EXPERIMENTAL FATIGUE TESTS ON AXIALLY LOADED GROUTED JOINTS

PETER SCHAUMANN*, ALEXANDER RABA* AND ANNE BECHTEL*

* ForWind Center for Wind Energy Research (ForWind)
Institute for Steel Construction
Leibniz Universität Hannover
Appelstraße 9a, 30167 Hannover, Germany
e-mail: stahlbau@stahl.uni-hannover.de, www.stahl.uni-hannover.de

Keywords: Grouted Joint, Jacket, Support Structure, Fatigue, Submerged

Summary: Grouted Joints are a typical connection detail of substructures for offshore wind turbines. Nevertheless, at present merely little knowledge is available for the fatigue behaviour of this connection regarding a large grout annulus and submerged ambient conditions. This paper presents results from small and large scale fatigue tests of grouted joints. The small scale tests reveal a significant impact of the surrounding water. The large scale tests indicate that a larger grout annulus results in a different damage pattern.

1 INTRODUCTION

By the year 2030, 15 GW of Germany's electric energy demand shall be covered by offshore wind farms according to the goals of the German government [1]. To achieve these goals about 30 to 40 wind farms with an overall amount of up to 3000 offshore wind turbines (OWT) need to be erected within the next 15 years. These offshore wind farms are mainly located in the German Exclusive Economic Zone (EEZ) of the North Sea. As the Maritime Spatial Plan for the North Sea [2] shows, most of these areas have water depths of 30 m and deeper. For these large water depths the preferred solution is currently a lattice substructure [2], the jacket (cf. Figure 1).

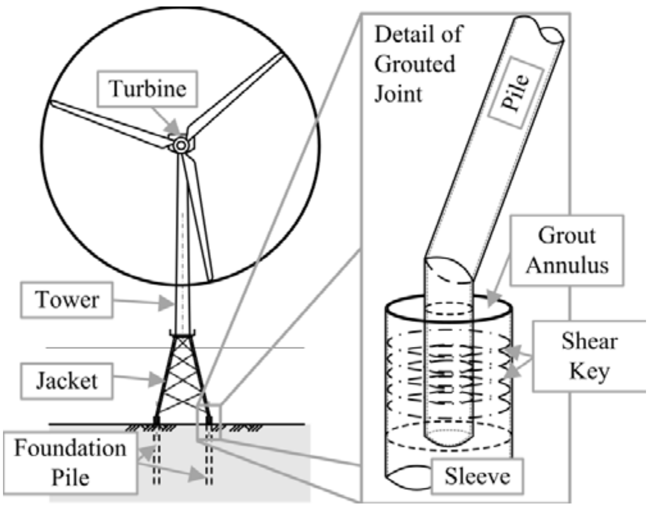

Figure 1: Grouted joints in a jacket substructure for OWTs and detail of grouted joint

A group of steel piles, which are driven into the seabed, forms the foundation for lattice substructures. Piles and substructure are connected via grouted joints, a connection well known from the oil and gas industry. The connection consists of an inner steel tube (pile) and an outer steel tube (sleeve) creating an annulus, which is filled with high performance grout (cf. Figure 1). For a reliable force transmission between steel and grout, the facing steel surfaces are equipped with shear keys made of weld beads.

Compared to grouted connections for Monopiles, the grout layer thickness in jackets is much larger and the connection is prevailingly axially loaded. Alternating loads from wind and waves are the decisive actions. The high alternating loads, the geometric variations and high strength filling materials differentiate the connection for OWTs from the ones utilized in oil and gas platforms. As a result, use of knowledge and experience from oil and gas for OWT grouted joints is limited and has to be verified. In addition, latest experiments and research investigations focusing on grouted connections for OWTs did not consider the effect of large grout annulus and submerged conditions. Hence, current research investigations concentrate on the fatigue behaviour of grouted joints with large grout annuli.

Therefore, the research project 'GROWup – grouted joints for Offshore Wind Energy Converters under reversed axial loadings and up scaled thicknesses' (funding sign: 0325290) funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) deals with the fatigue behaviour and execution perspectives of grouted joints in jackets. The joint project is conducted at the Institutes for Steel Construction and Building Materials Science at the Leibniz University in Hannover, Germany. The Institute for Steel Construction investigates the fatigue behaviour of small and large scale grouted joint specimens. In this paper results of the conducted tests are presented.

