.
- Space frames are more transparent to wind and waves than tubular towers.
- The large diameter monopile is replaced with 4 smaller piles.
- Less sensitive to soil uncertainties than a monopile.
- Cheaper transition piece than the hybrid designs in figure 2.1.
- Assumed to be lighter than conventional designs.

Disadvantages

- Larger structure complicates fabrication and installation.
- Many members and welded joints increases production cost.
- Braces can be a excited and cause local vibrations.
- Many variables makes site-specific optimization time-consuming and not straightforward.
- Access and maintenance is less straightforward and economical than for tubular towers.

Figure 2.2: 1.25 MW Smith-Putnan from the 1940s.

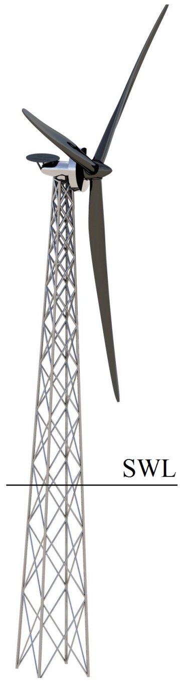


Figure 2.3: Nowitech 10 MW Reference Turbine(NRT).

The Nowitech Reference Turbine

Nowitech has developed a conceptual design and load model for a future 10 MW wind turbine as a common testcase and platform for open simulation studies. A 150 meter tall full-height lattice tower is used as support structure, and previous studies have successfully optimized its design. Details about the current design is given in table 2.1.

In figure 2.4, the lower part of the structure is used to explain important terminology. Each section consists of both legs and braces that are welded together in K-joints and X-joints. Constant brace angle makes section height lower toward the top, as leg distance decreases from bottom to top. The bottom four K-joints are connected to driven piles, which are 28 meters long, and 3.5 meters in diameter.

Variable	Value
Tower height	151 m
Top leg distance	4 m
Bottom leg distance	16 m
Number of sections	11
Section height	Constant brace angle
Member dimensions	Optimized per section

Table 2.1: Details of the support structure for the NRT.

2.3 Fatigue Calculations

Oscillatory excitation from rotor and waves makes fatigue limit state the design driver for space frame support structures. This section explains how simulations in the time domain is used to estimate fatigue damage in a joint for the complete lifetime.

Stress Concentration Factors and Hot Spot Stresses

For a general beam problem, stress in any point can be found by superposition of force and moment:

$$\sigma_i = (\frac{F}{A} + \frac{My_i}{I}) \tag{2.2}$$

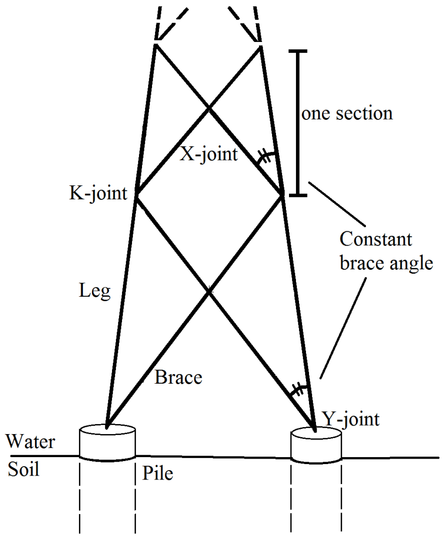


Figure 2.4: Lattice tower terminology

where σ_i is the stress, and y_i is distance from the bending moments neutral axis to the point. F is force, M is moment, and I is moment of inertia.

In welded space frames, there will be stress concentrations along the weld, and it is assumed that the joint will be the weakest link in every section. The recommended practice *Fatigue design of offshore steel structures* from DNV[3] is used to evaluate stress at 8 hot spots along each weld. Hot spot stresses (HSS) at these points are derived by summation of single stress components from axial (ax), in-plane (mip) and out-of-plane (mop) action (see figure 2.5).

Stress components are found with standard formulas

$$\sigma_{ax} = \frac{F}{A} \tag{2.3}$$

$$\sigma_{mip} = \frac{M_{IP} y}{I} \tag{2.4}$$

$$\sigma_{mop} = \frac{M_{OP} y}{I} \tag{2.5}$$

These stress components are then multiplied with a stress concentration factor, and then weighted according to each hot spot. Axial stress component is constant along the whole weld, while moments attack differently:

$$\sigma_1 = SCF_{ax}\sigma_{ax} + SCF_{mip}\sigma_{mip} \tag{2.6}$$

$$\vdots \tag{2.7}$$

$$\sigma_8 = SCF_{ax}\sigma_{ax} + \frac{\sqrt{2}}{2}SCF_{mip}\sigma_{mip} + \frac{\sqrt{2}}{2}SCF_{mop}\sigma_{mop} \tag{2.8}$$

SCFs for each stress component depend on joint topology, and is found from curve fitted formulas as seen in figure 2.6

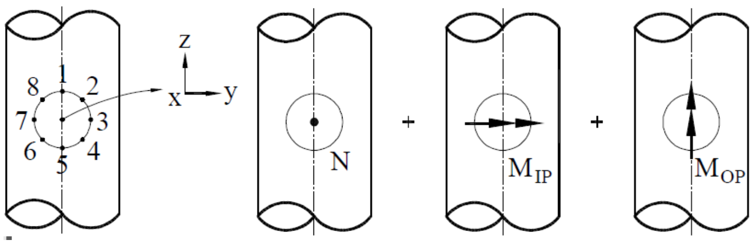


Figure 2.5: Superposition of stresses in tubular joints (adapted from DVN-RP-C203 [3])

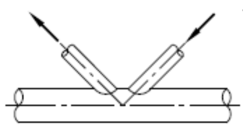
Balanced axial load	Chord: $\tau^{0.9}\gamma^{0.5}\left(0.67-\beta^2+1.16\beta\right)\sin\theta\left(\frac{\sin\theta_{max}}{\sin\theta_{min}}\right)^{0.30}\cdot\left(\frac{\beta_{max}}{\beta_{min}}\right)^{0.30}\left(1.64+0.29\beta^{-0.38}ATAN(8\zeta)\right)$	(20)
	Brace: $1+\left(1.97-1.57\beta^{0.25}\right)\tau^{-0.14}(\sin\theta)^{0.7}\cdot(\text{Eqn. }(20))$	

Figure 2.6: Formula for SCF_{ax} for legs (chord) and braces in a K-joint. (adapted from DVN-RP-C203 [3])

SN-Curve Estimation of Fatigue Damage

Fatigue is the phenomenon in which a material is weakened due to cyclic loading below the yield stress. The physical explanation is that pre-existing cracks in the material will grow during cycling loading. The speed of this crack growth, $\frac{da}{dN}$ (where a is crack length and N is number of cycles), depends on the stress intensity at the crack tip as described by equation 2.9. Stress intensity, K_I is a function of the geometry factor Y, nominal stress and crack length. A fracture toughness K_{IC} is defined such that if $K_I \geq K_{IC}$ the material will fail due to unstable crack propagation. From the Paris relation (2.9) [4] and the definition of K_I (2.10) the SN-curve relation can be derived (2.11).

$$\frac{da}{dN} = C(\Delta K)^m \tag{2.9}$$

$$K = Y\sigma\sqrt{\pi a} \tag{2.10}$$

$$\log(N_c) = \log(\bar{a}) - m\log(\Delta\sigma) \tag{2.11}$$

In the SN-equation 2.11, the constants are summed up in $\bar{a}$, and N_c is the number of cycles to failure. If equation 2.11 is plotted on log-log axis', a straight line with slope $\frac{1}{m}$ relates stress amplitude with number of cycles N_c before failure. This curve is always fitted to empirical observations, and common practice is to shift the curve 2 standard deviations down, such that the curve is associated with 97.7 percent probability of survival[3].

$$\log(N) = \log(\bar{a}) - m\log(\Delta\sigma(\frac{t}{t_{ref}})^k) \tag{2.12}$$

In the DNV standard, equation 2.12 and figure 2.7 is given for tubular joints. m changes from 3 to 5 at $N = 10^6$ in seawater and 10^7 in air. Also note that a thickness exponent $k = 0.25$ is included, where $t_{ref} = 32mm$. The ratio between maximum and minimum stress within a cycle is often assumed to impact the SN-curve, but in this report it is not. [3], pg. 12: *"The procedure for the fatigue analysis is based on the assumption that it is only necessary to consider the ranges of cyclic stresses in determining the fatigue endurance (i. e. mean stresses are neglected for fatigue assessment of welded connections)."*

Palmgren Miners Rule

Palmgren Miner linear damage hypothesis is a common assumption in fatigue calculations. It states that there is a linear and additive relationship between

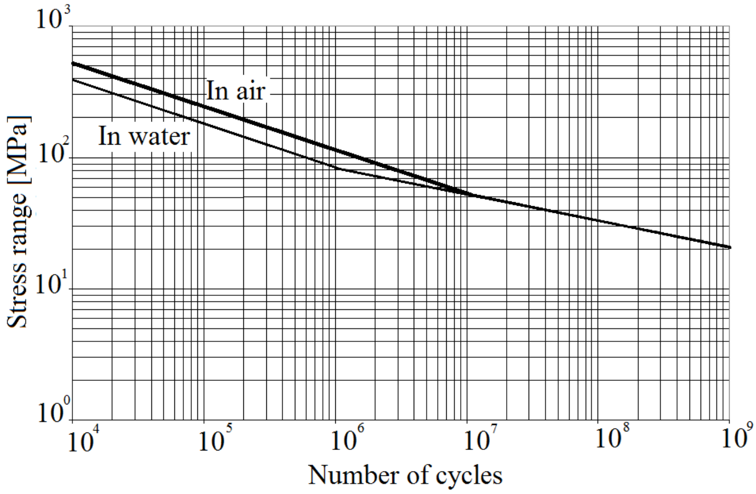


Figure 2.7: SN-curve for tubular joints.

the fatigue damages accumulated at different stress amplitudes.

$$D = \sum_i \frac{n_i(\Delta\sigma_i)}{N_i} \tag{2.13}$$

At each stress amplitude $\Delta\sigma_i$, the number of cycles to failure N_i is found from the SN-curve. The number of cycles the material experiences is n_i. This hypothesis enables the engineer to compute fatigue damage from a complex load history. If $D \geq 1$ the member will fail. When fatigue is a design constraint, the damage can be thought of as a utilization factor that is not allowed to reach one. In this thesis U_L and U_B will denote utilization factors for legs and braces respectively.

$$U = D_{20years} \leq 1 \tag{2.14}$$

Rainflow Counting

To use the SN-curve, stress history must be decomposed into oscillations of different stress ranges, and then the number of cycles in each stress range must be counted. Rainflow counting is assumed to be the best algorithm. The method was first developed by Matsuishi and Endo[10] and then redefined for statistical analysis by Rychlik[11]. The only difference between alternative rainflow methods is in the appreciation of the leftovers after combining cycle pairs[9]. In this analysis these are assumed to do half the damage as the full cycle.

