Proceedings of the Twenty-third (2013) International Offshore and Polar Engineering
Anchorage, Alaska, USA, June 30–July 5, 2013
Copyright © 2013 by the International Society of Offshore and Polar Engineers (ISOPE)
ISBN 978-1-880653-99–9 (Set); ISSN 1098-6189 (Set)

www.isope.org

Numerical Investigations on Local Degradation and Vertical Misalignments of Grouted Joints in Monopile Foundations

Peter Schaumann[1], *Stephan Lochte-Holtgreven*[1], *Rasmus Eichstädt*[1]
Tim Camp[2] *and Graeme McCann*[2]
[1]ForWind - Centre for Wind Energy Research, Institute for Steel Construction, Leibniz Universität Hannover, Germany
[2]GL Garrad Hassan, Bristol, United Kingdom

ABSTRACT

The underestimation of cyclic effects on the axial capacity of grouted connections in monopile foundations led to vertical slippages, recently observed in a large number of offshore wind turbines. In this paper a progressive vertical misalignment of the grouted connection inside an oscillating structure is demonstrated by use of non-linear finite element simulations. Based on a fully integrated load calculation of a reference structure and results from numerical analyses, parameters are evaluated that may affect the long term behavior of the connection's axial capacity. Additionally, the influence of mechanical interlock on the fatigue performance of grouted joints is demonstrated.

KEY WORDS: Offshore wind turbines; dynamic; misalignments; settlements; degradation; grouted joints; time domain simulation; non-linear, grout fatigue.

INTRODUCTION

Offshore wind turbines (OWT), which are characterized by slender support structures and high top masses, are decidedly susceptible to dynamic excitation. Furthermore, they are characterized by a highly dynamic loading environment. Consequently, an accurate dynamic assessment of all structural components is of highest importance.

Currently different foundation solutions for offshore wind turbines are under discussion and development. However, simple monopile foundations can be regarded as an economical design solution for low and intermediate water depths up to about 30 m. The joint between monopile and tower of the turbine support structure is usually realized by an overlapping tube-to-tube connection. A transition piece, also referred to as sleeve, and the monopile are arranged with a certain overlap where the resulting annulus is filled with a high performance grout. With this type of connection, commonly denoted as grouted joint, inclinations of the pile from the driving process can be compensated (Fig.1).

Axial forces, in particular caused by the dead load of rotor-nacelle-assembly and tower of a wind turbine, are small compared to the bending moments caused by wind and wave actions. The load conditions experienced by grouted joints on monopiles of OWT are thus characterized by predominating cyclic bending loads superimposed by the axial dead load of turbine and tower.

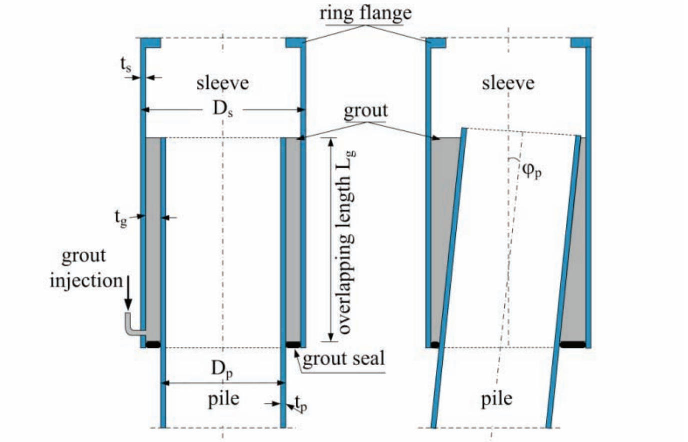

Fig.1. Schematic overview of grouted joint with plain pipes

Up to the end of the last decade it was assumed that the application of a mechanical interlock such as shear keys is not required in the design of grouted joints on monopiles. Grouted joints were therefore mostly executed with plain pipes, relying solely on the shear capacity of the interface between steel and grout for the transfer of the axial loads. Interactions between dynamic bending loading and axial shear forces were not considered in the applied design approaches.

However, vertical misalignments within grouted connections have been observed recently on a considerable number of offshore wind turbines with monopiles. It is assumed that these settlements result from degradation effects within the interfaces between steel and grout, caused by cyclic bending loading, in combination with the high slenderness, characteristic for grouted joints on monopiles, cf. Schaumann & Wilke (2008a) and Lotsberg (2010). In order to investigate vertical settlements it is necessary to analyze the grouted connection under dynamic conditions with simultaneously acting bending moments and axial forces in a representative order of magnitude.

Within a joint research cooperation of the Institute for Steel Construction, Leibniz University Hannover and GL Garrad Hassan influences of the overall dynamic behavior of the wind turbine support structure on vertical misalignments and local degradation effects were investigated.

CYLINCRICAL GROUTED JOINTS WITH PLAIN PIPES

Load transfer

Grouted joints with plain steel pipes, as hybrid steel-grout-steel connections, which are held together only by the contact of the interfaces, are characterized by a complex non-linear load bearing behavior. In most cases the design is simplified by using engineering models. As a general approach for connections with plain pipe surfaces it is distinguished between two different ways of load transfer. Bending moment and shear loading are transferred by contact pressure, which occurs dominantly at the outer limits of the connection, while axial forces and torsion have to be transmitted by shear in the interface between grout and steel.

A description of the load transfer of plain pipe grouted joints for monopiles is given by Nielsen (2007). Furthermore, the physical behavior of grouted connections subjected to bending moments has been investigated extensively at the Institute for Steel Construction, Leibniz University Hannover based on large scale experiments and complimentary numerical investigations. For a detailed depiction of test results reference is given to Schaumann and Wilke (2007).