2 SMALL SCALE TESTS

To investigate a broad range of different filling materials and the influence of various loading parameters at an economic level a small scale grouted joint specimen (cf. Figure 3, left) was developed [4]. The specimen is equipped with machined shear keys and comparatively stiff steel tubes. As a result, the decisive damage mode is a failure of the grout matrix in the occurring compression struts. Moreover, the specimen is not really to scale of grouted joints in real substructures. Nevertheless, the grout's stress state in the small scale specimen is comparable to the multiaxial stress state in real connections.

The test procedure for small scale specimens is composed by two major parts. The first part is an Ultimate Limit State (ULS) test in which the specimen's quasi static resistance F_{ULS} is determined. The specimen is compressed in a displacement controlled test rig with a load application speed of 0.2 mm/min (cf. Figure 2, right) beyond its maximum resistance. The average F_{ULS} of three specimens is chosen to be representative for a batch of specimens produced at once with the same filling material.

Figure 3, top left, shows the force displacement behaviour of test specimens under quasi static compression. The behaviour can be separated into three stages. Up to about 50 % F_{ULS} (cf. P1) the connection shows a linear elastic behaviour. Then the first cracks due to tensile stresses transverse to the compression struts occur and cause a stiffness reduction in stage 2. Finally, the static resistance F_{ULS} is reached at P3 and after that the displacement increases while the bearable load reduces in stage 3.

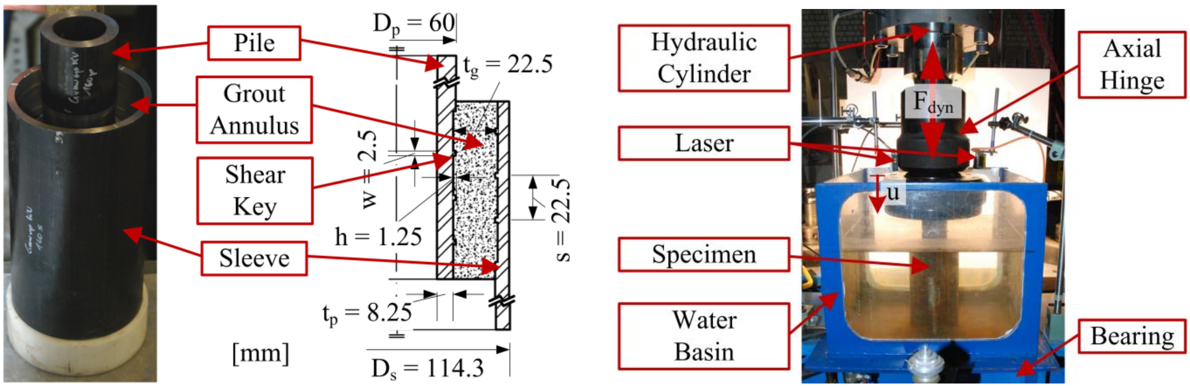

Figure 2: Geometry of small scale specimens (left) and test rig for the small scale tests (right)

Within the second part of the test setup specimens are tested regarding their fatigue behaviour. Within these tests the ambient condition (AC) is varied between dry and wet. Where wet means, that the specimen is loaded while being fully submerged in a water basin. Also, the maximum load level F_{max} is varied between 50 % and 25 % of the static resistance F_{ULS}. And finally, the loading frequency f is varied between 5 Hz, 1 Hz and 0.3 Hz. Since real support structures are mainly loaded at their first eigenfrequency of about 0.3 Hz [5], the influence of the loading frequency on the connection's fatigue behaviour is investigated additionally. All tests are conducted until N = 2 m load cycles or failure of the specimen.