Rainflow counting is a well proven algorithm, and for this part of the analysis, a complete file package from Matlab file exchange has been used. This package has been available for 10 years, and the response is approving(4,6 of 5 stars from 49 voters). Simple tests also gives reasonable results.

2.4 Design Optimization of Wind Turbine Support Structures

Structural optimization is a well developed field, though fatigue constraints are not so common. This section presents the problem and its challenges, as well as relevant works.

General Considerations

Structural optimization is a common tool in industries such as automotive and aerospace, but offshore support structures have seen few applications. In oil and gas industry these structures comprise a negligible part of total capital cost, and conservative designs have been the rule of thumb. For offshore wind however, reduction of cost is of great concern, and this is an area with a high potential for cost reduction [19]. Methods are currently being developed, and 6 specific challenges have been identified:

- Non-linearities: Coupled simulations in the time-domain is needed to capture all physical effects and their interactions.

- Complex environment: Long simulations are needed to obtain sufficiently accurate results, 1 hour of each load case is recommended.

- Fatigue as design-driver: Quasi-periodic structural motions excited from both turbine and waves makes the structure prone to failure from fatigue.

- Specialized analysis software: Only a handful of simulation codes can handle the complexity, and their speed is comparable to real-time.

- Tightly coupled and strongly interrelated systems: Parts can not be optimized separately.
- Many design variables and constraints: The structural optimization problem is highly constrained and non-convex.

This thesis have tried to overcome some of these challenges by reducing computation expenses and reduce the potential for non-convexity.

Existing Approaches

The optimization-of-lifetimes or **the iterative optimization approach** was the first attempt to optimize the design of the full-height lattice tower[12]. It uses tower weight as objective function, and lifetime of joints as constraint. The algorithm is based on locality assumptions, and structural members are sized independently of each other, assuming the loads will stay the same. This is only approximately true, but works well enough in practice, and only around 20-30 iterations are needed for convergence [15]. Only a fifth of the iterations require simulations, so the method is computationally cheap. Limits to the approach is that it uses gradients to evaluate step length in a non-convex optimization problem. Figure 2.8 shows the logic of this approach. The assumptions and methods from this approach have been used for this thesis as well.

The simultaneous perturbation stochastic approximation (SPSA) was used to automatically optimize thickness and diameter of the members in the full-height lattice tower. A combination of tower weight and joint lifetimes was used as objective function, and the method was able to generate considerably improved designs compared to other methods. Limits to the approach is that it uses a few hundred iterations to find a suitable design. With the number of simulations on the order of several hundreds, the optimization is computational expensive.

Frequency Considerations

Safe operation of the turbine must be ensured by avoiding resonance. Both waves and rotor are causing periodic excitations, and the tower should be designed such that its eigenfrequencies are not interfering with the frequency of the external forcings. A Campbell diagram can be used to identify the ideal frequency for the tower (see figure 2.9). Resonance may occur at rotor frequency, 1P, or at blade passing frequency, 3P. In the Campbell diagram, the excitation

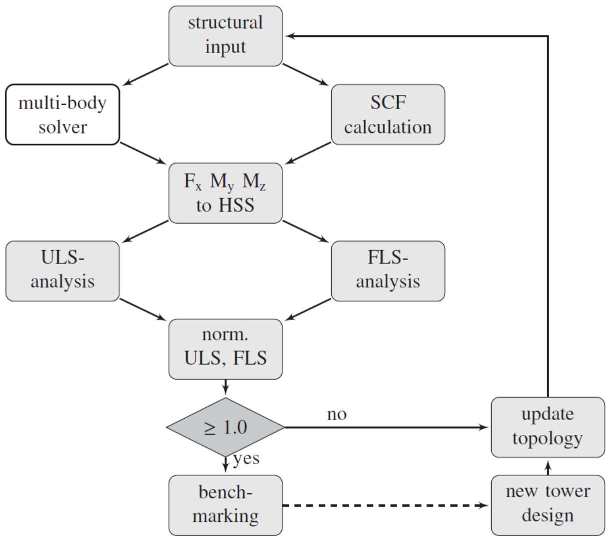


Figure 2.8: Iterative optimization approach

frequency is plotted against rotor frequency. The dotted lines indicate the operating interval for the NRT turbine, and black lines are the excitation frequencies of the rotor. From this diagram it can be seen that if the tower is designed with an eigenfrequency above 0.6 or in the interval $(0.21, 0.31)$, resonance will not occur. It was also found that wave frequencies does not pose a risk of resonance if the frequency is kept above 0.21. The lattice-tower is a soft-stiff design, meaning it has its 1^{st} eigenfrequency in the interval between 1P and 3P, and secondary modes above the 3P frequency.

2.5 Convexity in Continuous Optimization

Convexity is a mathematical term, defining that something is curved outward. If a straight line between two points in a domain never can be drawn such that the line crosses the domain boundary, the mentioned domain is a convex one. Similar; if the domain $S \geq f$ is a convex domain, f is a convex function. In continuous optimization, a convex problem is the special case where a convex function is optimized over a convex domain. The advantage of a convex problem is that any local minima will also be a global minima. On the other hand,

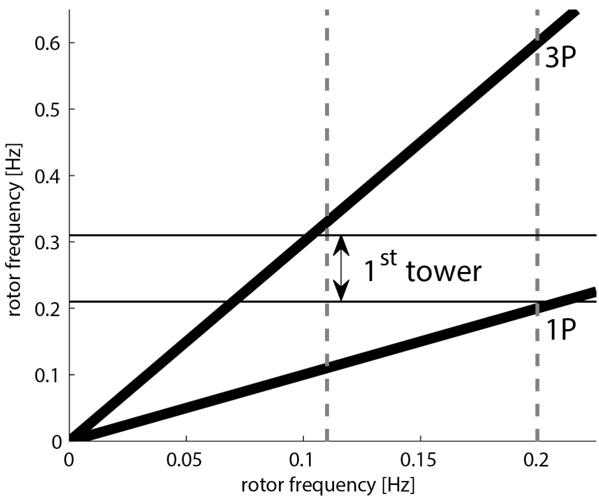


Figure 2.9: Campbell diagram for NRT

if either the objective function or the domain are non-convex, they introduce possibilities for local minima. FIgure 2.10 illustrates the difference between convex and non-convex optimization problems. A convex problem can be solved for example by a gradient method.

2.6 Software for Simulations and Fatigue Load Assessment

This section presents the software that has been used in this thesis. Both commercial programs and scripts from a previous project have been used.

Fedem Windpower

Fedem is a flexible multi-body solver that use a reduction technique to reduce FE-models into super elements, which are more convenient to run through long time series. Fedem Windpower is a version of Fedem specialized for simulating onshore and offshore wind turbines, with integrated soil description and control system. Turbulent wind files are generated from TurbSim[2], and waves are generated with a JONSWAP wave spectrum.

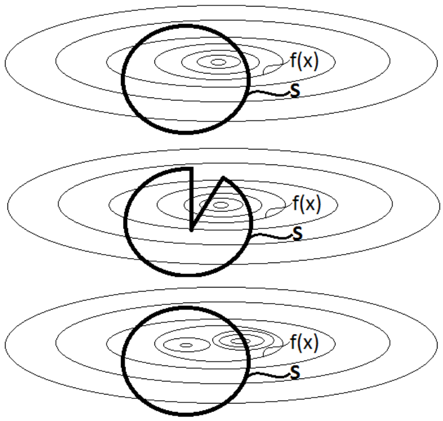


Figure 2.10: One convex problem(top), and two non-convex problems.

Variables like wind speed, significant wave height, peak period, sea growth, member dimensions etc. can be specified for each simulation in an event file. One event is associated with one load case, and many events are listed in one event file. This enables the possibility of simulating many events, and then compare the effect of different variables. The fatigue damage due to variation of member dimensions has been the focus of this study.

The model used in this thesis is developed in Nowitech, and the following changes have been made:

- Weight of parts have been corrected.
- Fictive eigenmode has been fixed.
- Properties previously defined within an assembly has been moved up, such that they can be changed with events.
- All simulations have used event files to specify turbulent wind field, wave spectrum, marine growth and cross section properties of all members.

Fatigue Load Assessment

Scripts and programs developed for fatigue load assessment of the full-height lattice tower was developed during a specialization project [16] in 2013, and these have been recycled and used again in this master thesis. The work flow is briefly explained in figure 2.11

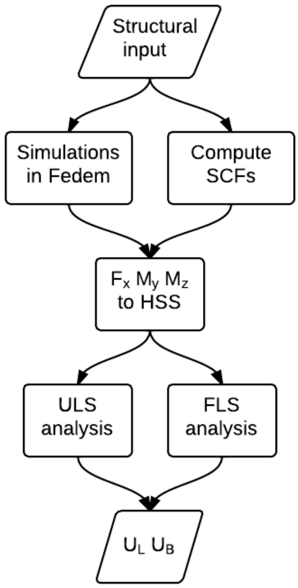


Figure 2.11: Fatigue load assessment

Simulation Details

A reference site from the UpWind project is used, and lumped wind speeds, wave spectrums, marine growth and soil data is taken from this document [8]. Simulations are done with time step of 0.025 seconds, and all simulations have a 200 seconds start-up period. That is, if a 180 second simulation is mentioned, the real simulation length is 380 seconds. It has been assumed that 200 seconds start up time is sufficient to avoid irregularities from the start up for all wind speeds. In figure 2.12, the rotor speed for a 600(well, 800) seconds simulation is plotted, and no irregularities can be observed after 200 seconds.

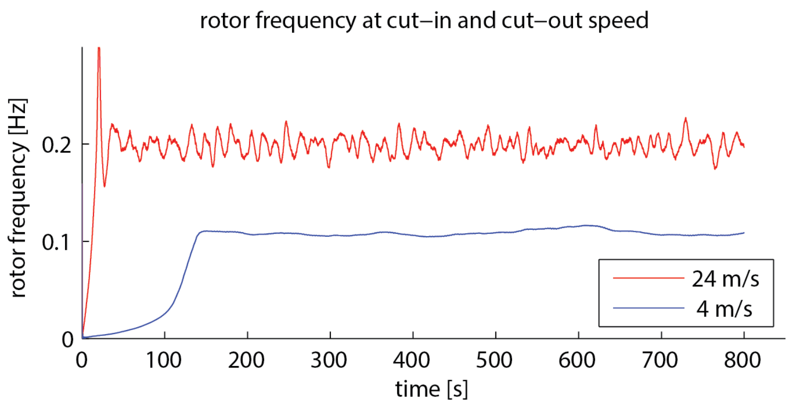


Figure 2.12: Rotor frequency at cut-in and cut-out speed

Chapter 3

Formulation of the Optimization Problem

3.1 Goal

Convexity is important in continuous optimization because it guarantees that any local minima is also a global minima. The aim of this chapter is to simplify the optimization problem for the iterative optimization approach such that a convex problem formulation is achieved. The basis for the problem will remain the same:

- Objective function: Minimize the tower mass.