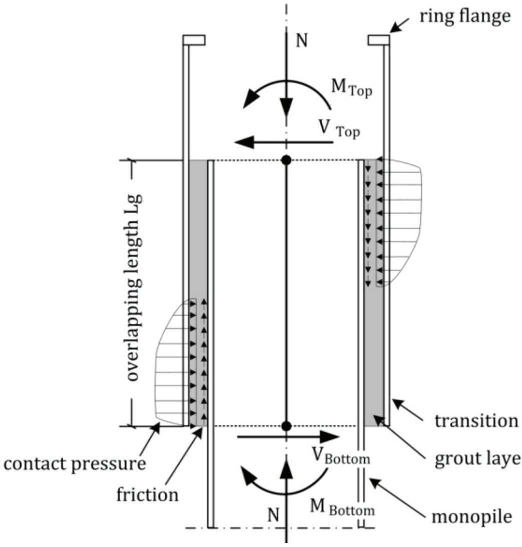

Fig.2. Simplified mechanical model for the transfer of bending moments (Schaumann et al., 2010)

Bending moments lead to vertical rotations of pile and sleeve. This movement gives rise to two opposing areas of contact pressure at top and bottom of the connection (Fig.2). A resulting force couple enables the load transfer between transition piece and monopile.

Axial loads and torque have to be transferred by shear and friction capacity in the plain grout-steel interfaces which result from a combination of several mechanisms. Adhesive bonds between the contiguous surface areas cause a certain shear capacity and furthermore a limited tensile capacity of the interfaces. Moreover, classic Coulomb friction, proportional to contact pressure induced by moment and shear loading, contribute to the axial capacity. Due to the large diameter of the connection, undulations, caused by fabrication tolerances, exist along the circumferential and longitudinal direction of the steel tubes. Albeit small, these surface irregularities cause a wedging effect between steel tubes and grout when relative slipping motions occur in the interfaces, leading to mechanical friction. According to Lotsberg (2010) and Nielsen (2007) these geometric tolerances are the primary contributor of passive shear capacity, which is independent from contact pressure.

Monopiles and transition pieces of OWT are generally characterised by high slenderness ratios D/t to an extent of $D/t > 100$. Thus, ovalisations of the tubular steel cross-sections are likely to occur, even due to smaller bending moments. Experimental investigations by Andersen & Petersen (2004) and Schaumann & Wilke (2007) have shown that ovalisations lead to a local gaping of the connection at the opposite sides of the areas of contact pressure. The combined shear capacity varies highly between the closed and the opened state of the interface because mechanical friction caused by surface tolerances diminishes with increasing magnitude of the opening (Fig.3).

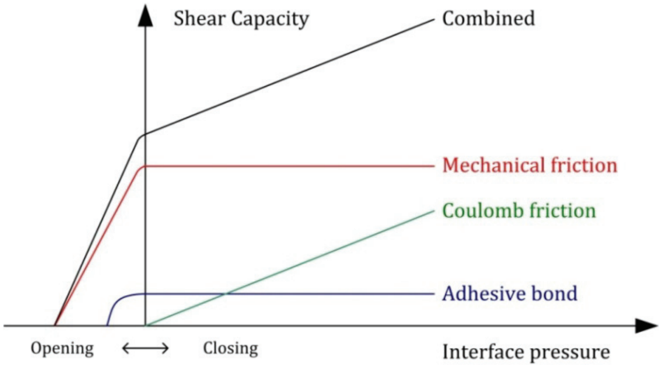

Fig.3. Idealized interaction of the three shear effects combined to the total vertical interface shear capacity (Nielsen, 2007)

Applied design philosophy

Until vertical slippages of grouted joints were observed, it was assumed that the exceedance of the mechanical friction capacity could only appear locally when the joint is subjected to very large bending moments. These simultaneously induce high contact pressure and thus establish significant amounts of Coulomb friction. Due to the high compressive strengths, it was not considered that grout degradation can occur to an extent which is big enough to effectively restrain the passive axial capacity of the connection (i.e. the capacity when no contact pressure is present).

The design principle, established by offshore design standards (e.g. DNV-OS-J101 or ISO 19902) and applied on certified turbines, was therefore to assess axial and moment capacity of the grouted joint independently from each other. According to DNV-OS-J101 (2007) the axial capacity was determined by use of analytic formulae, depending on friction properties of the grout to steel interface, height of surface irregularities and radial stiffness of the connection. The method complied with the rules for conventional offshore structures with prevailingly axial loaded grouted connections. For documentation of the moment capacity static finite element analysis was required.

Vertical settlements

After observation of vertical misalignments at operating turbines a Joint Industry Project (JIP) was initiated by Det Norske Veritas, Norway in order to investigate failure reasons and improved design solutions. Results have been published in the JIP Summary Report (Lotsberg, 2010). Within the JIP it was found out that local degradation effects in the grout steel interfaces may have caused a progressive reduction of the axial capacity under dynamic bending loading. The main degradation mechanisms, affecting the axial shear resistance, are a proceeding de-lamination of adhesive bonds on the one hand and wear of the grout material, reducing the capacity provided by surface irregularities, on the other. Subsequently, mentioned degradation effects are briefly described.

As stated previously bending leads to oval deformations of the steel tubes because of their relatively high slenderness and resulting radial flexibility. As a result, a radial displacement in outwards direction occurs at the opposite sites of the areas of contact pressure (cf. Fig.2), leading to tensile stresses between steel and grout. When the tensile stresses exceed the adhesive bond capacity of the interface, gaps are opening. Due to the fact that adhesive bonds cannot be re-established after initial de-bonding, the adhesive axial capacity is lost in areas where gap openings occur. Moreover, sliding motions between steel and grout caused by bending moments also imply that the adhesive bonds in these areas are broken.

According to Lotsberg (2011 & 2010) sliding motions, caused by the high flexibility of the connection, must be expected under cyclic bending loading. It was concluded that sliding evoked by bending moments cannot be resisted by high friction coefficients or initial bonding strength of the interface. Hence, a certain amount of sliding has to be expected even as a result of smaller bending moments. Even though the sliding length of each load cycle might be only a fraction of a millimetre, the sliding length can accumulate significantly over the operational lifetime of the structure. Lotsberg assumes that, despite a high grout compression strength, each relative sliding process in the grout-steel interface leads to an abrasive wear of the grout material. This reduces the surface undulations which are necessary for the provision of vertical shear resistance. Consequently, with an increasing number of load cycles mechanical friction capacity is reduced progressively.

Considering a significant loss of adhesive bond and mechanical friction capacity, the only remaining resistance against vertical sliding is given by Coulomb friction. However, this depends on the acting alternating bending moments. No information is provided regarding how and when the slippages of the operating turbines did occur. Nor it is known how much the passive axial shear resistance was reduced at this point. However, it could be hypothesized that the observed settlements are the consequence of a progressive vertical movement caused by small slippages during the dynamic load cycles.

