Fatigue Behaviour of Axial Loaded Grouted Joints in Tests

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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. These offshore wind farms are mainly located in the German Exclusive Economic Zone (EEZ) in the North Sea. As the Maritime Spatial Plan for the North Sea [2] shows, most of of these areas have water depths of 30 m and deeper. For these large water depths up to now the preferred solution is a lattice substructure [3], the jacket (cf. Figure 1).

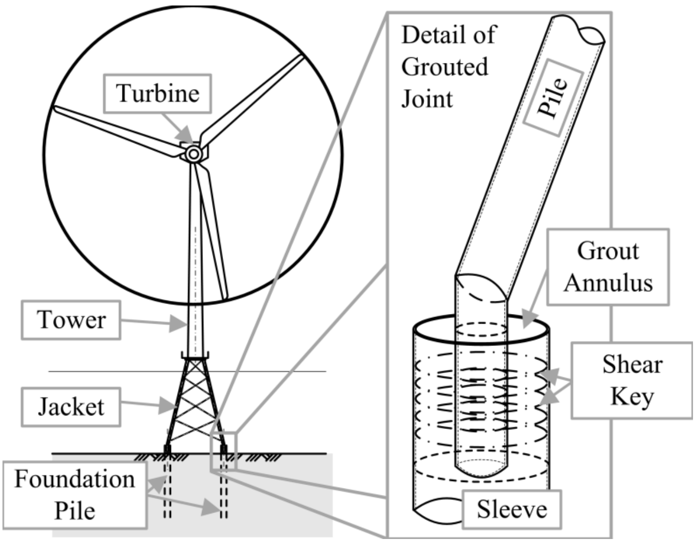

Figure 1: Grouted joints in a jacket substructure for OWTs and detail of grouted joint

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). By inserting the pile in the sleeve an annulus is created 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.

In jackets, Grouted Joints are characterized by a large grout annulus, due to the substructure's installation procedure. Compared to grouted connections for Monopiles, the grout layer thickness in jackets is much larger. Grouted Joints in lattice substructures for OWTs are prevailingly axial loaded. Alternating loads from wind and waves are the decisive actions. The high alternating loads, the geometric variations and filling materials with higher strength differentiate the connection for OWTs from the ones utilized in oil and gas plattforms. As a result, usage of knowledge and experience from oil and gas for OWT grouted joints is limited and has to be verified. Experimental knowledge marginally exits for this type and size of connection. 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) investigates the fatigue behvaiour and execution perspectives of grouted joints in jacktes. The joint project is conducted at the Institute for Steel Construction and the Insititute for Building Materials Science at the Leibniz University in Hannover, Germany. The Institute for Steel Construction investigates the fatigue behviour of small and large scale grouted joint specimens. In the following, results of the conducted tests will be presented.

Small Scale Tests

To investigate a broad range of different filling materials and the influence of various loading parameters at a quiet economic level a small scale grouted joint specimen (cf. Figure 2, top 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 occuring 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 setup for small scale specimens contains two major parts. The first part is an Ulimate Limit State (ULS) test in which the specimen's quasi static capacity F_{ULS} is determined. The specimen is compressed in a displacement controlled test rig beyond its maximum capacity. 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.

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 speciman 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 maximum static capacity F_{ULS}. And finally, the loading frequency f is varied between 5 Hz, 1 Hz and 0.3 Hz. Hereby, a loading frequency of 5 Hz represents an advantage for a short testing duration. 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 are endured by the specimen or until the specimen's stiffness decreases rapidly.

Results from several fatigue tests are presented in Figure 2. The major influence of the varied paramters described before can be attributed to the ambient condition. As Figure 2, 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 2, top right). A halving of F_{max} (cf. Figure 2, 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 2, bottom right).

Three different processes can be addressed as influence of the water to the connection's fatigue behaviour. 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 wears down. 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 cavitation and damaging of the grout material.

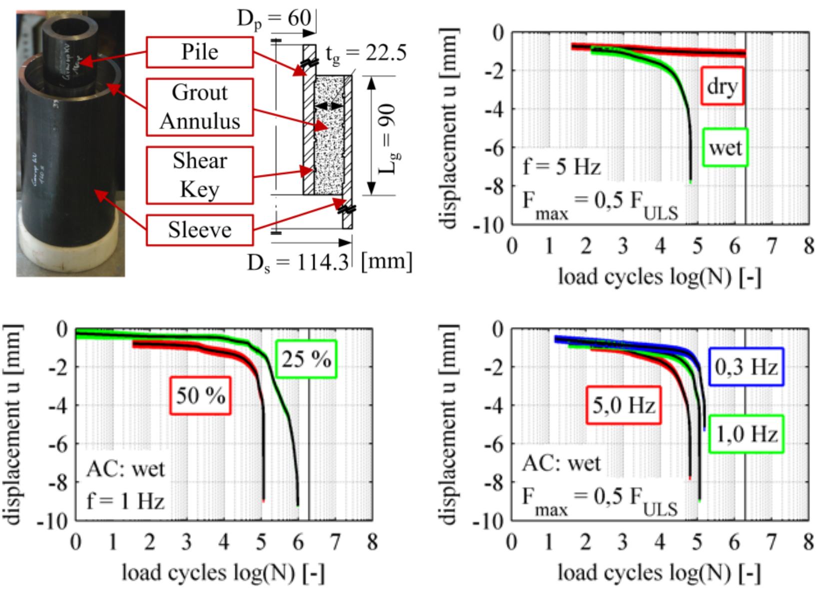

Figure 2: Geometry of small scale specimens (top left), load cycle dependent displacement u of small scale specimens for different ambient conditions (AC) (top right), different load levels F_{max} (bottom, left) and different loading frequencies f (bottom, right)