- Constraint: Utilization factors $U \leq 1$.

3.2 Method

General assumptions about the the loads and joint geometry are used to derive a relationship between fatigue life and member dimensions. Scaling considerations are then used to reduce the number of variables and derive explicit expressions for step length.

Assumptions

This approach will be limited to only modify thickness and diameter of structural members. Other parameters will be assumed constant, as defined in chapter 2.2. Further on, the following assumptions will be used to simplify the problem:

- Loads are not changed when changing one member.
- Loads are not changed when changing other members in the structure.
- Hot spot stresses are dominated by axial force.
- Braces will always fail at the X-joint.
- Gap between braces in K-joint is constant.

The first assumption means that given a load history, the optimal geometry of all members can be determined analytically, without the need for further simulations. The second assumption means that all structural members can be sized at the same time, independently of each other. The third and fourth assumptions mean that each hot spot stress will scale with only one SCF. Finally, the last assumption remove the only non-continuous element in the SCF-formulas. The advantages of using these assumptions are:

- Each section can be optimized independently.
- Few simulations are needed.
- Fatigue life can be scaled with member dimensions.

The three last assumptions are new, while the other two have been used for the iterative optimization approach in several published papers ([12], [15]). Contributions to hot spot stresses have been checked, and it seems about 80 percent of the stress is from axial forces, a little less for the upper sections. It has also been confirmed that braces fail at the X-joint, at least for the low D/T ratio used in this structure. The assumption about the gap is a common practice in engineering, but not physically true for the analysed model because this assumes the joint as a single point rather than a 3-dimensional geometry.

Derivation

The SN-curve scales stress amplitude $\Delta\sigma_i$ with the maximum number of cycles (Paris' law).

$$\log N_i = \log a - m \log \Delta\sigma_i \tag{3.1}$$

$$\Rightarrow \frac{1}{N_i} \propto \Delta\sigma_i^m \tag{3.2}$$

Palmgren Miners rule scale the utilization factor U with the maximum number of cycles.

$$U = \sum_i \frac{n_i}{N_i} \tag{3.3}$$

$$\Rightarrow U \propto \sum_i n_i \Delta\sigma_i^m \tag{3.4}$$

Assuming axial force to dominate the hot spot stress:

$$\sigma_i \simeq \frac{F}{A} SCF_{ax} \tag{3.5}$$

$$\Rightarrow \Delta\sigma_i \propto \frac{SCF_{ax}}{A} \tag{3.6}$$

Since stress amplitude scales with SCF and cross section area regardless of load history, this can be extracted from the summation:

$$U \propto (\frac{SCF_{ax}}{Area})^m \sum_i n_i \tag{3.7}$$

$$\Rightarrow U_L \propto (\frac{SCF_L}{A_L})^m \tag{3.8}$$

$$\Rightarrow U_B \propto (\frac{SCF_B}{A_B})^m \tag{3.9}$$

Subscripts L and B means Leg and Brace. There are four variables that can be modified in each section, namely diameter and thickness of both legs and braces(see figure 3.1). Scaling laws for the SCFs in equations 3.10 and 3.11 are derived in appendix C, while the validity domains are taken directly from the standard [3].

$$SCF_L \propto \tau^{0.9} \gamma_L^{0.5} \tag{3.10}$$

$$SCF_B \propto \gamma_B \tag{3.11}$$

$$\tau = \frac{t}{T} \in (0.2, 1) \tag{3.12}$$

$$\beta = \frac{d}{D} \in (0.2, 1) \tag{3.13}$$

$$\gamma_L = \frac{D}{64T} \in (0.25, 1) \tag{3.14}$$

$$\gamma_B = \frac{d}{64t} \in (0.25, 1) \tag{3.15}$$

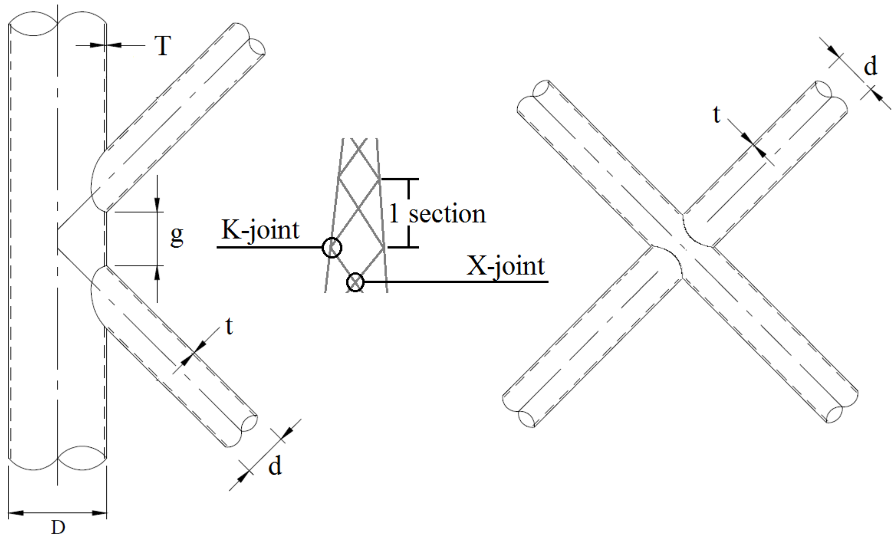


Figure 3.1: A K-joint and an X-joint. The gap between braces in K-joints is assumed to be constant.

The cross section area of legs and braces, A_L and A_B, are useful to scale with thickness and γ:

$$A = \frac{\pi}{4}(D^2 - (D - 2T)^2) \tag{3.16}$$

$$\propto T^2(\frac{D}{T} - 1) \tag{3.17}$$

$$\Rightarrow A_L \propto T^2\gamma_L \tag{3.18}$$

$$\Rightarrow A_B \propto t^2\gamma_B \tag{3.19}$$

This can be used to express a simple scaling relationship for the weight(objective function f) of the section where r is a constant that relates length of legs with length of braces.

$$Weight = \rho(4A_L L_{Leg} + 16 A_B L_{Brace}) \tag{3.20}$$
$$\Rightarrow f \propto T^2 \gamma_L + r t^2 \gamma_B \tag{3.21}$$

A relationship between utilization factors and member dimensions can then be found by inserting expressions for SCFs and areas into equations 3.8 and 3.9.

$$U_L \propto (\frac{\tau^{0.9}}{T\gamma_L^{0.5}})^m \tag{3.22}$$
$$U_B \propto (\frac{1}{t^2})^m \tag{3.23}$$

Further simplification can be achieved by minimizing γ_L and γ_B. It is proved in appendix C that this also minimizes the objective function.

$$U_L \propto \frac{\tau^{0.9m}}{T^m} \tag{3.24}$$
$$U_B \propto \frac{1}{t^{2m}} \tag{3.25}$$
$$\tag{3.26}$$

The optimization problem can now be stated with one objective function, two constraint functions and a domain. It is intuitive that the domain is convex, as it is simply a triangle in two dimensions, but also f, g_1 and g_2 are now convex. It can be proven by evaluating their second derivatives, and checking that they are positive on the whole domain.

$$f(t,T) \propto T^2 + rt^2 \tag{3.27}$$
$$g_1(t,T) = U_L - 1 \leq 0 \tag{3.28}$$
$$g_2(t) = U_B - 1 \leq 0 \tag{3.29}$$
$$t \in (t_{min}, T) \tag{3.30}$$
$$T \in (t, T_{max}) \tag{3.31}$$

Figure 3.2 shows the geometric interpretation of the problem. Since the problem formulation is convex, the global optima could be found with a gradient-based approach, but the scaling relationships also allow for analytic solutions.

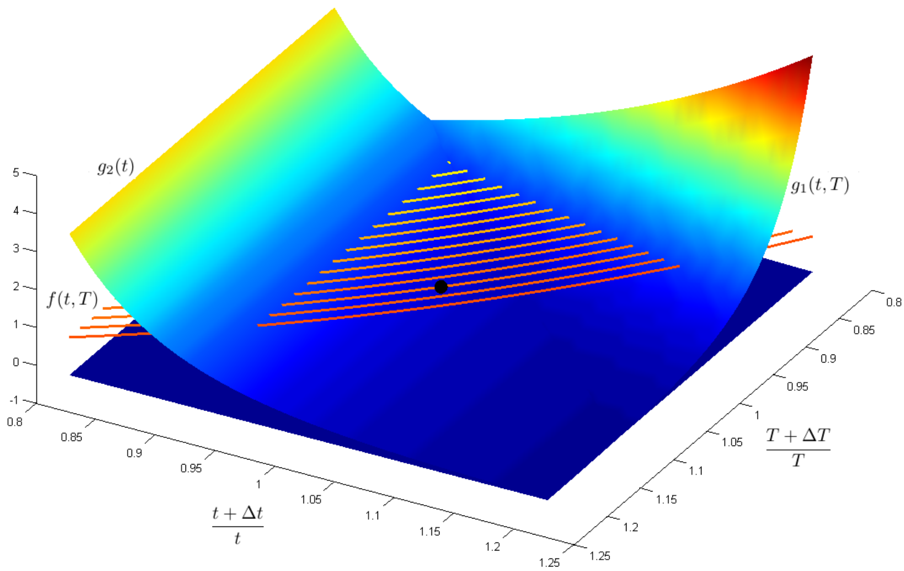


Figure 3.2: The convex optimization problem. The curved surfaces are the constraint functions, and the level curves represents the weight function.

$$U_B^{n+1} = \frac{(t+\Delta t)^{2m}}{t^{2m}} U_B^n \tag{3.32}$$

$$U_L^{n+1} = \frac{t^{0.9m}(T+\Delta T)^{2.9m}}{(t+\Delta t)^{0.9m} T^{2.9m}} U_L^n \tag{3.33}$$

This can be used to estimate the required step length to get full utilization. Inserting $U_B^{n+1} = U_L^{n+1} = 1$ and $m = 5$, step length can be solved for:

$$\Delta t = t((U_B^n)^{\frac{1}{10}} - 1) \tag{3.34}$$

$$\Delta T = T((U_L^n)^{\frac{1}{14.5}} (\frac{t+\Delta t}{t})^{\frac{4.5}{14.5}} - 1) \tag{3.35}$$

3.3 Result

The formulated optimization problem was used to optimize a tower with constant dimensions. The weight of the tower is plotted versus iterations in figures 3.3, 3.5 and 3.6. Each iteration means that the dimensions of all variables in all sections have been modified with one step length, according to the expressions in equations 3.34 and 3.35. Thus, before a step can be computed, a simulation and subsequent fatigue load assessment must be performed to compute U_L and U_B. Complete and simple analysis is described in chapter 4.

