Design of Grouted Connections in Offshore Wind Turbines

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Summary

At the widely-used grouted connection for monopile founded offshore wind turbines unexpected settlements have been detected. These findings have led to a withdrawal of the mostly applied design code for grouted connections. Without having a valid design guide and under the impression of failing connections alternative designs had to be developed. A review of existing codes shows remarkable differences in the assessment of the capacity of grouted connections. Based on extensive and advanced finite element analyses the structural behaviour of grouted connections is investigated. It becomes obvious that the existing codes cannot directly be used for the design of grouted connections for monopile founded offshore wind turbines. Furthermore, a plane cylindrical connection is not appropriate. Cylindrical connections with shear keys or conical connection are alternatives. Approaches for the structural verification of theses types are presented.

Keywords: Grouted connection; grouted joint; offshore; wind turbine; monopile; fatigue; shear key; finite element.

1. Introduction

One of the most difficult technical challenges faced by engineers designing foundations for offshore wind turbines first came to light in October 2009, when the booming offshore wind industry suffered a technical setback. A design fault was discovered in the grouted connection used to fix the transition piece to the monopile. The transition piece is plugged on the monopile and the annulus in between is filled with grout (Fig. 1). The design fault results in settlement of the transition piece leading to an undesirable change in the force flow in the connection. The mostly applied design code DNV-OSJ101 [1] was withdrawn and alternative solutions had to be considered.

2. Review of existing standards

A striking divergence especially for high shear keys or high grout strength can be observed. This behavior results from the fact that the empirical formulations of the codes are based on regression of lab tests. The extrapolation of small-scale test is also seen as one reason for the design fault.

3. Analysis of structural behavior

Extensive complex finite element analyses have been conducted to understand the structural behavior of grouted connections. The models consider the special characteristic of the interface between steel and grout, the non-linear behavior of the grout material, and the combined loading [2]. The models are validated with experiments and detect some behavior which is in contrast to earlier assumptions.

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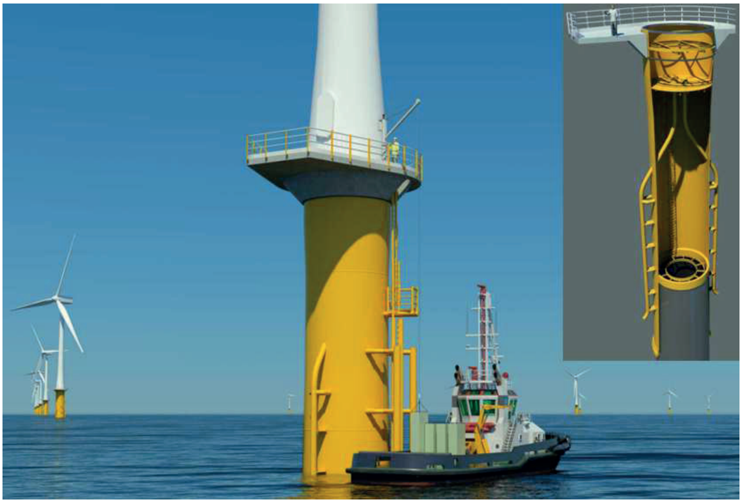

Fig. 1: Monopile founded offshore wind turbines with grouted connection.

4. Design approaches

At conical grouted connection the lower grout edge with a distinctive stress peak is governing for the design. At grouted connections with shear keys the extreme grout stresses appear directly next to the shear keys, where the failure is initiated by cracking due to splitting forces.The fatigue verification applies the Palmgren-Miner approach. A transfer function is used to determine the accumulated damage. For the FLS design of the grout between the shear keys an additional local strut and tie model is applied.

The positive effects of fibers such as increased ductility and integrity depend on the type of fibers and grout and go along with hindered workability. Within the hardening process the grout is sensitive against movements, namely rigid body movements and local relative displacement between the monopile and the transition piece. Furthermore shrinkage and temperature development due to curing has to be considered. Specified environmental temperature load scenarios are not critical.

5. Conclusions

Conical grouted connections and grouted connections with shear keys are alternatives to the failing connections of the monopile founded offshore wind turbines. The simple extrapolation of the capacity from small-scale tests to large monopile connections as applied in former codes is inappropriate. Finite element analyses considering contact interaction and non-linear material provide a deep insight in the structural behavior of the connections. For conical grouted connections the stress peak at the grout edges is governing for the design. The grout stresses at the shear key are governing for connections with shear keys. For the shear key fatigue verification an additional strut and tie model and a transfer function is applied. Early-age grout damage has to be considered, whereas thermal action due to daily or seasonal climatic changes is insignificant. Special attention has to be paid to possible fibres in the grout.

6. References

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