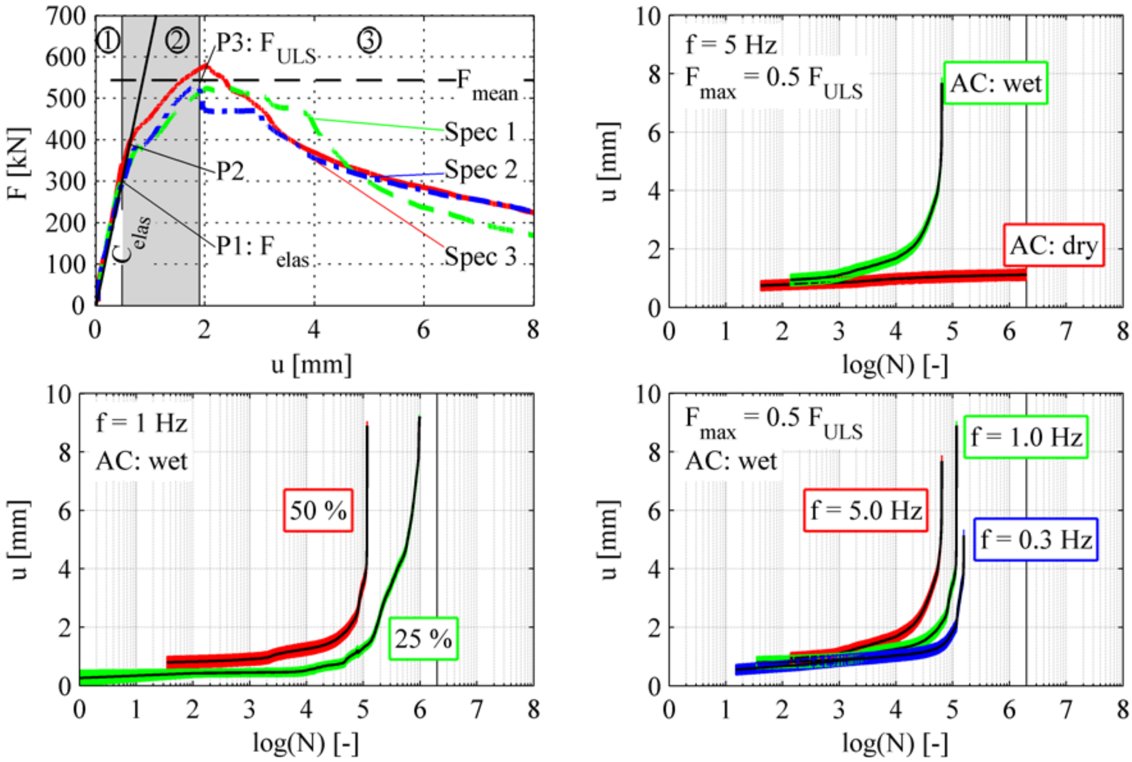

Figure 3: Force displacement behaviour of three specimen under quasi static compression (top left), load cycle dependent displacement u of small scale specimens for different ambient conditions (AC) (top right), different load levels F_{max} (bottom, left) and different loading frequencies f (bottom, right)

Results from several fatigue tests are presented in Figure 3. The major influence of the varied parameters described before can be attributed to the ambient condition. As Figure 3, top right shows, testing under water reduces the number of endurable load cycles to N ~ 35,000, while the specimen in dry ACs passes the load cycle limit at N = 2 m. (cf. Figure 3, top right). A halving of F_{max} (cf. Figure 3, bottom left) leads to an increase of endurable load cycles from N ~ 100,000 to N ~ 1 m. The influence of F_{max} can be reduced if the number of endurable load cycles is defined as the first point of a major stiffness decrease. For the results presented, this can be defined at N ~ 200,000. A reduction of the loading frequency f also leads to an increase of endurable load cycles from N ~ 35,000 at 5 Hz, N ~ 100,000 at 1 Hz to N ~ 150,000 at 0.3 Hz (cf. Figure 3, bottom right).

During the submerged tests processes of grout material flushing were observed (cf. Figure 4, left). As a result the volume of the grout section reduces and the stiffness of the connection decreases like it is visible in the displacement plots (cf. Figure 3). After the specimens were tested, they were opened to investigate the grout section. Figure 4, right, shows the grout section of a specimen tested in dry and one tested in wet ambient conditions. Both specimens were loaded identically. While in dry ambient conditions no effects of attrition are visible, the submerged specimen shows significant cracks due to transverse tensile stresses in the lower part, as well as vertical cracks in the upper part at the pile surface.