BASIS OF ANALYSIS

Numerical model

Numerical investigations were performed on a representative reference structure, containing realistic dimensions for monopile, transition piece, grout layer and steel tower. The rotor-nacelle-assembly (RNA) was represented simplified by its mass. The main support structure dimensions are given in Table 1.

Table 1. Dimensions of reference structure

Member	**Parameter**	**Value**
Monopile	Outer diameter	4 700 mm
	Thickness	50 mm
Transition Piece / Sleeve	Outer diameter	5 100 mm
	Thickness	55 mm
Grout Layer	Overlapping Length	7 050 mm
	Thickness	145 mm
Tower	Height	65 m
RNA	Mass	220 t

For the numerical analyses with the finite element software tool ANSYS© a combined modeling approach was applied. The grouted joint was incorporated by a full solid element representation. Consequently, geometric and material non-linearities as well as frictional contact could be considered in the analysis. The remaining parts of the support structure, which were of less importance in the investigation, were considered by use of Timoshenko beam elements. The conjunction between both parts of the model is established by rigid links. The combined modelling approach (Fig.4), first presented by Schaumann & Wilke (2008a), enables a reasonable limitation of DOF.

Sleeve, pile and grout material of the grouted joint were modeled with three dimensional first order structural elements. A bi-linear material model was used for the steel members. The material behavior of the high strength grout was represented by use of a Drucker-Prager model. Investigations by Schaumann et al. (2008b) revealed that this leads to accurate results for global analysis purposes of grouted connections.

The definition of contact within the grout-steel interfaces was accomplished by use of contact and target elements.

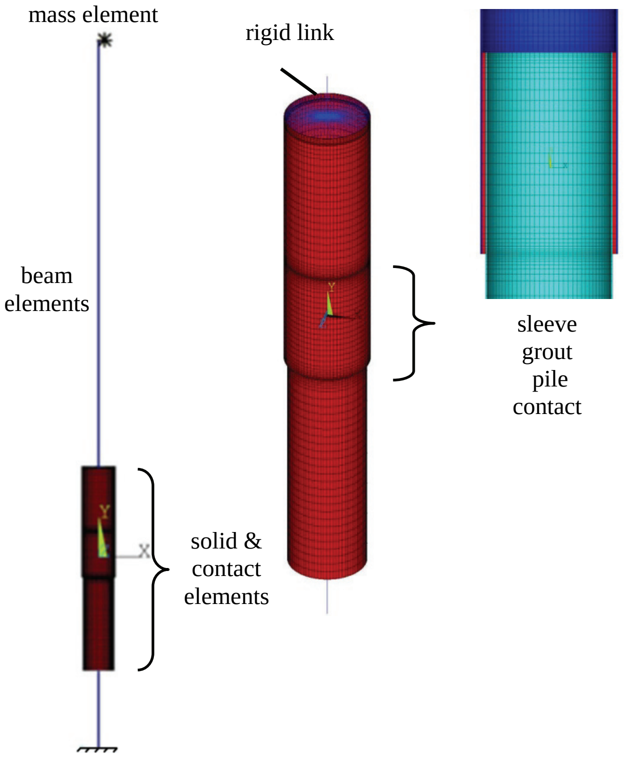

Fig.4. Combined modelling approach

The applied contact model is based on isotropic Coulomb friction, where the resistance against sliding depends on contact pressure and the assigned friction coefficient. Additionally, a passive shear resistance was defined, which provided a certain resistance against sliding independent from contact pressure. The passive shear strength, defined within the ANSYS© by use of the COHE parameter, does not contribute any tensile capacity against opening effects and can be reactivated after an opening of the connection. These characteristics are rather comparable to mechanical friction than to adhesive bonds. However, mechanical friction is not physically represented either because the surfaces of the element layers are perfectly plane. The parameter may therefore be interpreted as an auxiliary parameter to establish passive resistance against sliding. As a reference value, the adhesive shear strength for a representative grout material of 0.31 MPa was used (cf. Keindorf, 2010). This is also in the same order of magnitude as the theoretical shear resistance due to mechanical friction of 0.33 MPa, calculated according to the design equation given in DNV-OS-J101 (2007). Both values are more than five times higher than necessary to carry the structure's dead loads under static conditions.

Load analysis

In order to obtain representative loads for the structural investigations the reference structure was analyzed with the certified wind turbine design tool BLADED©. Additionally to a beam element representation of the support structure a generic representative model of a commercial-scale multi megawatt wind turbine was implemented. The model included discrete modeling of rotor blades and allows in a representative way for dynamic components like rotor azimuth, yaw bearing, pitch actuator, drive train dynamics and control system.

The load assessment was performed under representative offshore environmental conditions. Aerodynamic conditions were applied according to IEC 61400-1 standard wind class 1A. Marine conditions, including sea states, sea levels and currents were specified according to offshore measurement results presented by Fischer et al. (2010) in the "Upwind" design basis. A shallow water site of 21 m water depth was chosen, which is representative for the application of monopile foundations.

For the assessment of the grouted joint's structural long term behaviour under dynamic loading and for analysis in the Fatigue Limit State (FLS), integrated time history load simulations were performed. The resulting loads of all relevant fatigue load cases were extrapolated acc. to the stress spectrum presented by Almar- Næss (1985) for a turbine operating lifetime of 20 years. The number of occurring load cycles were determined using a rainflow cycle count procedure. Additionally, the decisive grouted joint bending moment in the Ultimate Limit State (ULS) was calculated for the structural investigations on the connection. The load calculation was performed based on the requirements and load case definitions specified in the international design standard for offshore wind turbines IEC 61400-3. In total 923 time-domain simulations were run.

QUASI-STATIC NON-LINEAR ANALYSIS

In order to assess the grouted joint behaviour regarding relative sliding and opening effects, the connection was subjected to a static bending moment of 198.73 MNm at the top of the grouted connection, which is equal to the design ULS bending moment determined in the load assessment. Since in the non-linear numerical simulation the load is increased incrementally, results are obtained in a range between zero and the design bending moment.

