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Published in:
Proceedings of EWEA Offshore 2015 Conference

Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

Optimal Design of Stiffeners for Bucket Foundations

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Summary

The potential for structural optimization of the bucket foundation's outer stiffeners is investigated using commercial optimization software. In order to obtain the optimal design both shape and topology optimization problems are formulated and solved using the structural optimization software *Tosca Structure* coupled with the finite element software *Abaqus*. The solutions to these optimization problems are then manually interpreted as a new design concept. Results show that shape optimization of the initial design can reduce stress concentrations by 38%. Additionally, topology optimization has led to a new design concept with a mass reduction of 25.5% (19.2 tons) when compared to the original design.

Introduction

The Bucket Foundation

The Bucket Foundation (Figure 1a) - developed by Universal Foundation A/S[1] - is a novel foundation concept that can potentially reduce the cost of energy for offshore wind farms. This foundation combines the cost savings of traditional monopiles with the easy installation of suction buckets. Additionally, the Bucket Foundation can be installed in a variety of site conditions, including sand, silt, clay, and layered strata. The project "Cost-Effective mass production of Universal Foundations for large offshore wind parks"[2] aims to move the Bucket Foundation from a research, development, and demonstration phase into commercialization and industrialization. As part of this project, the objective of this work is to further reduce the cost of the bucket foundation by reducing the mass of the stiffeners through structural optimization, while considering mass production and manufacturability.

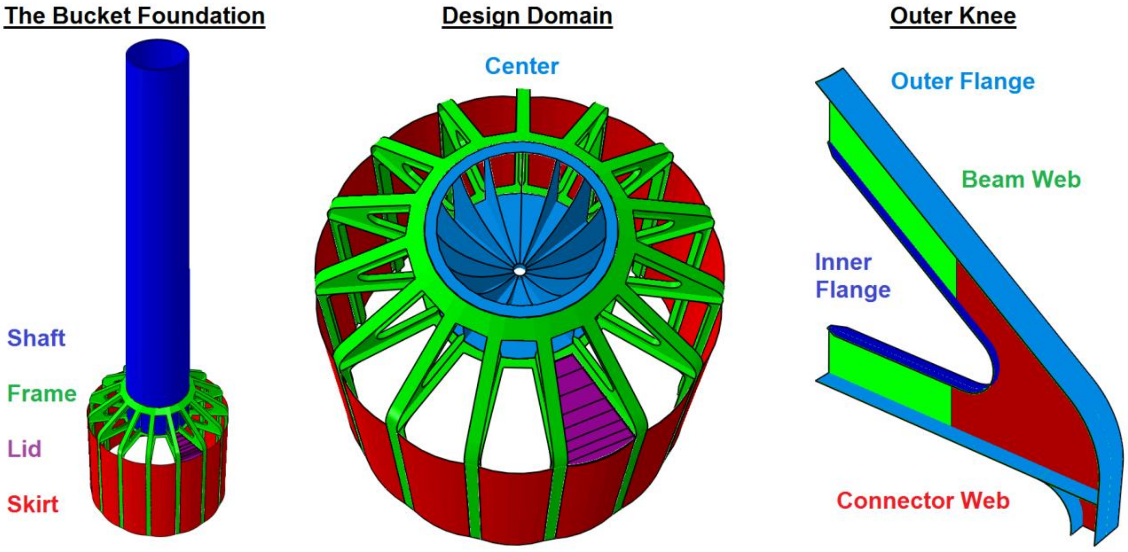

Figure 1 – a) The Bucket Foundation b) Design Domain c) The Outer Knee

Design Domain

While the larger project examines the potential to optimize the entire structure, this work focuses on optimization of the bucket, excluding the shaft (Figure 1b). Although initial investigations into optimization of the center, lid, and skirt have been conducted, the focus thus far has been on the outer knee of the frame (Figure 1c).

The outer knee is responsible for transferring loads from the shaft to the bucket and into the soil, and thus acts a stiffener. It consists of two I-beams joined by a circular connector piece and can be subdivided into beam webs, connector web, inner flange, and outer flange as shown in Figure 1c. The examined design consists of fifteen of such knees with a height of 4.85*m*, a width of 5*m*, and weighing 5.01 tons each for a total of 75.15 tons.

