INFLUENCE OF THE LOADING FREQUENCY ON THE FATIGUE PERFORMANCE OF SUBMERGED SMALL-SCALE GROUTED JOINTS

Prof. Peter Schaumann, Alexander Raba
ForWind – Center for Wind Energy Research
Institute for Steel Construction, Leibniz University Hannover, Germany

Summary

Germany's offshore wind farms are mostly located in water depth of 30 m and deeper. Lattice substructures which can be installed in such water depths are connected to the foundation piles via grouted joints. For these submerged hybrid connections only few test results are available, dealing with the influence of the surrounding water on the connection's fatigue performance. This paper presents results from tests focusing on the influence of the loading frequency on the fatigue performance of submerged small-scale grouted joints. A distinct proportionality between the number of endurable load cycles and the loading frequency is visible in the test results. From the results a frequency dependent correction factor for the number of endurable load cycles is developed. Moreover, this correction factor is implemented in a fatigue curve derived for small-scale grouted joints in wet ambient conditions.

1 Introduction

Within the next 15 years, the German government intends to expand the electricity production from German offshore wind farms to an amount of 15 GW of electrical energy. This corresponds roughly to an erection of 3000 new offshore wind turbines (OWT) until the year 2030. Most of these will be located far from shore in water depths deeper than 30 m. For such water depths, lattice substructures like tripods or jackets are possible solutions (cf. Figure 1). The substructures are founded on piles and connected to the piles via submerged grouted joints. Even though, the grouted joint is well known from the offshore oil & gas industry, only few results on the effects of water on the connection's fatigue performance exist.

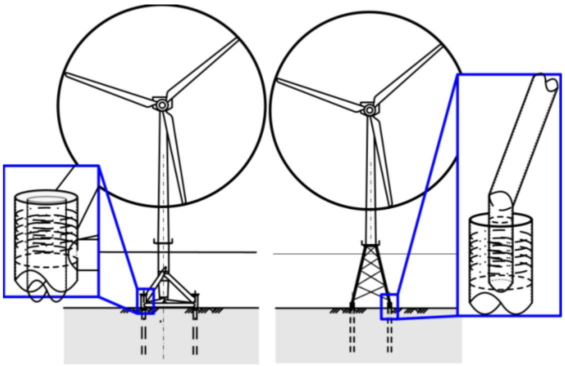

Fig. 1 Grouted joints in tripod (left) and jacket (right) substructures for OWTs [1]

At the Institute for Steel Construction, Leibniz University Hannover, Germany within the joint research project "GROWup" investigations focus on the fatigue performance of grouted joints under predominant axial loading. The project is funded by the Federal Ministry for Economic Affairs and Energy (BMWi, funding sign: 0325290) and is the third project in a row dealing with grouted joints. As part of this research project, fatigue tests on small-scale grouted joints with shear keys are conducted. The specimens are filled with two different industrial grout products and tests are executed in a water basin to investigate the influence of water on the fatigue performance of the connection.

First published test results [1] showed that water reduces the fatigue performance of the connection significantly compared to results from tests under dry conditions. Moreover, the impact of water showed proportionality to the applied loading frequency and decreased with lower frequencies. Based on these first results, a systematic approach for testing small-scale grouted joints with varied loading frequency was developed and conducted.

This paper presents the systematic testing approach as well as test results from 26 tests on submerged small-scale grouted joints with different loading frequencies. All test results are evaluated regarding the influence of the loading frequency. An engineering approach to consider the influence of the frequency is derived. Moreover, a fatigue curve is developed from test results and a combined procedure for a loading frequency dependent fatigue curve is proposed.

2 Materials and Methods

2.1 Test setup

The test specimen is a small-scale grouted joint with shear keys on the grout facing steel surfaces. The grout section has a length of 90 mm and a thickness of 22.5 mm. Further dimensions and the manufacturing procedure are described in detail by Schaumann et al. in [2].

The fatigue limit state (FLS) test rig shown in Fig. 2 consists of a hydraulic cylinder with a capacity of 400 kN, an axial hinge and a water basin. The specimens are cyclically loaded in axial direction with a load ratio of $R = 0.05$ (compression-compression loading). With regard to the specimens' static capacity F_{ULS} the maximum compressive load in the FLS tests is set to $F_{max} = 50\%\ F_{ULS}$. For each batch of the produced specimens F_{ULS} is determined separately.