As previously described, bending loading causes areas of concentrated contact pressure at the edges of the connections enabling the load transfer via a force couple. At the opposite sides oval deformation of the steel tubes lead to gap formations on the steel-grout interfaces (Fig.5). These openings can reach values of several millimetres (Fig.6). The biggest gaps occur at the edges of the connection, where the supporting action from the other steel tube is least. Nevertheless, the results show that the interface separations are extended significantly into the connection, even under smaller bending moments. However, it has to be kept in mind that the numerical results overestimate the gap formation because no adhesive tensile capacity is defined.

Relative sliding motions are encountered over the entire compressed areas of the interfaces (Fig. 7). Primary sliding occurs in vertical direction, caused by the relative rotation of the two steel members under bending loading. Additionally, smaller amounts of horizontal sliding are evoked by the oval deformation of the tubes. However, considerable horizontal sliding is restricted to small areas at top and bottom of the interfaces.

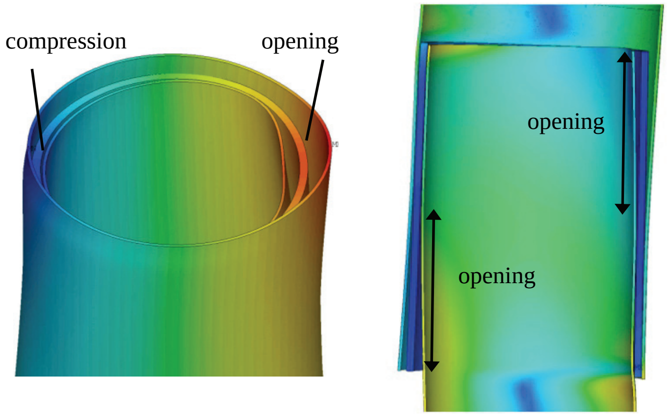

Fig.5. Oval deformations (left, deformations U, up scaled) and opening in interfaces between steel and grout (right, stresses S_{equv}, up scaled) under extreme loads

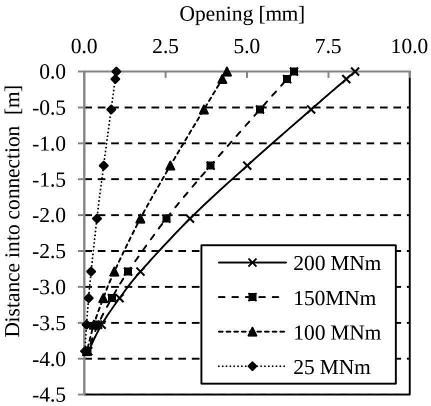

Fig.6. Opening in sleeve-grout interfaces at top of connection

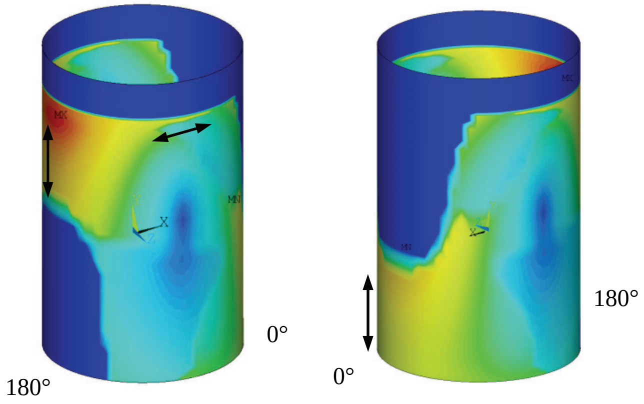

Fig. 7. Relative sliding motions in grout-sleeve interface

The maximal sliding intensities were observed in vertical directions at locations close to the edges of the connection. Fig.8 shows the sliding lengths for sleeve-gout and pile-gout interfaces at both ends at locations of 0.25 m into the connection. In all interfaces this location is within the area where the highest sliding distances are encountered. Generally, sliding motions exhibit an upward direction at the top and a downward direction at the bottom. Even though sliding distances vary between the analysed locations, significant sliding motions were observed at all interfaces, with a maximum vertical sliding distance of nearly 6 mm under extreme bending loading. Horizontal sliding motions reach values of up to 3 mm.

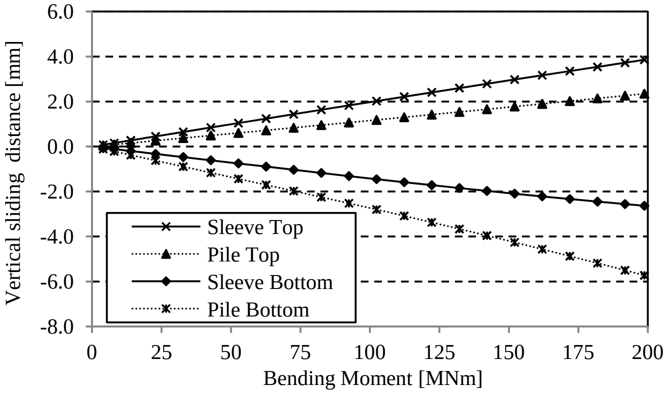

Fig.8. Relative sliding in vertical direction at top and bottom of the connection at distance of 0.25 m into the connection

While sliding distances increase linearly with the bending moment, no influence of the load's magnitude could be observed on the expansion of areas where relative sliding occurs. Furthermore, an increased friction coefficient did not substantially affect the sliding distances. This is consistent with the assumption that sliding cannot be restrained by friction and thus occurs even at small bending moments (Lotsberg, 2011 & 2012).

The obtained results emphasise that the connection is characterized by the occurrence of significant gap openings and relative sliding motions in both sleeve-grout and pile-grout interfaces. It has to be considered that in reality the magnitude of the opening is initially restrained by an adhesive tensile capacity. However, it can be assumed that after some depletion of adhesive bonds realistic opening effects are closer to the numerically obtained results. Furthermore, relative sliding is observed with significant expansions also for small bending moments. Moreover, a real structure is subjected to bending moments over the full range of possible directions. Gap opening and relative sliding both imply the loss of adhesive bonds. Hence, the obtained results underline that adhesive bonds cannot be considered to make a reliable contribution to axial shear resistance of the connection and that adhesive capacity which is present directly after the installation is reduced significantly after a short time of operation.