[1] universal-foundation.com
[2] hoejteknologifonden.dk

Structural Optimization

The field of structural optimization (summarized in [1]) has existed in its modern form for many decades and has been extensively used in the automotive and aerospace industry. The objective of a structural optimization problem can vary to include objective functions such as minimize weight, maximize stiffness, etc. and can consider other aspects of the design as constraints (e.g. geometry or maximum allowable stress). The field is often subdivided into three classes of problems, topology, shape, and sizing optimization. While topology optimization (summarized in [2]) is often used to arrive at a design concept, shape optimization (summarized in [3]) and sizing optimization can be used to refine an existing design. Commercial software such as *Tosca Structure* [4] is capable of solving all three types of problems and is compatible with most commercial finite element solvers (e.g. *Abaqus* [5]).

Finite Element Model

A bucket foundation design has been provided by Universal Foundation A/S and is modelled using the finite element software *Abaqus*. The foundation has a bucket diameter of 18*m* and a 52*m* tall shaft with a bottom diameter of 8*m* and a top diameter of 6.5*m*. All parts are steel and are modelled as shell elements with welds represented by tie constraints. The model is meshed into a combination of linear quadrilateral (S4R) elements and linear triangular (S3) elements. In total, the model consists of 67,773 elements and has 216,162 degrees of freedom. In order to save computational time, the lid is not modelled as it has little influence on the load case examined.

A single static load case is used for the optimization. It consists of a static 8*MN* horizontal load positioned 50*m* above the lid as well as the foundation's self-weight. The load is applied at the center of the shaft's cross section with a coupling constraint to the shell elements. The model assumes fixed (zero displacement/rotation) boundary conditions on the entire skirt and therefore neglects soil interactions. This assumption is used to reduce computational time and the resulting stress distribution has been validated against results that include a soil model.

Shape Optimization

In this section, the inner shape of the outer knee is investigated using shape optimization. The objective of this optimization is to find the shape which minimizes stress, thereby allowing a reduction in plate thickness and therefore mass.

Problem Formulation

In this problem, the inner shape of the outer knee is described by the position of a set of nodes. For simplicity's sake, this set, the design variables, consists of all 1029 nodes in the beam webs and connector web except for the outer nodes, which connect to the flanges and shaft. In Figure 2 these nodes are marked by red dots. As *Tosca Structure* requires this set to include outer nodes, the inner flange had to be removed for this problem (also shown in Figure 2). While removal of the inner flange has led to higher stresses, the stress distribution has remained qualitatively unchanged and therefore it is assumed that the optimal shape of the web is independent of the flange.

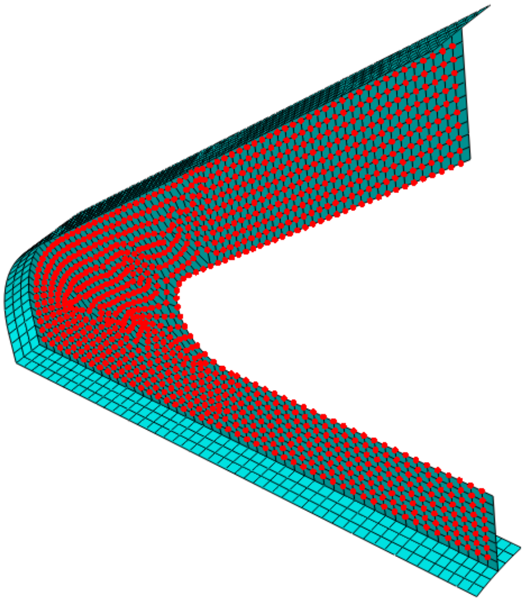

Figure 2 – Shape Optimization Design Variables

Additionally, a constraint is applied to the displacement direction of the design variables in order to ensure they remain in a two-dimensional web. The optimization problem is then formulated as minimize the maximum von Mises stress in the web subject to a volume (and therefore mass) constraint of 100%. This problem is then solved using *Tosca Structure* and on average takes around one to two hours to compute on a modern laptop computer.

Results

In Figure 3, the initial stress distribution (3a) is shown along with the stress distribution of the optimization results (3b). These results have been scaled with a constant in order to correspond to the maximum von Mises stress of the outer knee including an inner flange.