If all assumptions had been true, one step length would would have been sufficient to find the optimal design for a given set of utilization factors. In figure 3.3 it can be observed that the first iteration changes the tower mass with almost 50 percent, getting the design very close to the optimum for this load history. However, a new fatigue load assessment (of the same load history, but with new dimensions) shows that utilization factors are not equal to one. Two new iterations are required to optimize the design for this load history.

When the design is completely optimized for a given load history, new simulations are initiated with the optimized design(marked as *simple analysis* in the figures). This produces a new load history, which is used to optimize the design again. This continues until the design have converged. In figure 3.3 it can be observed that two different initial designs require a different number of iterations to converge. The heavy design needs 6 simulations, compared to only 4 for the lighter design. Nevertheless, both converge towards the same weight, and figure 3.4 shows that they also converge towards the same dimensions.

Simulations are generally more time-consuming than fatigue load assessment, though not with more than a factor of 3. It can be observed from figure 3.3 that the new simulations are needed to drive the optimization towards the final design. It is therefor interesting to know if very accurate optimization is really necessary for each load history. Figures 3.5 to 3.6 show the difference between optimization as described for figure 3.3, and optimization where new simulations are run for each iteration. It can be observed that fewer iterations are needed for convergence, but more 1 more simulation.

In the optimizations described in this chapter, the design is assumed to have converged if the weight difference between two simulations is less than 20 tons. It is therefore assumed that a potential of approximately 10 tons is left. In figures 3.7 and 3.8, the weight error of the optimizations in figures 3.5 to 3.6 is plotted. A linear relationship can be observed between logarithmic error and iteration number. Slightly faster convergence with respect to simulation number is achieved when the design is completely optimized for each load history.

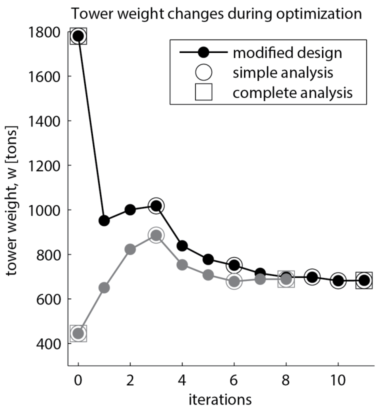


Figure 3.3: Weight optimization of two different initial designs.

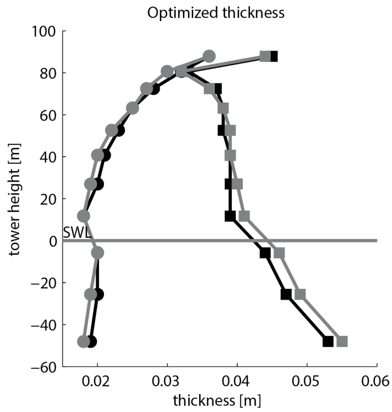


Figure 3.4: [
Optimized thickness of two different initial designs.]Optimized thickness of two different initial designs. Dots are brace thickness, squares are leg thickness.

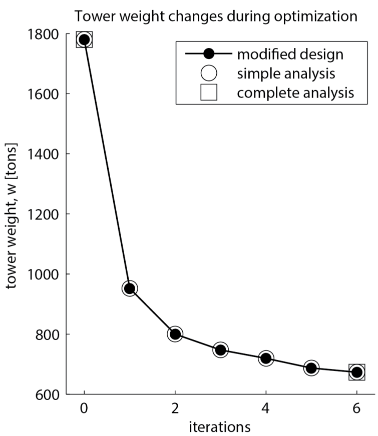


Figure 3.5: Weight converges in 6 iterations with simulations every iteration.

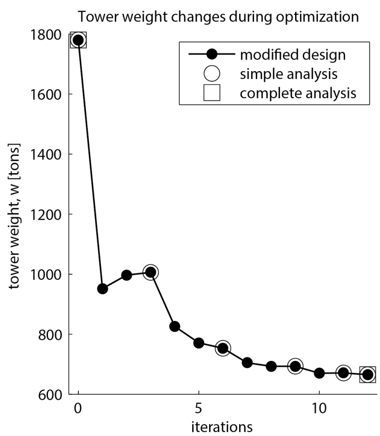


Figure 3.6: Weight converges in 12 iterations with simulations every third iteration.

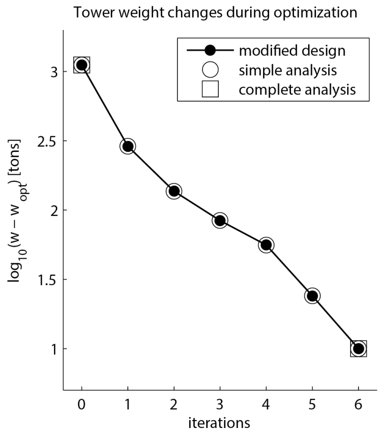


Figure 3.7: The error is reduced with an order of magnitude every third simulation with simulation every iteration.

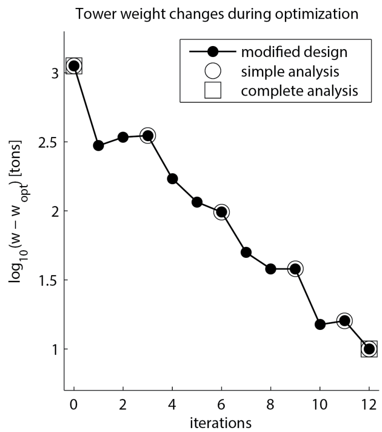


Figure 3.8: The error is reduced with an order of magnitude every second simulation with simulation every third iteration.

3.4 Discussion

The derived optimization problem only regards individual sections for a given load history. However, the results show that variations in initial design and number of iterations per simulations all generate the same final design. This indicates that the result is a global optimal design.

The analytic step length were assumed to find the optimal design for a given load history in one iteration. The results show that this was only approximately true, as the first step get very close, but two more steps are needed to converge. However, the results also show that one iteration per load history gives convergence of the final design after approximately the same number of simulations.

It can be observed that one step per simulation gives slightly less decrease in logarithmic error per new simulation, but far less fatigue load assessments are needed, and that makes this the faster method. It can thus be stated that the optimization converge after 6 iterations, however the number of simulations have not been reduced compared to [12].

Chapter 4

Simplified Fatigue Load Assessment in Site-Specific Optimization

4.1 Goal

Space frame support structures for offshore wind turbines are prone to failure in fatigue, and the engineer must therefore be able to accurately estimate the fatigue damage during the design lifetime. Due to irregular and transient loads, this requires simulations in the time domain for a broad range of load cases. In structural optimization, many different designs are evaluated, and it is inconvenient with such a comprehensive and computationally expensive analysis. The aim of this chapter is to investigate the accuracy of simplified fatigue load assessment, for use in structural optimization. Two hypotheses will be tested:

1. A reduced number of load cases can accurately represent a lifetime of loads.

2. Short time simulations can accurately represent 60 minutes simulations.

Previous studies have used simplified analysis in optimization approaches, though accuracy have not been assessed. This chapter presents 8 different simplified analysis, and comments on their accuracy.

4.2 Method

Two types of analyses are used in this chapter:

- **Complete analysis** means simulation of 11 load cases with 60 minutes simulation length and subsequent fatigue load assessment. This is assumed to be accurate, that is, this is assumed to be the lifetime of loads.
- **Simple analysis** uses a reduced number of load cases and/or reduced simulation length with subsequent fatigue load assessment. It is the accuracy of this that shall be determined in this chapter.

The two hypotheses will be tested empirically by using different simple analyses to optimize the full-height lattice tower. The accuracy of each simple analysis will be determined by checking the respective optimized designs with a complete analysis.

Assumptions

If the number of load cases is reduced, some assumptions are needed to estimate the fatigue damage in the missing load cases. Because the load history vary for each load case, the accumulated fatigue damage will also be different. In this thesis it has been assumed that normalized damage distribution with respect to wind speed for each member will:

- Remain constant when the design is modified.
- Remain constant when simulation length is changed.

The first assumption means that a complete fatigue assessment of the initial design can be used to establish the damage distribution for each member. The damage distribution can be used to estimate complete fatigue damage from a simplified set, or even a single load case. The second assumption means that the damage distribution of the initial model can be applied to fatigue assessments that are based on different simulation lengths. For these assumptions to be of any value, it must also be assumed that the damage distribution of all members in the initial model is known.

Initial Design

The initial design that is to be optimized 8 times with different simple analyses, is designed rather conservatively and with constant member dimensions for all sections (see table 4.1). A complete analysis of the initial design makes it possible to look at how the individual members accumulate a different amount of fatigue damage from each wind speeds. The normalized damage distribution for each member in the initial design is shown in figure 4.3. Little damage is accumulated at low wind speeds, even though the probability of occurrence is high. At high wind speeds there is also a low percentage of damage accumulation, but this is due to the low probability of occurrence. The total weight of this design is 1780 tons.

	Thickness [mm]	Diameter [mm]
Legs	50	1000
Braces	40	800

Table 4.1: Dimensions of initial design.

Study I: Reduced Number of Load Cases

The first hypothesis is tested by varying the number of load cases that are used. Simplified sets of one, three, five, and eleven load cases are used for four different simple analyses. The sets of load cases are chosen as subsequent wind speeds with 2 m/s interval and 14 m/s as the median(see table 4.2). Since this study focus on load case sensitivity, a short simulation length of 3 minutes is used.

Number of load cases	Load case by mean wind speed [m/s]
1	14
3	12,14,16
5	10,12,14,16,18
11	4-24

Table 4.2: The optimization is performed with 4 different number of load cases.

Correction factors relate damage from a simplified set of load cases, e.g. d_{3min}^{12-16}, to the total damage, d^{tot}. Since damage distribution is assumed to be constant, this can be computed from the complete analysis of the initial design.

$$d^{tot} = CF^{12-16} \cdot d^{12-16}_{3min} \tag{4.1}$$

$$CF^{12-16} = \frac{d^{tot}}{d^{12-16}_{60min}} \tag{4.2}$$

Here it has been assumed that the damage distribution from a 3 minutes analysis is the same as for a 60 minutes analysis. Superscript $12-16$ indicates that this is the correction factor for the simplified set of 3 load cases, while other correction factors are used for the other simple analyses.