For the assessment of depletion of axial capacity caused by mechanical friction, accumulated relative sliding motions, which lead to wear of the grout material, were estimated based on the determined life time loading environment. The linear relations between sliding distance and bending moments are extracted from the results for locations of highest sliding intensities presented in Fig.8. Since no sliding motions occur under an opening state of the interfaces, sliding lengths are only considered in positive bending direction. The calculation of accumulated sliding lengths was therefore performed by use of a Markov - matrix, which contains information about the mean value of the load cycles. Thus, the upper and lower bound of every load cycle could be determined. For a realistic assessment the varying directionality of the acting bending moments must be considered. Therefore, the numbers of the applied load cycles were calculated under consideration of the annual probability distribution of the wind direction at the reference site given by Fischer et al. (2010). The relative abrasion sliding lengths, accumulated over a service time of 20 years, are presented in Table 2.

The accumulated relative sliding lengths at the considered nodes are in the dimension of at least 20 km and more. In the area of maximal sliding intensity an accumulated sliding distance of more than 50 km is reached. Obviously, no direct conclusions can be made regarding the influence on the vertical capacity because it can hardly be assessed how strongly the sliding causes degradation of the grout. However, the results emphasize that relative sliding and wear at the grout-steel interfaces are issues which have to be considered in the fatigue assessment of the connection. Furthermore, it is shown that even small increases of sliding intensity under a single load cycle can lead to significantly amplified accumulated sliding distances. Variations of grouted joint parameters have shown that especially a decreased overlap length L_g leads to significantly amplified relative sliding lengths at the reference locations. A smaller, albeit still notable influence, was observed for the slenderness ratios D/t of the steel tubes. Furthermore, the slenderness strongly affects the magnitude of the gap openings of the connection.

Table 2. Accumulated abrasion sliding length

	Sleeve - Grout		Pile-Grout	
	Top	Bottom	Top	Bottom
Accumulated sliding length	36.0 km	24.9 km	21.9 km	53.0 km

NON-LINEAR TIME DOMAIN SIMULATIONS

For the dynamic non-linear analysis of the grouted joint the structure is simulated in a decaying free oscillation in its first eigenmode. This approach allows conclusions about the vertical stability of the grouted joint in an oscillating structure and under alternating bending moments with acceptable numerical effort.

In order to initiate the oscillation, a deflection of the structure is generated by application of a horizontal force at the top node of the model. The applied load history for the time domain simulations is subdivided into the following load steps.

1. Application of gravity
2. Application of static horizontal force at top of the structure
3. Removal of the top load and activation of time integration

The activation of the time integration implies the consideration of damping and inertia forces. The generated free oscillation is simulated for a time period of 100 seconds which equals almost 30 oscillatory cycles. The simulations are performed as full, direct transient analyses which enable the consideration of the non-linear grouted joint behaviour. For the stepwise solution of the equation of motion a Newmark-integration scheme is applied (cf. e.g. Bathe, 1990). The decay of the oscillation is generated in terms of viscous Rayleigh damping by application of appropriate damping coefficients (cf. Schaumann & Wilke 2008a).

Time history results of the displacements at the top node of the model in horizontal and in vertical directions are depicted in Fig. 10. In every cycle the top node is moving upwards and downwards twice in a radial motion. Thus, the graph of the vertical displacement is alternating with half the frequency of the horizontal motion. The peak values of the vertical displacement correspond to the zero crossings of the horizontal displacement, i.e. where the structure is passing its static resting point.

The vertical displacement, resulting from the static gravity loads is indicated by the red, dashed line. This value is not reached after the structure is released from its initial displacement. In the further progression of the oscillation the graph is characterised by a downwards tendency of its peak values (thin red line).

This successive global down shifting of the support structure is caused by sliding motions in the grout-steel interfaces. The vertical movements are most pronounced in the first oscillatory cycles, where the joint is subjected to bigger bending moments. Even though the amount of slippage reduces with decreasing bending moments, a slight downwards tendency can be observed until the end of the time series.

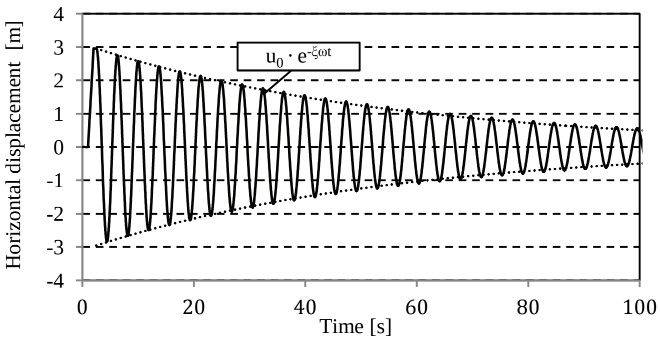

Fig. 9. Horizontal displacement

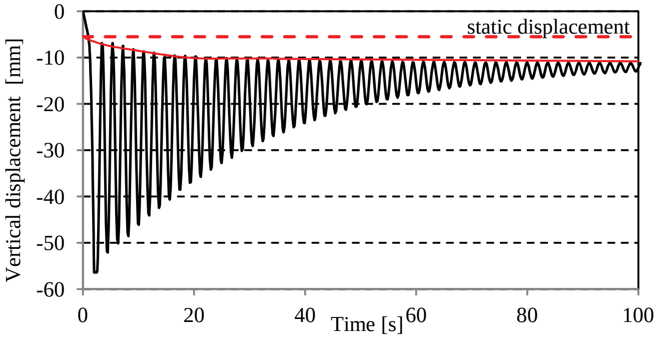

Fig. 10. Vertical displacement (passive shear resistance of 0.3 MPa)

It was elaborated that the passive axial capacity of a real grouted connection, provided by mechanical friction and adhesive bonds, can be considerably reduced over time. In simulations with a reduced passive axial shear resistance the down shifting was found to be dramatically increased (Fig.11). For comparison purposes a simulation is performed where the contact elements are defined as entirely bonded, meaning that neither sliding nor opening between the interfaces is permitted throughout the simulation. Fig.12 presents the vertical deflections in relation to the horizontal displacement for simulations with isotropic Coulomb and bonded contact option.