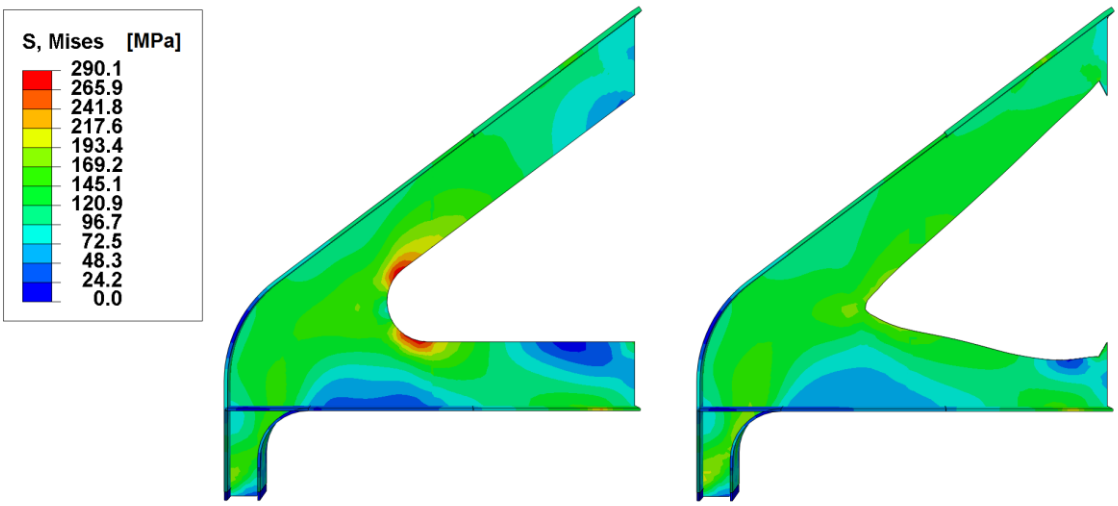

Figure 3 – a) Initial Stress Distribution b) Shape Optimization Results

Results from shape optimization show that the maximum von Mises stress in the outer knee can be reduced by 38% without adding mass to the design. It is then anticipated that a significant reduction in mass can be achieved through sizing optimization of the new shape, a mass reduction significant enough to outweigh the increased manufacturing complexity.

Topology Optimization

In this section, a new design concept is developed using topology optimization. First a topology optimization problem is formulated and then the results are manually interpreted as a new concept taking buckling, manufacturability, and mass production into consideration (Figure 4).

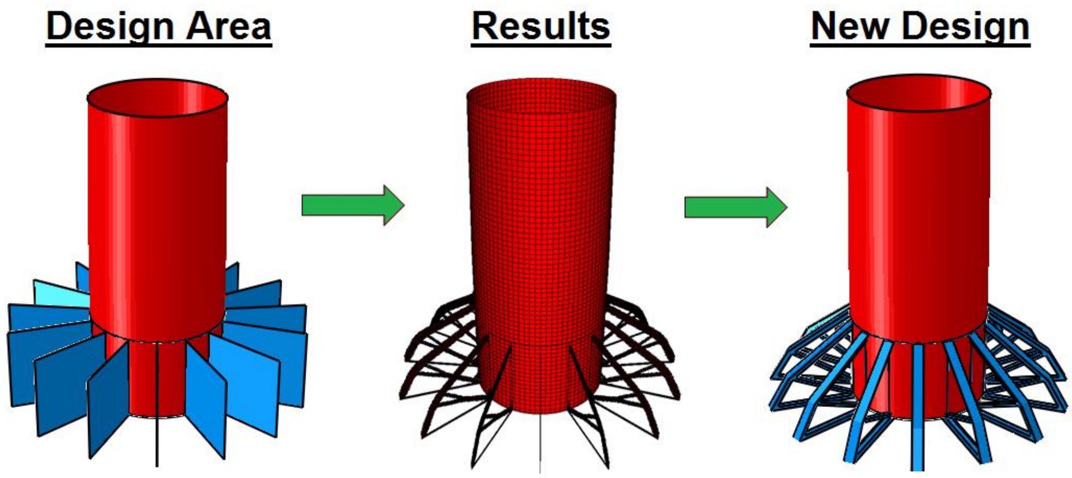

Figure 4 – Topology Optimization Process a) Design Area b) Results c) New Design

Problem Formulation

In this problem, the design area is modeled as 15 rectangular shells with a height of 4.85*m*, a width of 5*m*, and a thickness of 10.5*cm* each. These shells are then meshed into 9700 5c*m* square shell elements (S4R) each (Figure 4). The mass densities of each of these elements are the design variables and a rotational symmetry constraint is applied to ensure all 15 knees are identical. The topology optimization problem is then formulated as minimize the structure's compliance (or maximize stiffness) subject to various different mass constraints.