Study II: Reduced Simulation Length

The second hypothesis is tested by varying the length of the simulations. Four different simple analyses are used, with simulation lengths of 1, 3, 10 and 60 minutes. Since this is a study of simulation length, only a single load case is used.

Correction factors are computed the same way as in study I, with one difference. Systematic errors were found in study I, that indicated that the damage distribution changed with simulation length. For that reason, correction factors were in this study evaluated from a simulation of the same length as used in the simple analysis.

$$d_{tot} = CF_{10min} \cdot d^{14}_{10min} \tag{4.3}$$

$$CF_{10min} = \frac{d_{tot}}{d^{14}_{10min}} \tag{4.4}$$

Subscript $10min$ indicates that this is the correction factor for the 10 min analysis, while other correction factors are used for the other simulation lengths. Superscript 14 indicates that a single load case of mean wind speed 14 m/s is used in this study.

Assessment of Accuracy

Accuracy of a simple analysis can be measured as the analysis ability to estimate the fatigue lifetime of a member. Normalized lifetime, L_{norm}, is defined as the inverse of the utilization factor:

$$L_{norm} = \frac{1}{U}$$

The optimization with a simple analysis will stop when all utilization factors, U^s are less than one, and the weight has converged. The correct utilization factors, U^c, can be evaluated from the complete analysis of the optimized design. The accuracy of U^s can then be assessed from its conformity to U^c. If $X < 1$, it means that fatigue damage is underestimated, and the design is likely to be non-conservative. That is, the design has too short lifetime. If $X > 1$, it means that fatigue damage is over estimated, and the design is conservative. The mean and variance of X is computed for legs and braces, such that both systematic and random errors can be assessed.

$$X = \frac{U^s}{U^c} \tag{4.5}$$

$$\mu = \frac{1}{11}\sum_i X_i \tag{4.6}$$

$$\sigma^2 = \frac{1}{10}\sum_i (X_i - \mu)^2 \tag{4.7}$$

4.3 Result

Study I: Reduced Number of Load Cases

The initial design was optimized with 4 different simplified sets of load cases, table 4.3 shows the accuracy of these. The systematic error is the same for all four analyses; leg design is non-conservative, brace design is conservative. Random error for legs is similar for all four analyses, while for braces the random error decreases with number of load cases. In figure 4.1, the correct normalized lifetime of legs and braces are plotted for all sections over the tower height.

Number of load cases	μ_L [-]	μ_B [-]	σ_L [%]	σ_B [%]	Tower mass [tons]
1	0.91	1.62	18	24	756
3	0.91	1.67	25	10	758
5	0.88	1.60	27	5	758
11	0.90	1.59	29	3	758

Table 4.3: Accuracy of simple analysis with varied number of load cases.

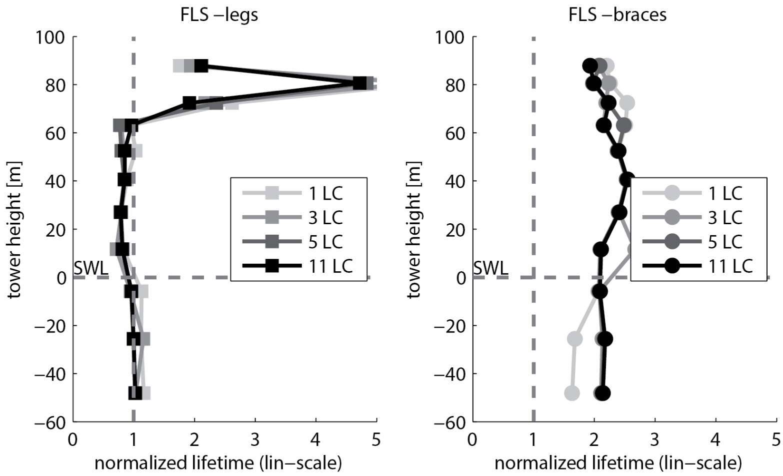


Figure 4.1: Normalized lifetime of optimized designs. Reduced number of load cases and 3 min simulation length.

Study II: Reduced Simulation Length

The initial design was optimized with a single load case with four different simulation lengths, table 4.4 shows the accuracy of these. In contrast to study I, these analyses show different accuracy. Most noteworthy is that the tower mass decreases with longer simulation length. It can also be observed that both systematic error and standard deviation of error is within 12 percent for simulation lengths of 10 and 60 minutes. Figure 4.2 shows normalized lifetime for legs and braces over tower height. It can be observed that shorter simulation length gives more conservative designs, and also with more variance.

Length of simulations[s]	μ_L [-]	μ_B [-]	σ_L [%]	σ_B [%]	Tower mass [tons]
60	1.00	1.32	25	33	804
180	1.51	1.10	34	4	760
600	1.09	0.91	8	9	683
3600	1.03	0.88	7	8	665

Table 4.4: Accuracy of simple analysis with varied simulation length.

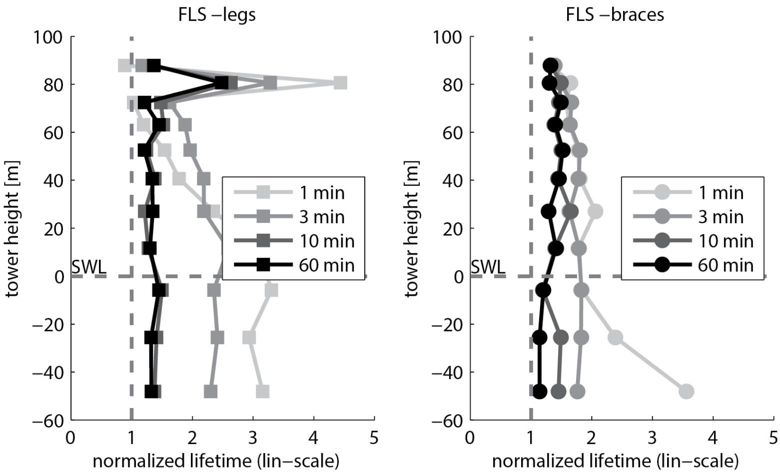


Figure 4.2: Normalized lifetime for all members. It can be observed that longer simulation length avoids unnecessary conservatism.

Damage Distribution

All the simple analyses used correction factors that assumed constant damage distribution. Figure 4.3 and 4.4 show the damage distribution from a complete analysis of the initial and an optimized model respectively. Figure 4.5 show the damage distribution of the initial model with 3 minutes simulation length. It can be observed that changes to the design does not change the damage distribution much, while a change of simulation length does.

4.4 Discussion

The results from study I indicates that a single load case can be almost as accurate as eleven. This supports the first hypothesis, and enables optimization to use an order of magnitude less computation expenses while retaining a high level of accuracy. This also goes a long way to confirm the assumption about constant damage distribution, which can be judged from figures 4.3 and 4.4.

In study II, the effect of simulation length was studied, and the results show that shorter simulations give more conservative results, and more errors. The second hypothesis can thus not be supported, however, if an error of less than

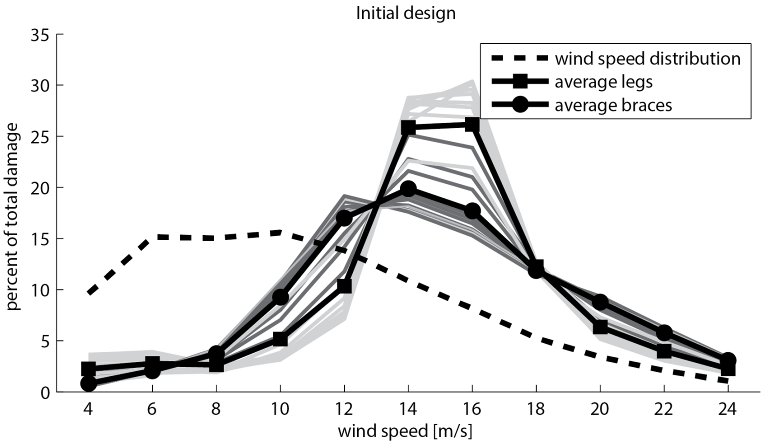


Figure 4.3: Distribution of damage accumulation normalized with total damage in each member. Note that the damage distribution is different from probability distribution, and that legs and braces have qualitatively different distributions.

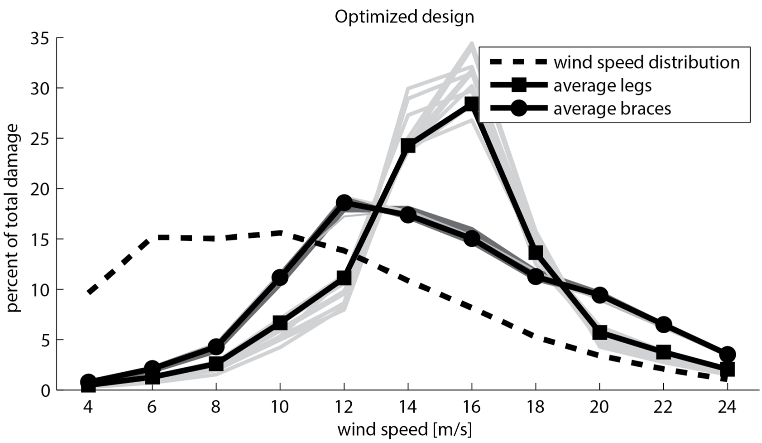


Figure 4.4: The damage distribution for the optimized model is not very different from the initial model. Simulation length = 60 min.

5 percent is accepted, 10 minute simulation length can be used.

In conclusion, it can be argued that one load case of 10 minutes gives suffi-

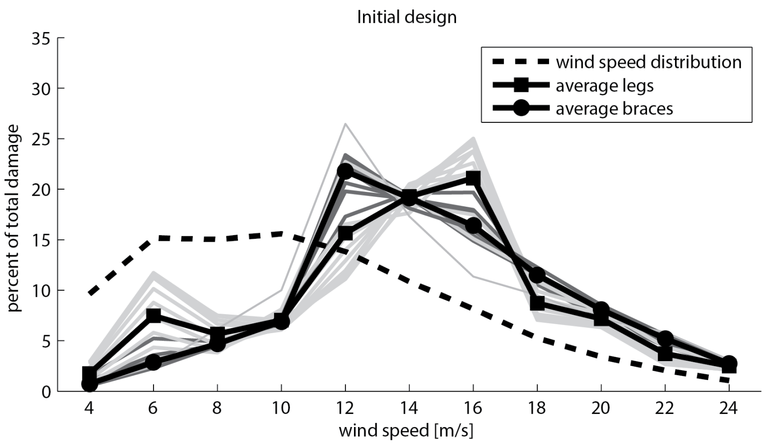


Figure 4.5: Short time simulation gives inaccurate damage distribution. Simulation length = 3 min.

cient accuracy for optimization purposes if the damage distribution of the initial design is known.