In all three simulations the structures dead load causes an equal vertical deflection under static conditions (load step 1). This proves that the defined passive axial capacity is sufficient to carry off the structure's dead load before the application of the bending moment. However, it cannot prevent the connection from stepwise shifting down when the structure is oscillating.

The progression of the settlement can be tracked in more detail in Fig.13. It can be observed that a stepwise down shifting occurs every time the structure passes its static resting point, whereas the upward and downwards paths of every cycle are nearly overlaying. The behaviour may therefore be illustratively denoted as a "ratcheting" effect. This can be explained with a reduced passive axial capacity after an initial opening of the interfaces. Since under bending loading significant amounts of shear resistance due to Coulomb friction are established the structure is prevented from shifting down. When the structure is passing its initial position in the vertical plane the shear resistance due to contact pressure is dissolved. Consequently, a downwards movement occurs until the bending process reconvenes in opposite direction. It may be argued that that axial resistance due to surface intolerances in real connections is re-established faster than the contact definition in the numerical model. However, it is plausible that, after a certain degradation of surface undulations of the grout, a comparable effect may have caused the vertical settlements observed in real structures.

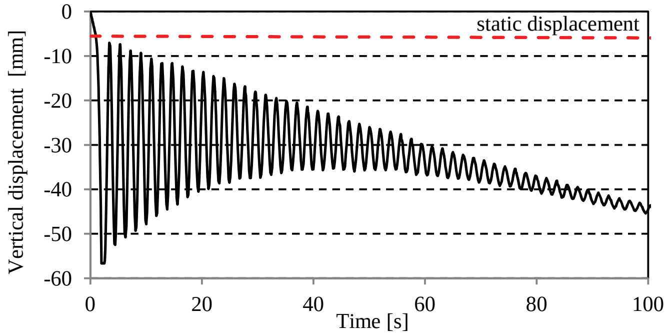

Fig.11. Vertical displacement (passive shear resistance of 0.1 MPa)

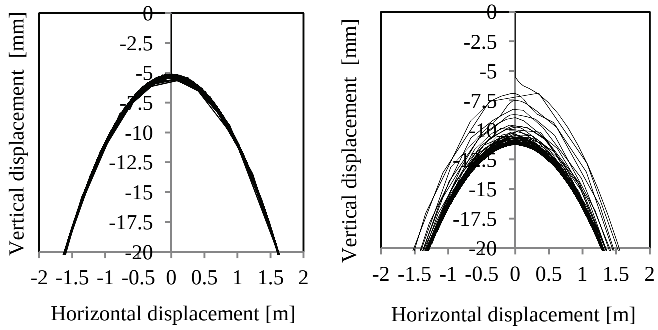

Fig.12. Vertical displacement in relation to horizontal displacement, left: bonded contact; right: isotropic Coulomb contact (passive shear resistance of 0.3 MPa)

Furthermore, the numerical results show that a slight downwards tendency is observable even for small bending moments and with considerable amounts of passive axial capacity. This can be explained with the relative sliding motions in the grout steel-interfaces which occur also for small bending moments. Thus, the results confirm the assumption that axial forces, induced by the gravity loads, lead to a global downward tendency of the sliding motion during cyclic bending loading.

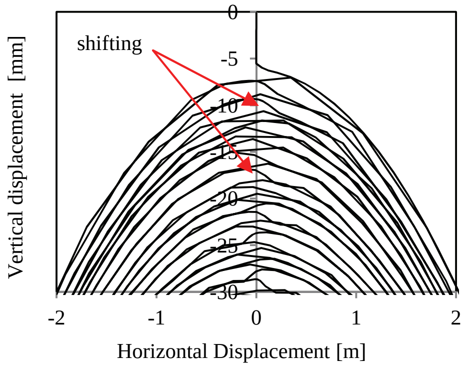

Fig.13. Vertical displacement in relation to horizontal displacement (passive shear resistance of 0.1 MPa)

FATIGUE DESIGN OF GROUTED JOINTS

To improve the axial load bearing capacity shear keys like weld beads can be arranged at the opposing surfaces of sleeve and pile. Since shear keys act as geometric notches, fatigue design is of high importance. Therefore, the influence of steel surfaces and shear keys on the fatigue performance of grouted connections was investigated. Grouted joint dimensions were chosen as stated in Table 1.

For the design of grouted joints in the Fatigue Limit State (FLS), fatigue loads are required. Due to a mean stress level dependency of anisotropic grouts, mean levels, amplitudes, and load cycles have to be taken into account. Therefore a Markov-Matrix resulting from the Rainflow count of moments is applied, see Fig.14.

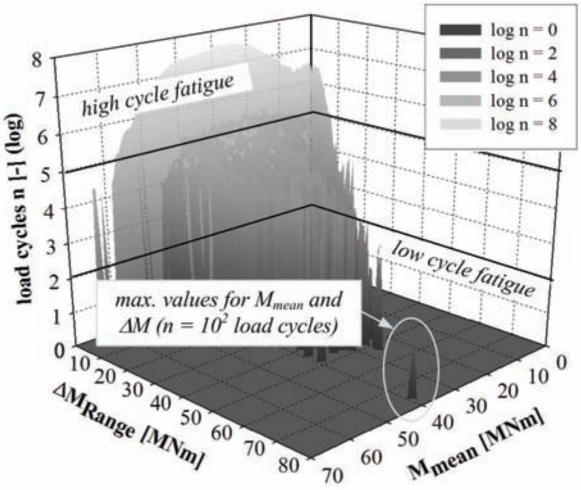

Fig.14. Markov-Matrix for the fatigue loads at grouted joint bottom

Under consideration of latest investigations of Lohaus et al. (2012), the number of endurable load cycles of high strength concrete under pure compression can be determined by modern S-N curves according to fib model code (2011). Investigations by Lochte-Holtgreven (2013) show that mentioned S-N curves are valid for high performance grouts in grouted joints, cf. Fig. 15.