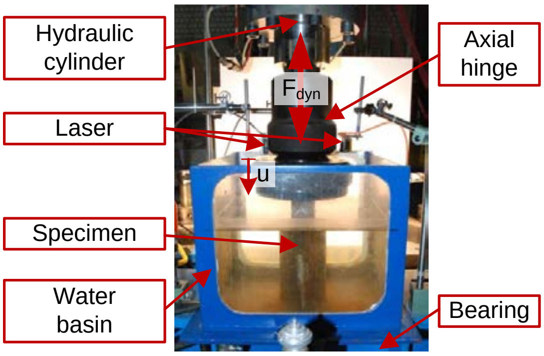

Fig. 2: Test rig for the submerged fatigue tests

The loading frequency is varied between $f = 0.3$ Hz and $f = 10$ Hz where $f = 0.3$ Hz is in the range of the first eigenfrequency of an OWT and therefore represents a realistic loading frequency. As opposed to this, $f = 10$ Hz is a favourable loading frequency for FLS tests due to test duration aspects. In between these limits, the loading frequency is set to 1, 2 and 5 Hz.

During the tests the vertical displacement u is measured via lasers pointed to the load application plate. Furthermore, the applied load F is measured via a force transducer placed between axial hinge and piston of the hydraulic cylinder.

The tests are conducted until the specimen endured 2 million load cycles N or it was no longer capable of bearing the applied load.

2.2 Grout materials

Two commercial grout materials from different manufacturers were chosen for the tests, differing in in their uniaxial compressive strength f_{cu}, their tensile strength f_t and their elastic compressive modulus E_c. The material properties provided by the manufacturers are presented in Tab. 1.

Tab. 1: Properties provided by the manufacturers for the used grout materials

		Material No.	
		1	2
f_{cu}	[N/mm²]	90.0	140.0
f_t	[N/mm²]	6.0	8.6
E_c	[N/mm²]	40,000.0	50,900.0

Material investigations carried out by the Institute for Building Materials Science (IfB), Leibniz University Hannover in parallel to the small-scale grouted joint tests showed deviating material properties. Especially for material no. 1 the material properties were distinctly higher. According to an evaluation by Schaumann et al. [3], no significant difference between the two materials could be determined from the test results. Thus, within the following investigation the two materials, as well as the different production batches will be treated as one sample.

2.3 Additional test results

For the later derivation of a fatigue curve, additional results from tests with a maximum compressive load $F_{max} = 20\%$ F_{ULS} are taken from Schaumann et al. [3].

3 Results

3.1 Preevaluation

The results of 26 small-scale grouted joint specimen tests are given in Tab. 2. Moreover, Tab. 2 includes information about the used material and batch of material as well as the noteworthy results of Dixon's Q-test [4] to determine probable outliers.

Tab. 2: Results of 26 small-scale grouted joint specimens tested at a load level of $F_{max} = 50\%$ F_{ULS} in wet ambient conditions

	Loading frequency *f* [Hz]	**Number of endurable load cycles *N* [-]**	**Material No. / Batch No.**	**Dixon Q-test**
1	0.3	95252	1/3	-
2	0.3	156305	1/1	-
3	0.3	248476	1/3	-
4	0.3	258353	1/3	-
5	0.3	403986	1/3	-
6	0.3	1796350	1/1	>99.8%
7	1.0	41805	2/1	-
8	1.0	49378	1/2	-
9	1.0	80157	1/2	-
10	1.0	102714	1/1	-
11	1.0	112152	2/1	-
12	1.0	116480	1/1	-
13	1.0	129999	2/1	-
14	2.0	65325	1/3	-
15	2.0	142194	1/3	-
16	2.0	204282	1/3	-
17	5.0	30717	2/1	-
18	5.0	31382	1/1	-
19	5.0	35299	1/1	-
20	5.0	39835	2/1	-
21	5.0	41348	2/1	-
22	5.0	64060	1/1	-
23	5.0	101209	1/1	>95.0%
24	10.0	16708	1/3	-
25	10.0	32466	1/3	-
26	10.0	60982	1/3	-

To appraise the validity of the test results a statistical evaluation is applied in the following. At first a probability function for the results must be assumed. Conditioned by the small sample size, only a visual distribution test is possible. In Fig. 3 all results are plotted in normal probability plots, separated according to the loading frequency f. On the basis of these plots, the results are assumed to be normal distributed for further investigations.