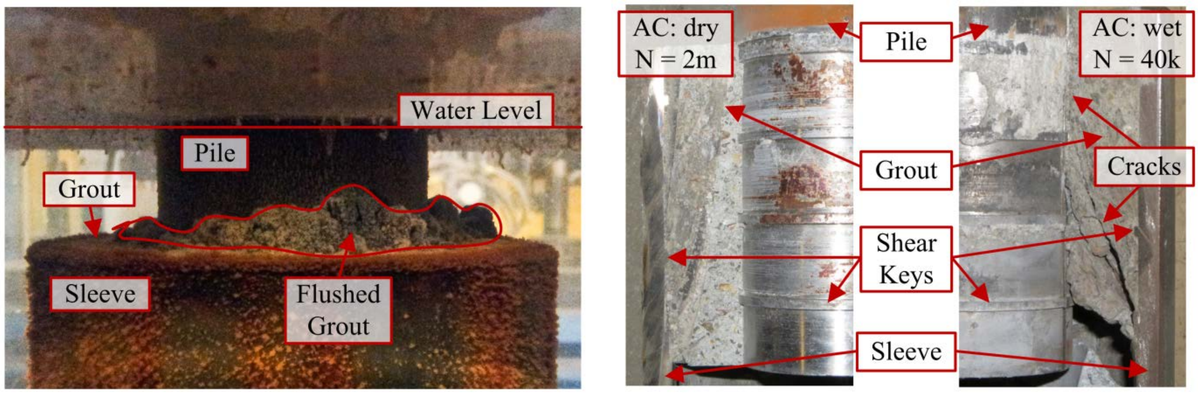

Figure 4: Flushed grout material on top of cyclically loaded submerged small scale specimen (left) and grout section of opened specimens tested in dry (left) and wet (right) ambient conditions

On basis of the presented results, three different processes can be addressed as influence of the water to the connection’s fatigue behaviour. At first, deformations of the loaded specimen lead to an opening of the contact interface between steel and grout. As a result water invades the contact interface and as the first degradation process hydro lubrication reduces the friction between steel and grout [6]. Due to high compressive stresses caused by the local load application of the shear keys, grout material in front of the shear keys crushes and resides as loose material in the connection. In the second process this loosened grout particles get washed out by the invading water [7]. And finally, as a third process, high water overpressure and flow speeds caused by pumping effects in the interface due to the cyclic loading, lead to cracking and wear of the grout material. This leads to a significant stiffness reduction and a decrease of the number of endurable load cycles of the specimen.

3 LARGE SCALE TESTS

In order to quantify the effect of large grout thicknesses to the fatigue behaviour of axially loaded grouted joints large scale fatigue tests were conducted. With reference to real jacket and tripod dimensions, two test specimens were developed, cf. Table 1. The grout layer thickness of test specimen no 1 and 2 are varied between ~82 mm and ~184 mm. Both specimens were equipped with five shear keys on pile and sleeve. For the filling material a high-performance grout with a nominal compressive strength of 140 MPa was chosen.