Chapter 5

Improved Tower Design for the Nowitech Reference Turbine

5.1 Goal

The full-height lattice tower has been the subject of several studies on optimization methods, but a final design has not been established. The NRT have been developed for several years, and specifications are useful both for further studies, references and benchmarking. It has been claimed that the full-height lattice tower can save weight compared to other concepts, though little hard evidence is brought forward to support this statement. The aim of this chapter is to use the findings from the previous chapters to present a site-specific optimization approach, and use this to find an improved tower design for the NRT.

5.2 Method

Results from chapter 3 and 4 provide a good basis for a site-specific optimization approach. In fact, the method that is being presented in this chapter was used in both chapter 3 and 4, but without proper explanation. This chapter discuss the assumptions behind the site-specific optimization approach used in this thesis, and applies it to the full-height lattice tower for the NRT. A reference site from the UpWind project is assumed to be representative for north sea wind and sea states.

Assumptions

This optimization will use the results from chapter 3 and 4, and thus the same assumptions will apply. However, while those are assumptions regarding the optimization itself, there are also assumptions regarding the validity of the result. This thesis have been limited to study only power production load cases, and only one structural model. Within these load cases it has been observed that fatigue limit state is the design driver. The most important assumptions are listed below:

- 100 percent power production.
- Aligned wind and waves.
- No buckling
- Fatigue limit state(FLS) drives the design.

For the lattice-tower support structure, 100 percent power production is assumed to be conservative, as the high stiffness of the space frame structure poses little risk of resonance with an idling turbine. Misalignment sensitivity was investigated in [16] and found to be low. This has thus not been further investigated here. Previous studies of the full-height lattice tower have checked for buckling, and it has not been an issue. Because the structure suffers such a large amount of fatigue loads, both from axial forces and bending moments, ultimate limit state is not driving the design in this optimization approach. Ultimate stresses for all members are showed in the results, though this is only a logging and have not affected any design choices. However, ULS load cases as well as buckling should be checked in a future study to confirm the design.

A Site-Specific Optimization Approach

Based on the iterative optimiziation approach and the results from chapter 3 and 4, a site-specific optimization approach have been developed for space-frame support structures. A flowchart is shown in figure 5.1. It uses the assumptions about constant damage distribution to evaluate correction factors for the simple analysis, such that the design can be iteratively optimized with only simple analyses. The optimization continues until the weight of the model has converged.

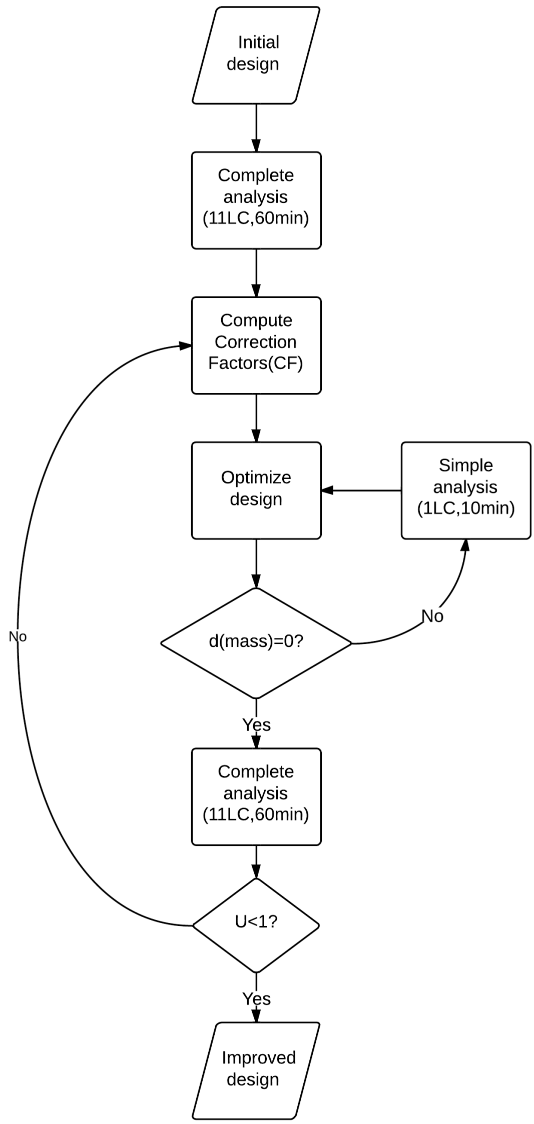


Figure 5.1: Site-specific optimization approach.

The optimized design is then checked with a complete analysis. If $U > 1$ for any members, it means that the damage distribution have changed, and the optimmized design is inaccurate. In that case, the damage distribution from this "nearly optimized" design can be used to update the correction factors. With a more accurate damage distribution it is more likely that the design will get the desired utilization. A buffer is built in by letting the optimization aim for utilization factors of 0.9 instead of 1.0. Allowing 10 percent buffer in the optimization will mean less than 2 percent on the tower mass. The loop that includes simple analysis, optimize design and d(Weight) is in principle the same as the iterative optimization approach in figure 2.8. The surrounding processes are added to get better accuracy as well as site-specific design.

5.3 Result

A significant weight saving was achieved compared to the initial design, and it is also substantially lighter than the current optimized design. With a single load case and 60 minutes simulation length, the final design was found to be 665 tons.

The optimized design was checked with a complete analysis, and fatigue limit state and ultimate limit state is shown in figure 5.2 and 5.3. Fatigue limit state is close tot he constraint for all members except legs in section 10. Ultimate limit state is a factor of 2 from yield in the most critical section.

The optimized dimensions for legs and braces over the tower height are shown in figure 5.4 and 5.5. The exact values are also printed in table 5.2. It can be noted that the thickness ratio, which is allowed to be in the range $(0.2, 1)$ only touches its boundary one time, in section 10. Elsewhere the dimensions of legs and braces appear to be independent.

The computational expenses of this optimization approach depend on the computer. In this thesis, a DELL Optiplex 9020 with Intel Core i7-4770 CPU @ 3,40GHz (= 4 cores) have been used. A rough estimate of the time for different parts of the optimization is given in table 5.1. Note that much of this time can be eliminated in practical applications. The presented method is used to find and confirm a site-specific design from an initial design. However, if the purpose is to compare the optimized weight of several incrementally different designs, several simplifications can be made. The two complete analyses can be avoided, and 1 load case of 10 minutes with simulation for every iteration can give an optimization time of about 2 hours, per model per core. That is, the mentioned computer could optimize 48 models a day, which is enough to test

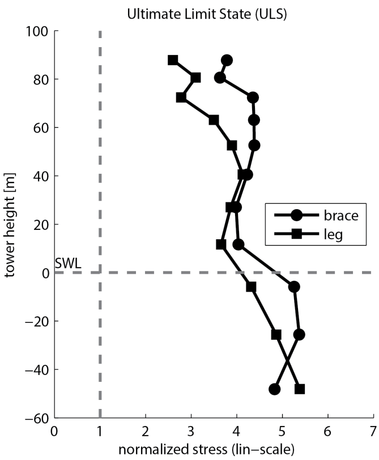


Figure 5.2: The ultimate stress in each member is normalized with a yield stress of 400 MPa.

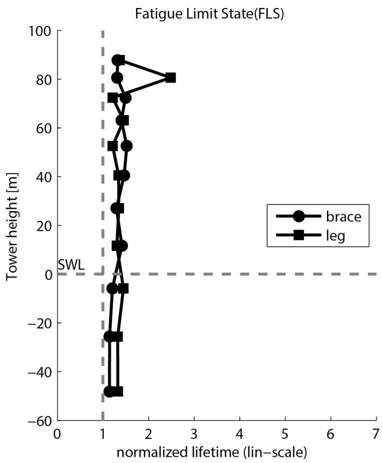


Figure 5.3: Fatiguelife of each member is normalize with design lifetime of 20 years.

many different design options.

Process name	Number of occurrences	Time [min]
Post-process (simple)	13	20
Post-process (complete)	2	220
Simulation (simple)	6	100
Simulation (complete)	2	300
Total		1900

Table 5.1: Estimated time for different parts of optimization.

5.4 Discussion

The optimal design was found using the site-specific optimization approach. It is evident that the method works well, with respect to both speed and accuracy. The dimensions of the members are quite as one would expect. Submerged legs

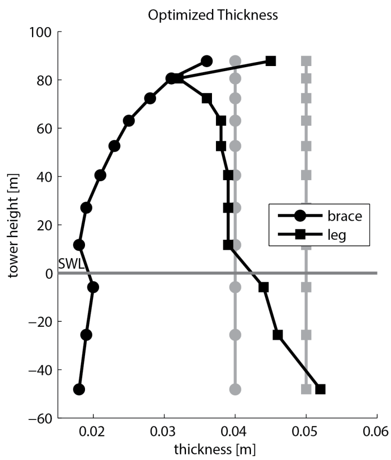


Figure 5.4: Thickness of braces increase towards the top, while leg thickness increas towards the bottom. Submerged braces are thicker than the trend.

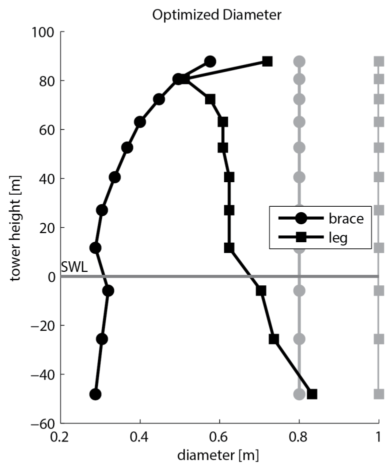


Figure 5.5: Diameters are scaled with thickness, and have the same distribution.