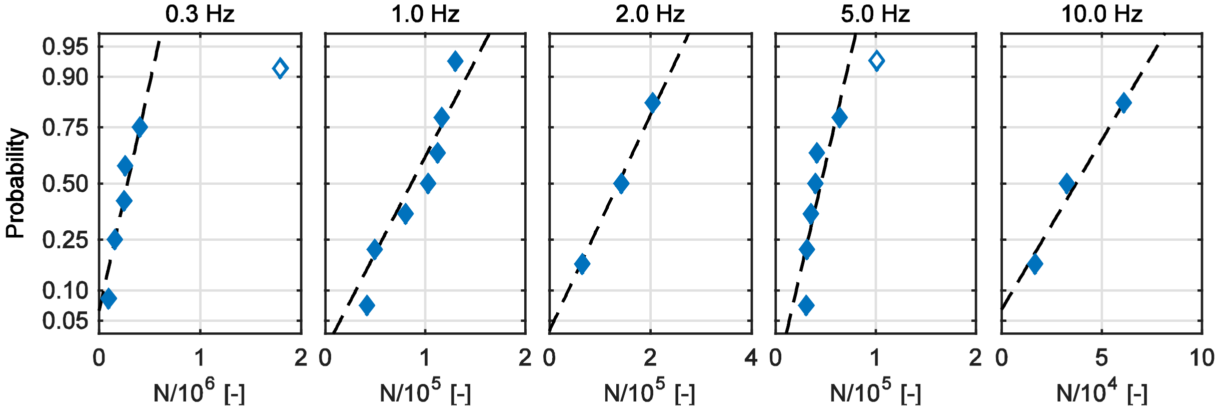

Fig. 3: Normal probability plot of test results with different loading frequencies, probable outliers according to Dixon's Q-test [4] are plotted as empty diamonds

The assumption of a normal distribution gives the opportunity to apply Dixon's Q-test [4] in a next step. This test finds probable outliers in very small sample sizes by comparing the interval between the probable outlier and its nearest result with the span of the full sample. The two results 6 and 23 (open diamonds in Fig. 3) are identified as probable outliers, which corresponds to the visual impression of Fig. 3.

Fig. 4 and Fig. 5 show the number of endurable load cycles *N* in dependency of the applied loading frequency *f*. In Fig. 5 the horizontal grey line represents the mean value for *N* and the grey box denotes the 95% confidence interval (CI) according to the student's t-distribution. These statistical properties are calculated including all data.

For loading frequencies of 1 and 5 Hz the confidence intervals are relatively small, which indents a high statistical validity. For the loading frequencies of 0.3, 2 and 10 Hz the confidence intervals are relatively large and they extend beyond zero in the y-direction. This is caused by a small sample size of three results at 2 and 10 Hz and a larger scatter of the results for 0.3 Hz. Due to these observations, the further evaluation approach covers three different data sets. The first set includes all data, in the second set the probable outliers are excluded and the third set considers only the results for 1 and 5 Hz loading frequency.

3.2 Effect of loading frequency

The relation between loading frequency *f* and the number of endurable load cycles *N* is plotted in Fig. 4 and Fig. 5. The plots show an inverse proportionality between loading frequency *f* and number of endurable load cycles *N* and thereby confirm the results of Schaumann et al. [3]. The proportionality can be expressed by a potential regression function of the following format:

$$N(f) = a \cdot f^{k} \,. \tag{1}$$

For the parameters *a* and *k* different values are outlined in the figures. With a reduced amount of results considered in the regression both parameters *a* and *k* decrease and the following ranges can be obtained.

$$a = 90.000 \ldots 164.000$$

$$k = -0.5 \ldots -0.7$$

The parameters seem to show a low scatter and the visual impression of the dense regression lines in Fig. 4 and Fig. 5 supports this assumption. For the presented evaluation all regression lines seem to be valid.

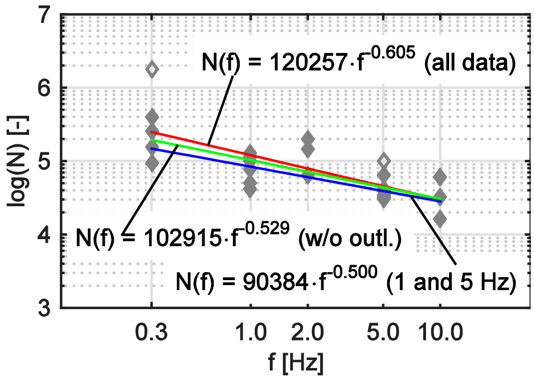

Fig. 4: Influence of the loading frequency *f* on the number of endurable load cycles *N* and potential regression functions without grouping results by loading frequency

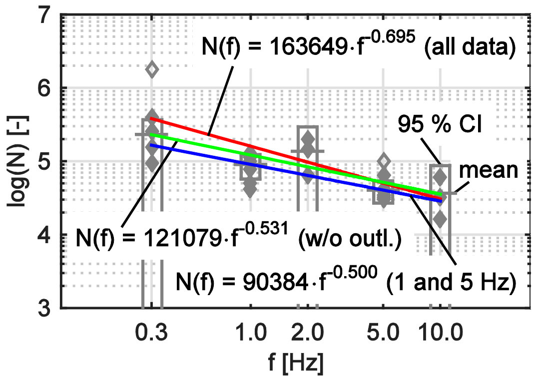

Fig. 5: Influence of the loading frequency *f* on the number of endurable load cycles *N* and potential regression functions considering only mean values of each loading frequency

Nevertheless, the further approach concentrates on the parameters from the regression analysis including the data without outliers and considering only mean values for N. Therefore, equation (1) results into:

$$N(f) = 121079 \cdot f^{-0.531} \quad (2)$$

Unfortunately, equation (2) is only dependent on the loading frequency f. But as the investigations by Schaumann et al. [3] showed, the number of endurable load cycles N also depends on the applied load. Thus, equation (2) should be transferred into a loading frequency dependent correction factor. This is realized by normalizing the parameter *a* for a loading frequency of $f = 5$ Hz.

$$c(f) = 2.351 \cdot f^{-0.531} \quad (3)$$

By equation (3) the correction factors given in Tab. 3 can be calculated.