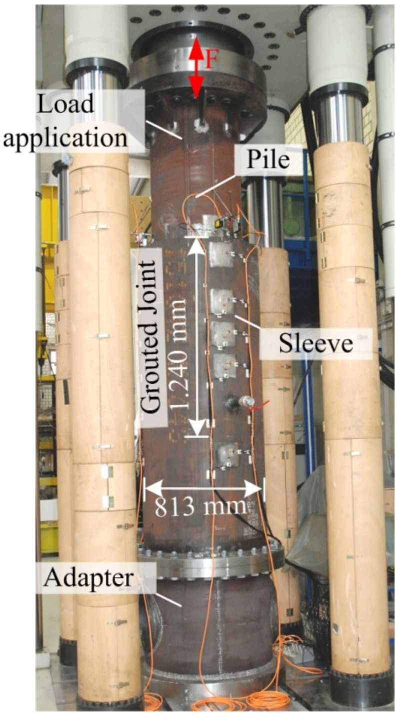

Figure 5: Test specimen in servo-hydraulic testing machine

Both specimens were tested in a 10 MN large servo-hydraulic testing machine (cf. Figure 5). The major testing was performed by applying six different load levels, each for 100,000 load cycles. In the first three load levels an alternating load (R = -1) was applied, which was followed by three load steps of pulsating-compression forces (R = ∞). As the first specimen did not show significant displacement changes or stiffness reduction after completion of the major test program, two additional load steps were applied: load step no 7 and 8. These load steps were used to analyse the fatigue and deformation behaviour of preloaded and predamaged specimens. Therefore it was sufficient to apply 15,000 load cycles. A test frequency of 1-2 Hz could be realized in all load steps, which are summarized in Table 2.

Table 1: Geometric dimensions of large scale grouted joint test specimens

Test specimen no	*Scale*	*Pile D_p/t_p [-]*	*Sleeve D_s/t_s [-]*	*Grout D_g/t_g [-]*	*Overlap length L_g [mm]*
1	~1:4	~24	~41	~10	1240
2	~1:2	~16	~41	~4	

For predominantly axially loaded grouted joints different failure modes are known. Substantially, it can be distinguished between the two material relating modes for steel and for grout. Shear key failure and local plasticization of the steel shell at the shear keys are typical steel failure modes that are covered by steel design approaches.

Table 2: Load level and related maximum and minimum forces of applied test program

Load level	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
F_{max} [MN]	1	2	3	0	0	0	0	3
F_{min} [MN]	-1	-2	-3	-4	-5	-6	-8	-3

In contrast, the grout failure modes being more sensitive to fatigue loading, especially regarding tension forces, display more complex multiaxial failure behaviour. An initial state of grout cracking (cf. Figure 6a)), reflects the first stage of failure considering a shear keyed grouted connection. The grout matrix failure in the local region around the shear key is influenced by arising stress concentrations and exceedance of the grout tensile strength. Rising stresses lead to compression strut failure (cf. Figure 6b)), on the force flux between facing shear keys. This failure mode is considered by design formula within current design standards, e.g. ISO 19902 [8]. Failure mode c) (cf. Figure 6) reflects a shear failure which is influenced significantly by the shear key spacing s.

With regard to experimental tests and results presented in literature, the major influencing parameters are the shear key height h, the shear key spacing s and the uniaxial compressive strength f_{cu} of the grout. These parameters are considered by empirical equations for the Ultimate Limit State design according to ISO 19902 [8], cf. Eq. 1 and 2.

$$f_{g,shear} = \left[0.75 + 1.4 \cdot \left(\frac{h}{s}\right)\right] \cdot f_{cu}^{0.5} \tag{1}$$

$$f_{g,sliding} = C_p \cdot \left[2 + 140 \cdot \left(\frac{h}{s}\right)^{0.8}\right] \cdot K^{0.6} \cdot f_{cu}^{0.3} \quad \text{with} \quad K = \left(\frac{D_p}{t_p} + \frac{D_s}{t_s}\right)^{-1} + \frac{E_g}{E_s} \cdot \left(\frac{D_g}{t_g}\right)^{-1} \tag{2}$$

In these equations, h is the shear key height, s the shear key distance, f_{cu} the compressive strength of the grout material, D the diameter, t the thickness, and E the young's modulus of grout (E_g) and steel (E_s). Subscript s represents the sleeve meaning the outer tube, p the pile as the inner tube, and g the grout layer. The first equation considers a grout matrix failure reflected by the grout cracking and compression strut failure depicted in Figure 5. The shear failure also named as sliding failure being depending on the radial connection stiffness is reflected by the second equation. Further developments to these equations for the Ultimate limit State design are presented in [9].