Section	Leg [mm]	Brace [mm]
11	45	36
10	32	31
9	36	28
8	38	25
7	38	23
6	39	21
5	39	19
4	39	18
3	44	20
2	46	19
1	52	18

Table 5.2: Thickness of legs and braces. Diameter is thickness times 16.

increase in thickness towards the bottom, as to resist the strong overturning moment from the waves. For the mid part of the tower, legs have rather constant dimensions, indication that the largest contributor to stress is simply the tower weight. Very close to the yaw base, there are some oscillations in the leg dimensions. The top section is directly connected to the yaw base, and absorbs all the forces from the RNA. Section 10 have rather low leg dimensions, likely because the brace dimensions are absorbing a large part of the forces. Braces are mostly resisting torque induced motion in the tower. Since torque is rather constant throughout the height, and leg distance decreases towards the top, it is expected that the brace dimensions should increase towards the top. It can also be observed that submerged braces have slightly larger dimensions than the trend.

Chapter 6

Benchmarking with Jacket Concept

6.1 Goal

The full-height lattice tower has been presented as a concept that can contribute to substantial weight savings for offshore wind turbine support structures. Monopile is the most common support structure to date, however, jackets have been introduced as a competitive concept for deeper waters and broader range of soil profiles. Since the full-height lattice tower is designed for water depths up to 60 meter, this makes jacket is the most natural competitor. The aim of this chapter is to do a benchmark of the full height lattice tower versus the jacket concept. The same turbine and piles are used, and the two structures are optimized for the same site. A rigid transition piece from the OC4 project [20] is used for the jacket concept, while the jacket itself is based on the lower part of the lattice-tower. The tubular tower is also similar to the tower from the OC4 project.

6.2 Method

A jacket model is built for the same conditions as the full-height lattice tower, and optimized with the same optimization approach. A benchmarking of the two concepts is then performed.

Assumptions

It is difficult to compare the full-height lattice tower to existing concepts for two reasons:

- The P/A ratio of the NRT is higher than most commercial as well as reference turbines designed to date.
- A fair benchmarking should include designs that are optimized for the same site, with the same optimization approach.

With these considerations, it was decided to build a simple model such that a jacket concept could be optimized for the same conditions as the full-height lattice tower. The most important assumptions for this model are listed below:

- The transition piece(TP) and scaled tubular tower from the 5MW OC4 model can be used.
- The ideal section hight and leg distance is the same for the jacket as for the full-height lattice tower.
- The jacket design will, as the lattice tower, be driven by fatigue.

The tubular tower was based on the tubular tower from the OC4 project, but scaled up to 50 percent higher mass. Scaling laws as described in 2.1 only suggest 20 percent increase, but this does not fully account for the doubling in rated power. Consequently, it should be noted that this design of the tubular tower is only a rough estimate.

Building the Jacket Model

The jacket model is similar to the lattice tower model, in that they share the same piles and RNA. The jacket design is based on the 4 bottom sections of the lattice tower, where section heights are decreased with 5 percent, and the angle of the legs relative to vertical is increased from 2.3 degrees to 3.0. These minor changes were made such that the transition piece from the OC4 project could remain unchanged. The two Fedem-models can be studied in figure 6.1. An important consideration in support structure design is the eigenfrequency (See chapter 2.4). With constant dimensions the jacket model were found to be within 10 percent of the lowest rotor frequency. However, it is expected that a decrease in dimensions will lower the eigenfrequency. Since the constant dimensions were assumed to be conservative, the model was accepted as an initial design.

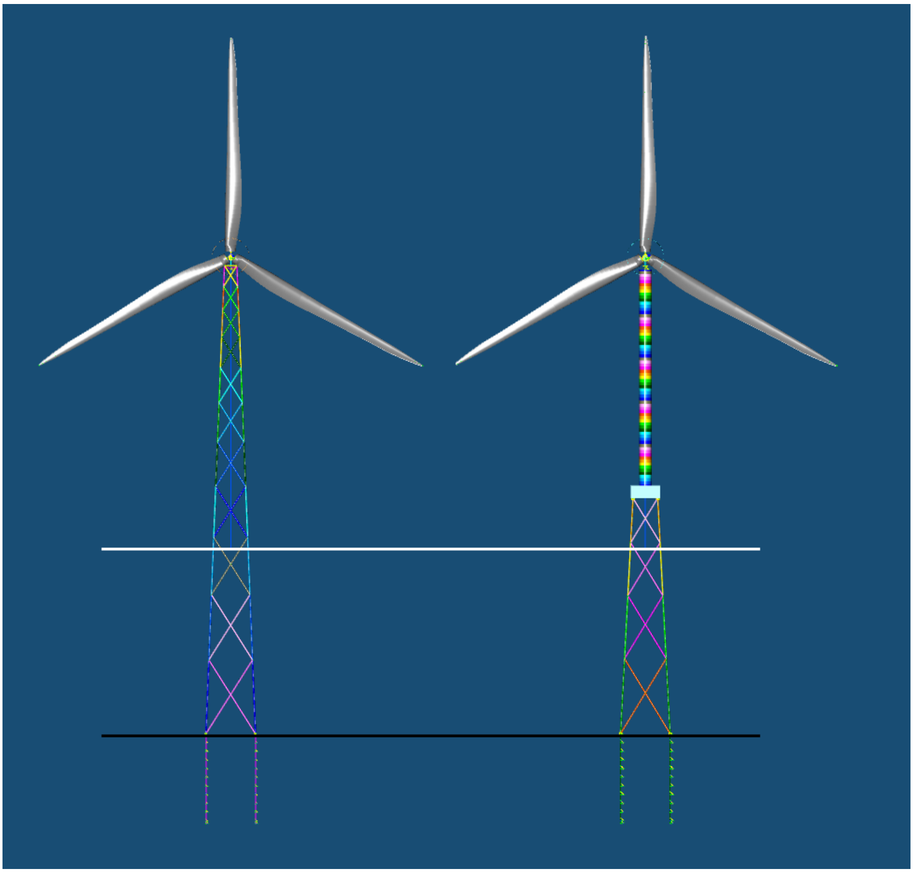


Figure 6.1: The full-height lattice tower(left) and the jacket concept(right). The two models are built as similar as possible to facilitate a fair benchmarking.

Optimization

The site-specific optimization approach described in chapter 5 was used with a single load case and 10 minute simulation length. A security factor was built in by aiming for 90 percent utilization.

6.3 Result

Weight

The optimized dimensions of the two models are shown in figure 6.2. It can be observed that the dimensions of the two space frame structures are quite similar. The jacket have slightly larger dimensions, and this results in a 7 percent higher weight for the lower part of the structure. The tubular tower however, is lighter than the respective part of the lattice tower. The weight of different parts of the two designs are given in table 6.1. Note that a single load case and 10 minutes simulation length was used to optimize both concepts.

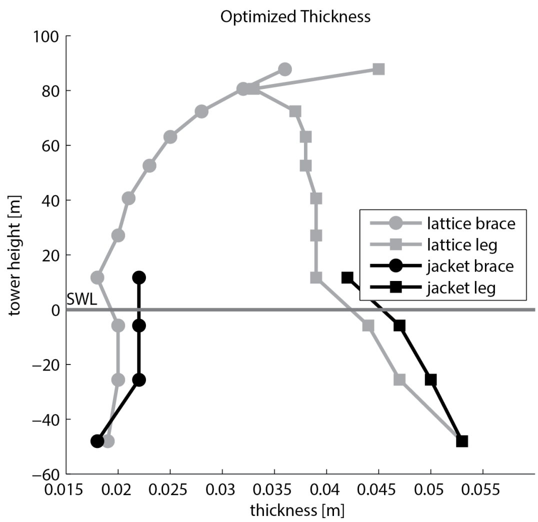


Figure 6.2: The jacket have slightly larger dimensions than the lattice tower

Optimization Results for the Jacket Concept

While the lattice tower was optimized based on the damage distribution from the initial design, the jacket failed the complete check, and was looped through the optimization once more (see section 6.4 for explaination to why the first optimization failed). In figure 6.3 one can observe how the jacket weight was first

	Jacket [tons]	Lattice [tons]
Lower	380	365
Upper	296	318
Total	676	683

Table 6.1: The weight of the two concepts are approximately the same, not included transition pieces.

optimized to approximately 250 tons. The second complete analysis updated the correction factors, and the new optimized design passed the complete check.

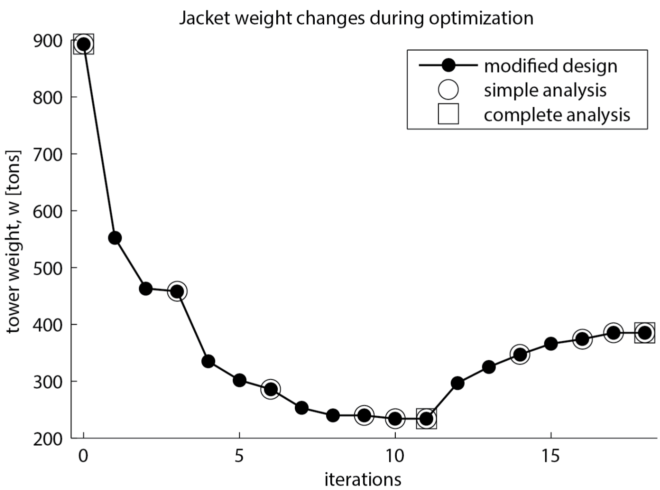


Figure 6.3: The jacket required an extra complete analysis.

6.4 Discussion

The results show that approximately the same amount of steel is required for the two concepts when the transition pieces(TPs) are ignored. This means that the lattice-tower can save weight similar to the weight difference of the two TPs. An master theses' design of the lattice tower TP resulted in a weight of less than

100 tons [21], while a jacket of this size would require a TP of several hundred tons.

It was noted that the optimization results for the jacket was somewhat confusing. A thorough check of the results discovered that due to a bug in the program, the first optimization didn't include the correction factors. As a result, the structure was optimized to only survive the 10 percent of the lifetime where mean wind speed is equal to 14 m/s. There was in other words not a problem with the optimization approach, but rather with the Matlab code as it was fitted from lattice tower to jacket. On the contrary, figure 6.3 shows the ability of the optimization approach to correct itself if the initial assumptions are not correct.

The high eigenfrequency that was observed for the initial jacket structure did not have any impact on the results, since the optimization failed from other reasons. It did however cause a incorrect damage distribution for the members, which would have caused a conservative design because the correction factors would have been estimated too high. Damage distribution for the jacket from the three different complete analyses are shown in figure 6.4.

