

Load Bearing Behaviour of Grouted Joints Subjected to Predominant Bending

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I Executive Summary

The large-scale generation of electricity from wind offshore shall contribute significantly to the targets of energy and climate policy in a number of countries, including Germany. As a consequence, a rapid growth of this industry sector is to be expected, if reliability is increased and economic optimization can be realized in the next years. One of the keys for optimization of offshore wind projects is the deployment of cost-effective and safe support structures. A major part of most of these support structures are grouted joints, not only for jackets but especially important for monopiles. Monopiles have been considered in the past as limited to medium water depths and smaller turbines. Due to the recent developments in the manufacturing equipment of large diameter tubes and installation vessels, there is a strong tendency to extend their application to deeper water and larger turbines.

Therefore, this thesis examines the bearing behaviour of currently used slender grouted joints subjected to predominating bending. Besides the interaction of the ductile steel shells with the brittle grout material, this work focuses on the analysis of the characteristics of shear keys in the connection under combined loading and their adequate representation in the design process.

Due to the limited test experience for grouted joints subjected to predominant bending, a test programme has been executed which comprises large and small scale tests under different types of loading. While the small scale tests mainly have been performed to gain knowledge about the local behaviour of the high strength material and to obtain base data for benchmarks of the numerical models, the large scale tests have been executed with realistic dimensions and static and dynamic loading. The tests confirmed that application of shear keys in the inner third of the connection effectively increases the robustness of the grout connection and distinctly reduces damage from ovalization. Local investigations showed only minor deterioration around the shear keys. This demonstrates that further economic optimization is possible.

On basis of the test results, numerical models have been developed and validated. Besides the implementation of a material model for adequate representation of the local grout characteristics, the development of a novel combined spring element-contact model for shear keyed connections forms main part of the analyses. Aligned to this model, a design approach for the local zone around the shear keys and the numerical derivation of parametric shear key fatigue classes is presented.

The developed numerical models and design approaches have been applied to real scale monopile structures whereby size and scale effects were considered adequately. Time domain analyses explain how the slip failure of grout connection without shear keys develops. The subsequent parametric studies concentrate on the three typical design tasks ultimate limit, fatigue limit and a serviceability limit state. Besides a separate treatment of the basic materials grout and steel, the focus is set on the effects of the shear keys in comparison to plain pipe connections and the variation of size and number of shear keys.

Based on the analyses, it is concluded that shear keys should be applied in the center area of the grout connection. Furthermore, distinct height to spacing ratios should be chosen but the number of shear keys is recommended to lie between five and nine shear keys in a row. If these construction principles are followed, shear keys effectively help to minimize the damage in the ultimate and fatigue limit state for both materials in the connection.

Keywords

Grouted Joint, Grout connection, Offshore Wind Energy Converters, Monopile, High Performance Concrete, Fatigue, Shear key

Kurzfassung

In naher Zukunft sollen die großmaßstäbliche Ausbaue der Offshore-Windenergie auch in Deutschland einen wichtigen Beitrag zur Energie- und Klimapolitik liefern. Somit kann ein enormes Wachstum dieses Industriesektors erwartet werden, wenn es gelingt, die Zuverlässigkeit zu steigern und gleichzeitig Kosten zu senken. Um dies zu erreichen, werden effiziente und robuste Tragstrukturen benötigt. Ein wichtiger Bestandteil der Mehrheit der Tragstrukturen sind Grouted Joints, die insbesondere bei Monopiles einen Kernbestandteil der Tragstruktur bilden. Während in der Vergangenheit der Einsatzbereich von Monopiles als limitiert angesehen wurde, machen es aktuelle Entwicklungen sowohl im Bereich der Großrohrherstellung als auch bei den Installationsschiffen möglich, deren Anwendungsgrenzen auf tieferes Wasser und große Turbinen auszuweiten.

Aus diesem Grund wird in dieser Arbeit das Tragverhalten von aktuellen ausgeführten, schlanken Grouted Joints unter überwiegender Biegebeanspruchung untersucht. Neben der Interaktion von duktilem Stahl mit dem spröden Groutmaterial wird hierbei der Fokus auf die Untersuchung der Eigenschaften der Schubknaggen unter kombinierter Beanspruchung und deren adäquate Abbildung und Berücksichtigung bei der Bemessung der Verbindung gelegt.

Aufgrund des Fehlens von Testergebnissen für Grouted Joints unter überwiegender Biegung wurde im Rahmen der Arbeit ein umfangreiches Versuchsprogramm durchgeführt. Während die kleinmaßstäblichen Versuchskörper überwiegend für die Untersuchung des spröden Groutmaterials und die spätere Validierung der Materialmodelle herangezogen wurden, konzentriert sich die Durchführung der Großversuche auf die Berücksichtigung realistischer Abmessungen und repräsentativer Belastungszustände. Die Versuche demonstrieren eindrucksvoll, dass Schubknaggen im mittleren Drittel der Verbindung ausreichen, um die Robustheit des Grouted Joint maßgeblich zu steigern und ovalisierungsbedingte Schädigungen zu minimieren. Lokale Untersuchungen des Groutmaterials um die Schubknaggen zeigen nur geringe Schäden und unterstützen, dass weitere Optimierungen im Hinblick auf niedrigste Groutmaterialien und kürzere Übergreifungslängen durchaus möglich sind.

Auf Basis der Versuchsergebnisse werden numerische Modelle entwickelt und validiert. Neben der Implementierung eines geeigneten Groutmaterials für lokale Betrachtungen ist die Entwicklung eines neuartigen Strukturmodells für Grouted Joints mit Schubknaggen ein wesentlicher Bestandteil der Untersuchungen. Das Modell zeichnet sich durch die Kombination von Volumenelementen mit Federelementen, die den Effekt der Schubknaggen abbilden, aus. Auf dieses Modell zugeschnitten, werden Bemessungsansätze für die lokale Zone um die Schubknagge sowie die numerische Herleitung von parametrischen Ermüdungsfestigkeitsklassen für typische Schubknaggen präsentiert.

Auf Grundlage der entwickelten Modelle werden im Weiteren reale Monopilestrukturen untersucht. Dabei gelingt es, das Durchrutschen der Grout-Verbindung ohne Schubknaggen im Zeitbereich nachzubilden. Weiterführende parametrische Studien konzentrieren sich auf die Unterschiede der Verbindungen mit und ohne Schubknaggen sowie die optimale Ausbildung von Anzahl und Größe der Schubknaggen. Die Untersuchungen erstrecken sich dabei auf die typischen Grenzzustände der Tragfähigkeit, Ermüdung und Gebrauchstauglichkeit. Es wird festgestellt, dass die Schubknaggen ein ausgeprägtes Verhältnis von Höhe zu Abstand aufweisen sollten und ihre ideale Anzahl bei fünf bis neun in der Reihenfolge liegt. Werden diese Konstruktionsempfehlungen befolgt, helfen die Schubknaggen, die Schädigung in beiden Materialien zu minimieren und die Robustheit des Grouted Joint deutlich zu erhöhen.

Stichwörter

Grouted Joint, Grout-Verbindung, Offshore-Windenergieanlagen, Monopile, Hochleistungsbeton, Groutmaterial, Ermüdung, Shear key, Schubknagge

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Fabian Wilke

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