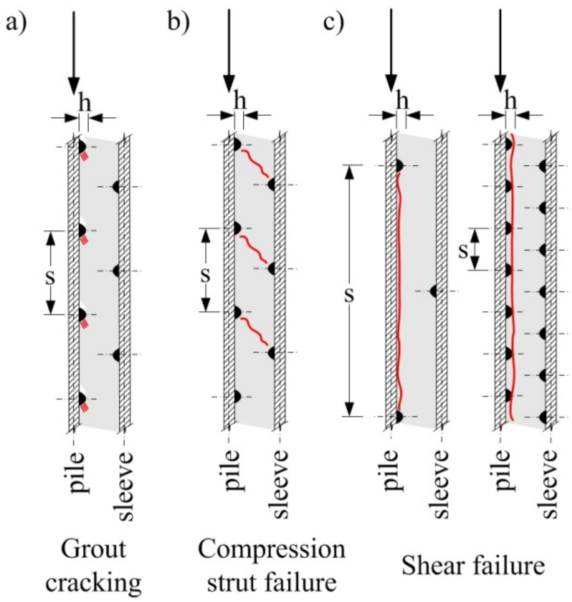

Figure 6: Failure modes for grouted joints

According to these design equations for the tested specimens a compression strut failure might occur due to the utilised geometric dimensions.

This initial indication of failure mode correlates to the cracks inside the tested specimens. Figure 7 shows the opened test specimens no 1 and 2 after completion of the testing procedure. Both damaged specimens indicate crossing compression strut cracks caused by tension and compression loads. In addition to these cracks a wedge of crushed grout appears on the load averted side of the pile shear keys. This grout wedge, primarily described by Krahl & Karsan [10], has an average height correlating to the shear key height and a length which is four-times larger than the shear key height. Comparing the different damaged grout cross-sections of test specimen no 1 and 2 depicts that the large grout thickness indicates a different damage pattern than the smaller grout layer, even though for both specimens crossing compression struts appear. For test specimen no 2 larger compression struts occur by skipping shear keys on the opposing side. The larger grout annulus and the smaller pile diameter influenced not only the damage pattern but also the applicable loads. Contrary to the test specimen no 1, it was not possible to apply the loads of load step 7 and 8 to test specimen no 2, after application of the major test steps 1 - 6. This implies that the test specimen no 2 has a reduced fatigue capacity compared to test specimen no 1. Further analyses of measured displacements and strains in combination with numerical simulation will improve the knowledge about the failure procedure and the fatigue behaviour of grouted joints with large grout annuli.

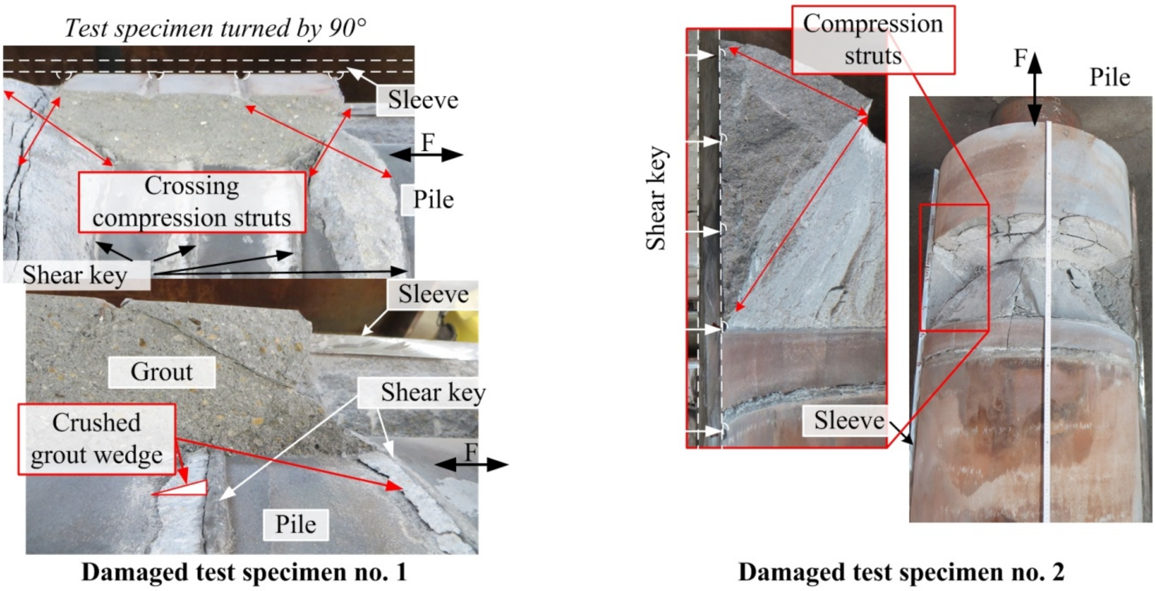

Figure 7: Damage pattern of opened tested large scale specimen no 1 (left) and no 2 (right)