Tab. 3: Correction factors for the number of endurable load cycles N in dependence of the applied loading frequency f

***f* [Hz]**	0.3	1.0	2.0	5.0	10.0
***c*(*f*) [-]**	4.5	2.4	1.6	1.0	0.7

3.3 Loading frequency dependent fatigue curve

As final step, a loading frequency dependent fatigue curve is derived including the previously defined correction factor. The presented test results as well as additional results [3] are plotted in the *S-N* diagram presented in Fig. 6. For a loading frequency of 5 Hz test results are available at loading levels of $F_{max} = 50\ \%\ F_{ULS}$ as well as $F_{max} = 20\ \%\ F_{ULS}$. From these results the red fatigue curve in Fig. 6 is developed as the logarithmic regression of the mean values N per load level. With the correction factor given in equation (3) the fatigue curve can be described by equation (4) and the green ($f = 1$ Hz) as well as the blue ($f = 0.3$ Hz) line in Fig. 6 can be calculated. Both lines agree very well with the presented test results.

$$S\left(N(f)\right) = -0.197 \cdot \log\left(\frac{N(f)}{2.351 \cdot f^{-0.531}}\right) + 1.423 \quad (4)$$

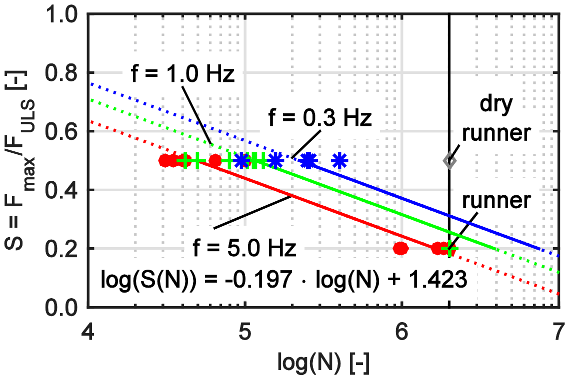

Fig. 6: Loading frequency dependent fatigue curve for small-scale grouted joint specimens tested in wet ambient conditions

4 Discussion

The presented results confirm the prior evaluation of Schaumann et al. [3] regarding the proportionality between number of endurable load cycles N and loading frequency f for the small-scale grouted joint specimens tested in wet ambient conditions. From parts of the test results a loading frequency dependent fatigue curve can be derived which is in good agreement with additional test results not considered for the fatigue curve development (cf. Fig. 6).

To improve the reliability of the new fatigue curve, additional tests at load levels above and below $F_{max} = 50\ \%\ F_{ULS}$ are desirable. Especially to validate the assumed frequency independent slope of the fatigue curve. Nevertheless, with the presented approach it is possible to transfer fatigue test results elaborated with a loading frequency of 5 Hz to a realistic OWT loading frequency of 0.3 Hz.

Finally, it is very important to keep in mind that the presented approach is validated only for the specific small-scale grouted joint geometry and the specific loading setup. For larger scales this has to be verified in further tests.

Acknowledgments

The presented 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 the German Federal Ministry for Economic Affairs and Energy (BMWi). The research partners are Institute for Steel Construction and Institute of Building Materials Science, both at Leibniz University Hannover, Germany. The authors thank the BMWi for funding and all accompanying industry project partners (Fraunhofer IWES, DNV GL, Senvion SE, RWE OLC, STRABAG) for their support. In addition the authors thank the material manufacturers for their material supply.

References

[1] Schaumann P., Raba A., and Bechtel A., 2013: "Impact of Contact Interface Conditions on the Axial Load Bearing Capacity of Grouted Connections". *Proceedings of the European Wind Energy Associoation Conference EWEA 2013*, Vienna, Austria.

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

[3] Schaumann P., and Raba A., 2015: "Systematic Testing of the Fatigue Performance of Submerged Small-Scale Grouted Joints". *Proceedings of the ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering*.

[4] Dean R. B., and Dixon W. J., 1951: "Simplified Statistics for Small Numbers of Observations". Analytical Chemistry, **23**(4), pp. 636–638.