Large Scale Tests

In order to quantify the effect of large grout thicknesses to the fatigue behaviour of axially loaded joints large scale grouted connection tests are conducted. With reference to real jacket and tripod dimensions two test specimens were established in a scale of ~1:2 und ~1:4. The grout layer thickness of test specimen no. 1 is ~80 mm, whereas test specimen no. 2 has a grout layer thickness of ~180mm.

These geometrical dimensions lie outside the validity ranges presented by current design guidelines as e.g. ISO 19902 [8]. Hence, the current design approaches can be reviewed by using the test results of these specimens.

Beside the geometry, the uniaxial grout material strength specified by e.g. ISO 19902 [8] is limited to 80 MPa. This value represents cement slurries used for offshore oil and gas platforms. Today high performance grout materials are used for offshore wind turbines. These materials have much higher compressive strength characteristics as considered by the design approaches. As a consequence, the test specimens used for the large scale fatigue tests are filled with two different high strength grout materials currently used for offshore wind turbines. Material I has a mean uniaxial compressive strength of 140 MPa. The second material (material II) has a lower mean uniaxial compressive strength of 90 MPa. Beside the grout layer thickness and the material strength, the shear key positions as well as the influence of water to the fatigue behaviour will additionally be analyzed in large scale tests.

The test program for the fatigue tests of large scale grouted joint specimens consists of different load cases. The first three load cases represent a stepwise incrementally increased alternating load ($R = -1$) with constant mean level followed by three load cases considering a stepwise incrementally increased pulsating compression loading ($R = \infty$) with varied mean level. All six load cases are applied for 100'000 load cycles. Load case 02 includes the maximum tension load applied with a value of F_{max}= 3MN. The maximum compression load is realized in load case 06 with F_{min}= -6MN. As the first test specimen did not show any significant stiffness reduction or failure after the six load cases the test program was extended by a pulsating compression loading with a maximum compression load of F_{min} = -8MN in load case 07. In order to analyse the fatigue behaviour of the predamaged test specimen a repeated conduction of load case 03 consisting of the alternating load condition with a force amplitude of 3MN was performed. To show the effect of high pulsating compression loads and alternating loading on predamaged specimens according to occuring deformations it was sufficient to apply 15'000 load cycles. During the fatigue tests measurements of the steel strain as well as relative local and global deformations were performed by applied strain gauges and laser. All test specimens were equipped with 5 shear keys as weld beads on inner and outer steel tube. Hence, for the test specimen no. 1 with a grout thickness of ~80 mm and material I the fatigue loads are within a range of 5% to 50% of the ultimate state capacity F_{ULS} according to ISO 19902 [8]. As all test specimens are exposed to the same test program, the test specimen no. 2 with the same filling material I, but with a larger grout thickness of ~180 mm was loaded in a range of 11% to 90% of the static capacity.

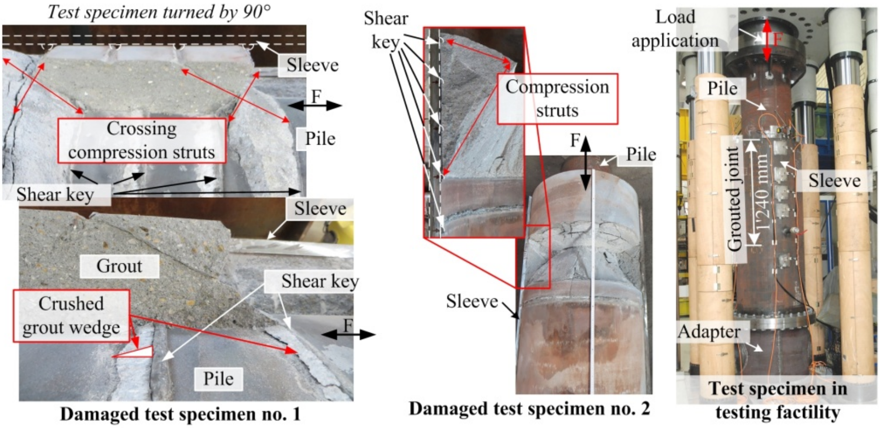

Figure 3: Large scale test specimen in testing facility (right) and opened damaged test specimen no. 1 (left) and no. 2 (center).

With regard to experimental tests and results presented in literature different failure modes are defined [9]. Mainly the compression strut failure due to a grout matrix failure and shear failure between grout and steel are known and considered by different design equations in ISO 19902 [8]. For both test specimens the decisive equations reveal that a compression strut failure may occur. This initial indication of failure mode correlates to the cracks inside the tested specimens. Figure 3 shows the test specimen installed in the testing facility of the Institute for Building Materials Science on the right hand side and the opened test spcimens no. 1 and 2 showing 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 inidicates 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. Further analyses of measured data in combination with numerical simulation will improve the knowledge about the failure procedure.

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 influence the damage pattern. 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.

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