4 CONCLUSIONS

In this paper, results of small and large scale specimen tests of axially loaded grouted joints are presented. The small scale specimen fatigue tests show a significant impact of water on the connection's fatigue behaviour. As mentioned, the small scale specimens are not real to scale and therefore, the presented results cannot be directly transferred to real connections. To overcome this uncertainty, submerged fatigue tests with large scale specimens are planned for the future.

Large scale fatigue tests have shown that differing grout thicknesses and pile diameter influence the damage pattern and fatigue capacity. The crack paths of the opened specimens have shown that compression struts for the large grout thickness skip opposing shear keys. Both test specimens have shown crossing compression struts which are induced by tension and compression loading. Investigations of measured data and numerical simulations are planned to comprehend the failure procedure and crack mechanism.

5 ACKNOWLEDGEMENT

The presented experimental tests and results are achieved within the research project 'GROWup - Grouted Joints for Offshore Wind Energy Converters under reversed axial loadings and up scaled thicknesses' (funding sign: 0325290) funded by BMWi. The authors thank the BMWi for financing and all accompanying industry project partners (Fraunhofer IWES, GL, Senvion, RWE Innogy, Strabag) for their support. A special thanks goes to the Institute for Building Materials Science, in particular to its head Prof. Ludger Lohaus, for the fruitfull cooperation within the project especially with regard to the use of the testing facility for the large scale test specimen.

6 REFERENCES

[1] Deutschlands Zukunft gestalten: Koalitionsvertrag zwischen CDU, CSU und SPD - 18. Legislaturperiode (in German). Available: http://www.tagesschau.de/inland/koalitionsvertrag152.pdf (2013, Dec. 16)

[2] German Maritime and Hydrographic Agency: "Spatial Offshore Grid Plan for the German Exclusive Economic Zone of the North Sea and Non-technical Summary of the Environmental Report 2012", Comprehensive Summary, Hamburg, Germany, 2013.

[3] Seidel, M.: "Substructures for Offshore Wind Turbines – Current Trends and Developments", in *Festschrift Peter Schaumann*, Hannover, Germany, pp. 363-368, 2014.

[4] Wilke, F.: Load bearing behaviour of grouted joints subjected to predominant bending, Dissertation, Vol.31, Institut für Stahlbau, Leibniz Universität Hannover, Shaker-Verlag, 2014.

[5] Schaumann, P.; Böker, C. and Wilke, F.: "Lebensdaueranalyse komplexer Tragstrukturen unter Seegangsbeanspruchung (Life Cycle Analysis for Complex Substructures in Maritime Loading)" (in German), *Stahlbau*, Vol. 74, No 6, pp. 406–411, 2005.

[6] Schaumann, P.; Raba, A. and Bechtel, A.: "Impact of Contact Interface Conditions on the Axial Load Bearing Capacity of Grouted Connections", in *Proceedings of EWEA 2013*, Vienna, Austria, 2013.

[7] Schaumann, P.; Raba, A. and Bechtel, A.: "Effects of Attrition Due to Water in Cyclically Loaded Grouted Joints", in *Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering*, San Francisco, USA, 2014.

[8] DIN EN ISO 19902: Petroleum and Natural Gas Industries - Fixed Steel Offshore Structures, DIN Deutsches Institut für Normung e.V, January 2014 (in German).

[9] Schaumann, P, Bechtel, A., Lochte-Holtgreven, S.: Nachweisverfahren zur Tragfähigkeit überwiegend axial beanspruchter Grouted Joints in Offshore-Tragstrukturen. *Stahlbau*, Vol. 81, No 9, S. 679-688, Verlag Ernst & Sohn, Berlin, Deutschland, 2012.

[10] Krahl, N. W., Karsan, D. I.: Axial Strength of Grouted Pile-to-Sleeve Connections, *Journal of Structural Engineering*, Vol. 111, No 4, S.889 - 905, April 1985.