This problem relies on several simplifications and assumptions. First, the height of the modelled portion of the shaft has been reduced (and a bending moment added to account for this reduction) in order to reduce the number of elements and speed up computational time. Second, the outer ring stiffener, which connects the knees, is not modeled due to the changing topology. Finally, zero displacement/rotation boundary conditions are applied to the outer bottom node of the design area instead, and the skirt is eliminated to reduce computational time. Comparisons between stress distributions of these two different boundary conditions confirm that this assumption has a negligible effect on the problem. The problem is then solved using *Tosca Structure* and takes around 30 iterations or one hour on a modern laptop computer.

Results & Interpretation

Figure 4b shows the mass density distribution resulting from the topology optimization problem. These results show a topology consisting of seven beams; varying the mass constraint between 15 - 20% of the design area results in this same topology but with different beam thicknesses. Stress distributions from these results show that a mass constraint of 18.8% (corresponding to a 25% mass reduction from the original knee design) can be used without exceeding the maximum von Mises stress in the original knee design.

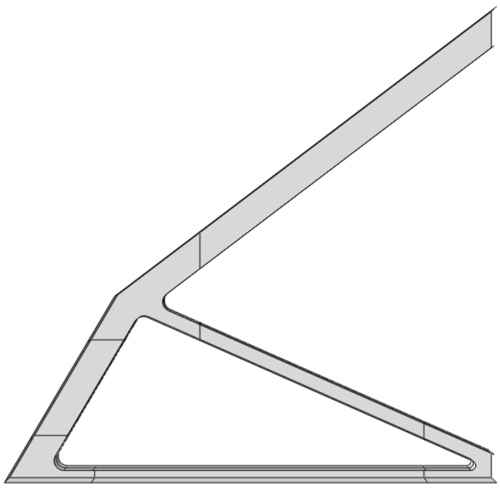

Figure 5 – New Concept

From these results, a new concept has been manually developed (Figure 5). The y-split visible in Figure 4b has been interpreted as a single beam, reducing the number of beams to four and thereby reducing manufacturing complexity and cost. The cross sectional areas of the design are based upon those of the topology optimization results. However, the cross sections have been extended to I-beams to account for buckling and an *Abaqus* eigenvalue buckling analysis confirms that buckling does not occur with a safety factor similar to that of the original design. Finally, manual sizing optimization of the concept ensures von Mises stress levels do not exceed that of the initial concept, while minimizing mass. The new concept weighs 55.95 tons compared to the original design of 75.15 tons, a mass reduction of 25.5% (19.2 tons total). A mass reduction of this magnitude likely justifies the slightly increased manufacturing complexity of the new design.

Future Work

While shape optimization has led to a reduction in maximum stress of 38%, the resulting mass reduction of this new shape has yet to be quantified. Therefore, a sizing optimization problem of the new shape has been planned with lumped variables and standardized thicknesses, in order to consider manufacturing and mass production. Additionally, the new design concept resulting from topology optimization has not been fully optimized. Shape optimization of the new concept's connectors can reduce stress concentrations and subsequent sizing optimization can further reduce mass. Finally, the assumption of a single static load case will be assessed by subjecting the new designs to all relevant time-dependent load cases.

Furthermore, future work on the topic will expand the design domain to include parts of the center, lid, and skirt (Figure 1b). Initial investigations into topology optimization of the center and lid suggest significant potential mass reductions. To achieve this, the design load cases will need to be extended to include the extreme suction loads during installation, as these loads drive the design of the center, lid, and skirt. Finally, focus will be placed on integrating these methods into the existing design cycle of bucket foundations.

Conclusion

The potential for structural optimization of the bucket foundation's outer stiffeners has been assessed. Shape and topology optimization problems have been formulated and solved for a specific foundation size and design. Results show that shape optimization can reduce the maximum von Mises stress in the outer stiffener by 38% without adding mass to the design. Additionally, topology optimization has led to a new outer stiffener design concept with a mass reduction of 25% (19 tons total). While these results are design specific, the methods developed can be integrated into the design process of suction bucket foundations and similar structures. These mass reductions can contribute to a lower cost of offshore wind energy as the Bucket Foundation begins entering the market.

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Acknowledgements

This work is a part of the project "Cost-Effective mass production of Universal Foundations for large offshore wind parks" funded by the Danish National Advanced Technology Foundation[2].

[2] hoejteknologifonden.dk