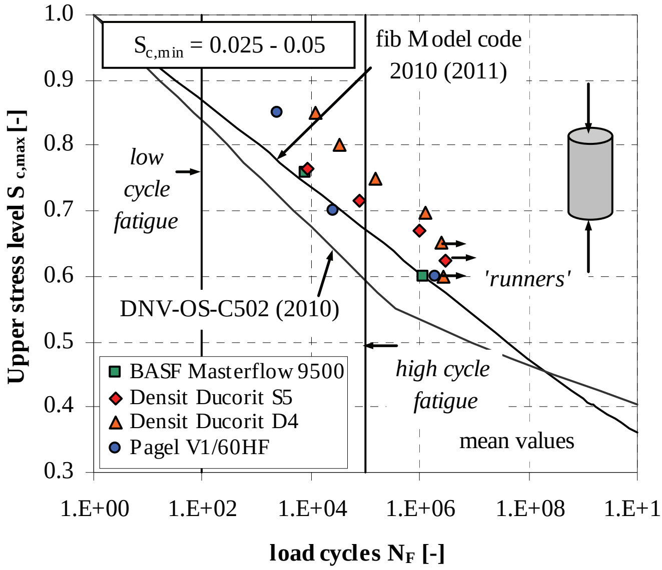

Fig. 15. Fatigue test results for grouts vs. SN-curves acc. to fib (2011) and Lochte-Holtgreven (2013)

Analogous to steel, the fatigue damage D for grout can be calculated using Miner's Rule (Eq.1). Influences of anisotropic materials and multiaxial stress states as well as fatigue resistances are commonly neglected.

$$D = \sum_{i=1}^{m} \frac{n_i}{N_{F,i}} \leq 1.0 \qquad (1)$$

In a first step the influence of shear keys was investigated. Therefore numerical calculations were performed for plain grouted joints and for joints with one, three, five, seven and nine shear keys per sleeve and pile. The longitudinal steel stresses showed that with an increase of shear key number, the local stress concentrations are distributed more equally and that local steel plastifications occur at the outer shear keys.

Regarding the fatigue design, it can be concluded that shear keys lead to local stress concentrations in the grout layers of grouted joints. For plain connections the maximum damage can be expected at the external grout regions. This can be shown by a fatigue calculation for a grouted joint w/o shear keys, see Fig. 17. The fatigue damage significantly results from tensile stresses due to ovalisations of the slender steel shells. This failure mode can be reduced if shear keys beads are arranged at the centre of the joint. Fig. 18 shows the grout damage for a grouted joint with seven shear keys.

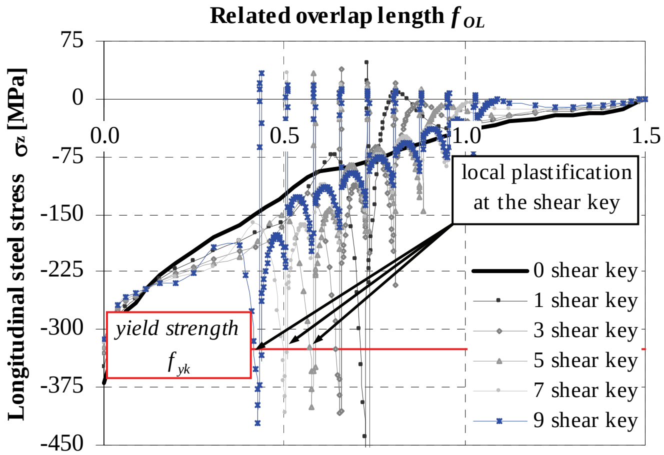

Fig. 16. Longitudinal steel stresses under static loads and varying numbers of shear keys

It can be seen that the external regions show no significant fatigue damage. Damage mainly occurs at the highly stressed grout regions around the shear keys.

In addition it can be seen that the grout fatigue failure can be described as a failure of a grout wedge. This failure mode was also described by Krahl et al. (1985) and could be confirmed for grouted joints under predominant bending loads by Lochte-Holtgreven (2013). With regard to the durability of grouted joints, the installation of shear keys is favorable.

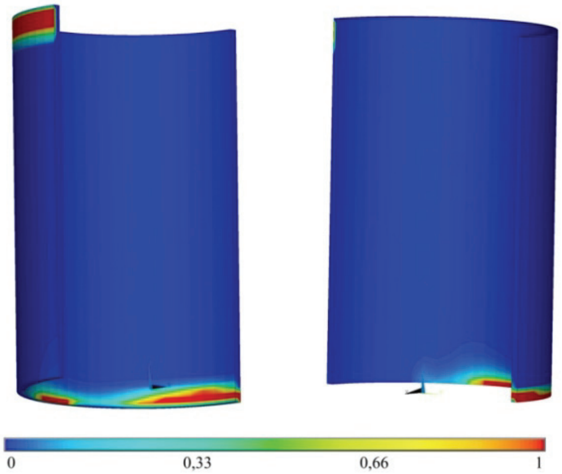

Fig. 17: Fatigue grout-damage for a plain pipe connection acc. to fib Model Code 2010.

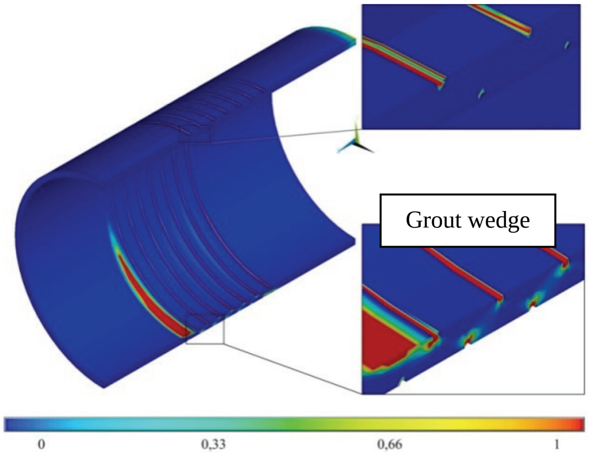

Fig. 18. Fatigue grout-damage for a grouted joint with seven shear keys

CONCLUSIONS

In this paper possible reasons for vertical misalignments of grouted connections on monopile foundations are analyzed and degradation effects of axial load bearing resistance are evaluated. It was shown that the connection is characterized by a high flexibility when it is subjected to bending moments. This is reflected by considerable gap openings and relative sliding motions between adjacent material surfaces of the hybrid connection. It could be demonstrated that no reliable long term shear resistance can be attributed to adhesive bonds. Based on an integrated fatigue load calculation it was shown that relative sliding motions, causing abrasive wear of the grout, accumulate up to values of several kilometres over the structure's service life. Experimental studies published recently have revealed that contrary to previously established assumptions the high compressive strength of the grout cannot prevent from wear of the material caused by relative sliding. Given the calculated sliding distances, it is undoubtedly that relative sliding may affect strongly the passive shear resistance introduced by surface intolerances and mechanical friction.