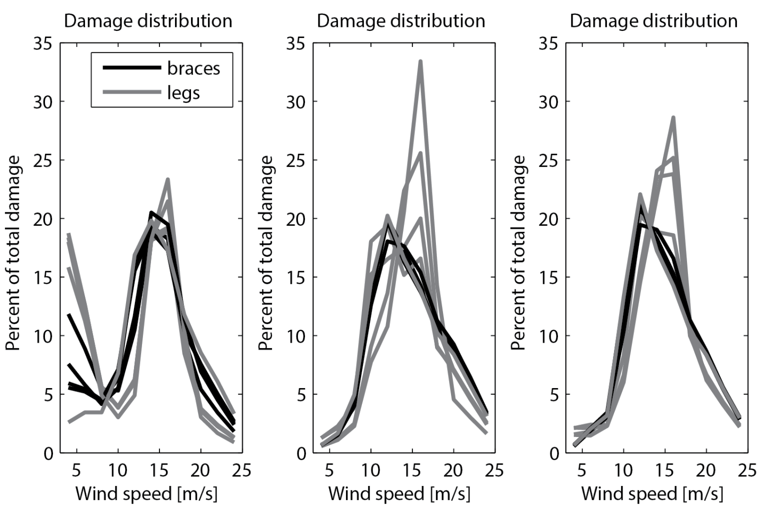


Figure 6.4: Resonance in the initial model causes large damage at low wind speeds

Chapter 7

Conclusion

This thesis have made progress in the field of optimization of support structures for offshore wind turbines. Out of the 6 specific challenges presented in chapter 2.4, several considerations have been made that reduce or eliminate the obstacles. Convex problem formulation, fast convergence, few variables and site-specific design are among the presented features.

Implications for the Nowitech Reference Turbine

The support structure for the Nowitech 10 MW Reference Turbine has been improved with a design that is more than 40 percent lighter than the current design. This has been accomplished by using an improved optimization approach. A complete check of the improved model confirmed that the design lifetime was satisfied in all joints. Furthermore, the competitiveness of the full-height lattice tower was investigated by optimizing a jacket concept for the exact same conditions. A benchmark showed that without transition pieces(TPs) the two models will have approximately the same weight. However, as the jacket comes with a heavier and more expensive TP, the lattice tower concept present significant advantages.

Implications for Optimization of Space Frame Support Structures

The iterative optimization approach [12] has been improved with three elements

- **Convex problem formulation.** Guarantees global optimum in each section.
- **Complete set of load cases.** Enables site-specific optimization.
- **Self-improving algorithm.** Continues optimization until design is confirmed.

These additions have resulted in an optimization approach that can be used for site-specific optimization of any space frame support structure that is limited by fatigue damage. The convex problem formulation guarantee a global minima per section per simulation, and results also indicate convex behaviour for all designs within the allowed frequency range. While the optimization is fast (it requires about 6 simulations of at least 10 minutes), the method requires a complete analysis both of the initial design as well as the optimized design. The first analysis is to determine damage distribution with respect to wind speed for all members, while the second is to confirm the design. For optimization of many similar structures, optimization time of 2 hours can be achieved with good accuracy.

Diversion from Original Task

The presented work is not completely in line with the task. Pile design for example, were found to have little effect on the tower dynamics, and thus not interesting from a fatigue life perspective. Ultimate limit state events such as extreme weather and emergency braking were also dismissed in this thesis. During all power production load cases, no joints experienced stress above 40 percent of the yield stress. With these considerations, it was decided to focus more on fatigue optimization and less on ultimate limit state.

Future Work

Convexity is important in continuous optimization, and future work should focus on implementing convexity considerations to all aspects of the structural optimization. Realistic optimization should also account for discrete variables, and possibilities for using the same dimensions for several members. Further on, a cost model that includes manufacturing and installation should be used to give a more fair comparison of the full-height lattice tower to existing concepts.

Bibliography

[1] Tande, J.O. *NOWITECH Annual Report 2012.* SINTEF Energy Research

[2] Jonkman, B.J. and Kilcher, L. *TurbSim User's Guide: Version 1.06.00.* Draft Version, National Renewable Energy Laboratory

[3] Det Norske Veritas, *Fatigue design of offshore steel structures.* 2008.

[4] P. C. Paris, M. P. Gomez and W. E. Anderson. *A rational analytic theory of fatigue.* The Trend in Engineering (1961). 13, 9-14.

[5] NOWITECH *Specification of the NOWITECH's 10 MW Reference Wind Turbine.* 2012.

[6] TU-D/ECN *The ICORASS Feasibility Study, Final Report*

[7] NREL *Definition of a 5-MW Reference Wind Turbine for Offshore System Development.* 2009

[8] T. Fischer, W. de Vries, B. Schmidt, *Upwind Design Basis* Delft University of Technology, The Netherlands, 2011.

[9] van der Tempel, J., 2006, *Design of Support Structures for Offshore Wind Turbines* Ph.D. thesis, Delft University of Technology, Delft, The Netherlands

[10] Matsuishi M, Endo T. *Fatigue of metals subjected to varying stress.* Fukuoka, Japan: Japan Society of Mechanical Engineers; 1968.

[11] Rychlik I. *A new definition of the rainflow cycle counting method.* Int J Fatigue 1987;9(2):119–21

[12] Zwick, D., Muskulus, M., Moe, G. *Iterative optimization approach for the design of full-height lattice towers for offshore wind turbines* Energy Procedia 24, 297–304, 2012

[13] International Electrotechnical Commission, *Wind turbines - Part 3: Design requirements for offshore wind turbines, International Standard, IEC 61400-3*, 2009. pg. 55

[14] Nieslony, A. *Rainflow Counting Algorithm* mathworks.com. Downloaded Okt. 12 2013.

[15] Muskulus, M., Christensen, E., Zwick, D., *Improved Tower Design of the NOWITECH 10 MW Reference Turbine*

[16] Sandal, K. *Lifetime analysis of the Nowitech 10 MW Reference Turbine*, Specialization project, NTNU 2013.

[17] National Renewable Energy Laboratory, *Wind Turbine Design Cost and Scaling Model*. 2006.

[18] Long, H, Moe, G, Fishcer, T (2012) *Lattice Towers for Bottom-Fixed Offshore Wind Turbines in the Ultimate Limit State: Variation of Some Geometric Parameters*, J Offshore Mech Arct Eng, Vol 134, pp 021202:1-13.

[19] Muskulus, M, Schafhirt, S (2014) *Design Optimization of Wind Turbine Support Structures-A Review*, Journal of Ocean and Wind Energy Vol. 1, pp. 12-22.

[20] Vorpahl, F., Popko, W., Kaufer, D., (2013) *Description of a basic model of the 'UpWind reference jacket' for code comparison in the OC4 project under IEA Wind Annex 30*, Technical Report, Fraunhofer IWES.

[21] Gong, W. (2011) *Lattice tower design of offshore wind turbine support structures*, Master's thesis, Department of civil and transport engineering, NTNU.

Appendix A

Problem formulation

The task is to improve the design of the support structure for the NOWITECH 10 MW Reference Turbine (NRT). The design of the pilses shall be considered, and the structure shall be checked with a more complete and realistic set of loadcases, including extreme wind and sea states and emergency shutdown.

This shall include the following subtasks:

- Literature study (pile design, relevant standards) [2 weeks]
- Implementing a simple method for pile sizing [6 weeks]
- Implementing a brake in the control system [1 week]
- Implementing additional ULS loadcases [2 weeks]
- Developing a method for optimal design [3 weeks]
- Demonstrating the method by determining an optimized design of the NRT [2 weeks]
- Writing [4 weeks]

Appendix B

Contents zip-file/CD

The following attachments are included in the zip-file called "CD":

- Fedem-file with the improved support structure.
- Matlab scripts used to create figures in the report.
- Matlab scripts used for the optimization approach.
- Result files from a selected set of optimization runs.

Appendix C

Supplementary Derivations

C.1 Scaling of SCFs

Assuming axial loads are dominating the hot spot stress, it can be assumed that hot spot stress scales with the SCF for balanced axial load. For legs this expression is:

$$SCF_L = \tau^{0.9}\gamma_L^{0.5}(0.67 - \beta^2 + 1.16\beta)\sin\theta(\frac{\sin\theta_{max}}{\sin\theta_{min}})^{0.30} \cdot (\frac{\beta_{max}}{\beta_{min}})(1.64 + 0.29\beta^{-0.38}\arctan(8\zeta)) \quad \text{(C.1)}$$

ζ is a variable that depends on the gap between braces in K-joints, and since this is assumed to be constant, ζ is also assumed to be constant. β is the ratio of brace diameter to leg diameter, but the polynomial is varying within a margin of 10 percent, so this is also assumed to be constant. The fractions with max and min subscripts are relating values for the sections above and below the joint. However, angles are constant, and β ratios are similar for neighbouring sections, so these are also assumed constant. This leaves only τ and γ, and the expression for leg SCF becomes:

$$SCF_L = \tau^{0.9}\gamma^{0.5} \quad \text{(C.2)}$$

Braces can fail both at the K-joint and X-joint, but it has been observed that X-joint failure is dominating for low γ values. It can also be observed that axial load is not dominating the hot spot stress, but all relevant SCFs scale in as similar manner:

$$SCF_B = \gamma_B^a \tau^b \beta^c \tag{C.3}$$

Since the members in an X-joint have the same dimensions, τ and β are constant, and only γ_B can vary. Depending on which SCF one looks at, the value of a is somewhere between 0.3 and 1. However, γ is set constant in the end, and the argument for that is valid for any $a \in (0.3, 1)$, so 1 is chosen arbitrarily to use in the derivation in chapter 3.

C.2 Reduction of Variables

When scaling relationships for both objective function and constraint is given in terms of thickness and gamma, it can be shown that gamma should be minimized. Assume that the utilization have reached one, which implies that the constraint function must be constant. That enables a scaling relation between thickness and gamma, which can be inserted to the objective function.

$$f \propto T^2 \gamma_L \tag{C.4}$$

$$g \propto T^{-14.5} \gamma^{-4.5} \tag{C.5}$$

$$\Rightarrow T \propto \gamma^{\frac{-4.5}{14.5}} \Rightarrow f \qquad \propto \gamma^{\frac{5.5}{14.5}} \tag{C.6}$$

The last expression implies that gamma should be minimized to minimize the objective function sucject to the given constraints. This argument is valid for both legs and braces as long as $SCF \propto \gamma^a$, and a is positive and less than 1.

Scaling relationship for objective function and constraint:

$$f \propto T^2 \gamma_L \tag{C.7}$$

$$g \propto T^{-14.5} \gamma^{-4.5} \tag{C.8}$$

$$\tag{C.9}$$

Fixing the constraint function gives a scaling between T and γ_L that can be used to show that γ_L should be minimized.

$$T^{-14.5} \gamma^{-4.5} = const \tag{C.10}$$

$$\Rightarrow T \propto \gamma_L^{\frac{-4.5}{14.5}} \tag{C.11}$$

$$\Rightarrow f \propto \gamma_L^{\frac{10}{14.5}} \tag{C.12}$$

$$\tag{C.13}$$