Furthermore, it was demonstrated in dynamic simulations that, regardless of the presence of significant amounts of passive axial shear resistance, a successive downwards shifting of the connection occurs under alternating bending moments. This effect can be explained by the flexible behaviour of the connection. Even though the observed effect may be exaggerated by the simplified numerical definition of the contact behaviour, it is likely to occur also in real connections. This applies especially if the passive shear resistance has suffered from degradation. Consequently it could be concluded, that the flexible characteristics of the slender connection in terms of oval tube deformations and sliding between the material layers can explain the vertical settlements observed on real structures. For an improvement of axial load bearing capacity and reduction of grout degradation the application of shear keys was shown to be favorable.

ACKNOWLEDGEMENTS

Parts of the presented investigations were performed within the framework of the research project "GROW – Experimental and numerical investigations on the structural behavior of grout structures for OWT" (Fzk.: 0327585). The project was founded by the BMU – German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. The BMU and the industry partners Germanischer Lloyd Industrial Services, Heijmans Oevermann GmbH and SIAG Anlagenbau Finsterwalde GmbH as well as the material manufactures BASF, Densit A/S and Pagel are kindly acknowledged.

REFERENCES

Almar-Næss, A. (1985): Fatigue Handbook - Offshore Steel Structures, Norges tekniske högskole, Trondheim NTH, Tapir Forlag, Trondheim, Norway, ISBN 82-519-0662-8.

Andersen, M.S. and Petersen, P. (2004): "Structural Design of Grouted Connections in Offshore Steel Monopile Foundations" *Proc. of the 2004 Global Windpower Conference,* Chicago.

Bathe, K.-J. (1990): Finite-Elemente-Methoden. Springer-Verlag, Berlin

Det Norske Veritas (2004, 2007, 2009, 2011): Design of Offshore Wind Turbine Support Structures, Offshore Standard DNV-OS-J101, Høvik.

fib (2011), "Model code 2010 - Final draft", International Federation of Structural Concrete (fib), Model Code prepared by Special Activity Group 5 'New Model Code'.

Fischer, T, de Vries, W and Schmidt, B (2010): "Upwind Design Basis – WP4: Offshore Foundation and Support Structures", Endowed Chair of Wind Energy (SWE) at the Institute of Aircraft Design, Universität Stuttgart.

Keindorf, C. (2010): "Tragverhalten Ermüdungsfestigkeiten von Sandwichtürmen für Windenergieanlagen", PhD-Thesis at the Institute for Steel Construction, Leibniz Universität Hannover, Shaker Verlag Aachen, in German.

Krahl, N. W., Karsan, D.I. (1985): "Axial Strength of Grouted Pile-To-Sleeve Connections", *Journal of Structural Engineering,* 111, No. 4, pp. 889 - 905.

Lochte-Holtgreven, S (2013), "On the Ultimate and Fatigue Capacity of Grouted Joints for Offshore Wind Turbines under Predominant Bending", PhD-Thesis, Institute for Steel Construction, Leibniz University Hannover, in German. (to be published)

Lohaus, L., Oneschkow, N., Elsmeier, K., Hümme, J. (2012), "Fatigue behaviour of high performance concrete in wind turbine structures", *Bautechnik,* Vol. 89, No. 8, Ernst & Sohn, Berlin, in German.

Lotsberg, I. (2010): "Summary Report from the JIP on the Capacity of Grouted Connections in Offshore Wind Turbine Structures" Det Norske Veritas. Technical Report Joint Industry Project, Report No. 2010-1053 Rev. No 04. Høvik.

Lotsberg, I. (2011): "On Capacity of grouted Connections in Wind Turbine Structures (Presentation slides)", Offshore Engineering Society London, London.

Lotsberg, I., Serednicki, A., Bertnes, H., Lervik, A. (2012): "Design of grouted connections for monopile offshore structures – Results from two Joint Industry Projects" *Stahlbau,* Vol. 81 (2012), No. 9, pp. 695-704, Ernst & Sohn Verlag, Berlin

Nielsen, L.P. (2007): "Finite Element Analysis of Large Diameter Grouted Connection" *Proc. of 26th Int. Conf. on Offshore Mechanics and Arctic Eng.,* San Diego. Paper

Schaumann, P. and Wilke, F. (2006): "Fatigue of Grouted Joint Connections", *Proc. of the 8th German Wind Energy Conf.* DEWEK2006, Bremen.

Schaumann, P. and Wilke, F (2007): "Design of Large Diameter Hybrid Connections Grouted with High Performance Concrete" *Proc. of 17th Int. Offshore and Polar Eng. Conf,* Lisbon, ISOPE, Portugal, Vol 1, www.isope.org .

Schaumann, P , and Wilke, F. (2008a): "Nonlinear Structural Dynamics of Offshore Wind Energy Converters with Grouted Transition Piece" *Proc. of the European Wind Energy Conference,* EWEC2008, Brussels.

Schaumann, P.; Wilke, F.; Lochte-Holtgreven, S. (2008b): "Grout-Verbindungen von Monopile-Gründungsstrukturen – Trag- und Ermüdungsverhalten", *Stahlbau,* Vol. 77 (2008), No. 9, pp. 647-658, Ernst & Sohn Verlag, Berlin, in German.

Schaumann, P, Lochte-Holtgreven, S, Lohaus, L and Lindschulte, N (2010): "Durchrutschende Grout-Verbindungen in OWEA –

Tragverhalten, Instandsetzung und Optimierung” *Stahlbau*, Vol. 79 (2010), No. 9, pp. 637-647, Ernst & Sohn Verlag, Berlin, in German.