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IMPACT OF WATER ON THE FATIGUE PERFORMANCE OF LARGE-SCALE GROUTED CONNECTION TESTS

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ABSTRACT

Grouted connections represent a common joining technique between substructure and foundation piles of offshore oil & gas platforms as well as of offshore wind turbines. Due to cyclic loads arising from wind and wave actions the fatigue performance of the connection has to be considered. In lattice substructures like jackets the grouted connections are located at seabed level being fully submerged during their entire lifetime. Today’s fatigue design regulations are based on investigations neglecting any influence of the surrounding water since they were conducted in dry ambient conditions. So far, only Germanischer Lloyd gives additional recommendations for submerged grouted connections.

At the Institute for Steel Construction, Leibniz Universität Hannover, Germany investigations of the joint research project ‘GROWup’ focus on the fatigue performance of axially loaded grouted connections. 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 connections. As part of this research project, cyclic loading tests on small-scale and large-scale grouted connections with shear keys are conducted. Small-scale fatigue tests showed a reduced number of endurable load cycles for connections when tested in wet ambient conditions.

However, the transferability of these findings to a larger scale was still doubtful due to unknown scale effects. Therefore, the impact of water on the fatigue performance was tested recently at large-scale grouted connections. Previous to the submerged large-scale grouted connection fatigue tests, similar test specimens were exposed to alternating loads at dry ambient conditions. Comparison of both large-scale test results under wet and dry conditions enable to estimate the influence of water on the fatigue performance of grouted connections. Reflection of the small-scale test results gives hints on the scale effect. Test preparation, test results and design recommendations are presented in the paper.

1 INTRODUCTION

Permanently fixed support structures for offshore platforms as well as offshore wind turbines are usually founded on steel piles driven into the seabed. In water depth of 30 m and deeper lattice substructures like jackets or tripods (cf. Figure 1) are a feasible type of foundation. To date these types of structures are connected to their foundation piles via grouted connections.

Figure 1: Common lattice substructures for offshore wind turbines, jacket (left, © FoundOcean) tripod (right, © Trianel)

The grouted connection consists of a smaller steel tube (pile) inserted into a larger steel tube (sleeve). The resulting annulus between the tubes is filled with grout to create a force-fitted connection (cf. Figure 2). Additionally, the steel surfaces facing the grout are equipped with shear keys for a secure interlocking.

Being developed and utilised for the oil and gas industry, this connection and especially its load bearing and fatigue behaviour, was subject matter of several research works by for example Krahl et al. [1], Lamport [2], Billington et al. [3,4] and Harwood et al. [5]. All of these works have in common that their structural loading tests were carried out under dry ambient conditions. In contrast to that grouted connections in lattice substructures are located at seabed level and are usually not sealed against water ingress.

Since the first offshore wind turbines were erected the grouted connection is applied to these structures. Two types of connection have to be distinguished by their loading situation. In monopile substructures the grouted connection is predominantly loaded by bending, whereas for the mentioned lattice substructures the connection is predominantly axially loaded. Although new connection types are coming up for monopiles, the grouted connection is to date the only commercially usable connection for fixed lattice substructures. Current design regulations for this type connection such as ISO 19902 [6], DNV-OS-J101 [7] and Norsok N-004 [8] are based on the before mentioned research results. Flaws of these design regulations are discussed e.g. by Lotsberg et al. [9]. Newer approaches are only available for monopiles (cf. [7,10]) but are not applicable for lattice substructures. Compared to oil and gas platforms wind turbine structures face significantly higher fatigue loads from wind and waves. Thus the grouted connection's fatigue behaviour is usually decisive for the design.

Experiences from onshore wind turbines (cf. [11,12]) as well as ballastless railroad tracks showed effects of attrition of concrete caused by alternating loads and pending water. Furthermore, investigations on reinforced concrete specimens by Waagaard et al. [13,14] and Nishiyama et al. [15] as well as investigations on concrete material specimens by Nygaard et al. [16], Soerensen [17] and Hümme [18,19] exhibited similar interactions between water and concrete.

Within the joint research project 'GROWup – Grouted Joints for Offshore Wind Energy Converters under reversed axial loadings and up scaled thicknesses' the Institute for Steel Construction, Leibniz Universität Hannover focuses on the load bearing and fatigue behaviour of grouted connections. The aim is to review and improve the current design methods for grouted connections of lattice offshore wind turbine substructures. Therefore a series of small- and large-scale fatigue tests is conducted.

The small-scale fatigue tests were carried out in dry and wet ambient conditions (AC) and revealed a significant impact of the AC (cf. [20,21]). Submerged specimens endured a lower amount of load cycles compared to specimens tested in dry AC. Thereby, the before mentioned investigations were confirmed. Moreover, for tests in wet AC a loading frequency dependent fatigue behaviour was identified (cf. [22]) leading to less endurable load cycles at higher loading frequencies. The investigated frequencies were in the range of 0.3 Hz to 10 Hz. Soerensen [17] also found a frequency effect for material specimens but with a contrary correlation leading to more endurable load cycles at higher loading frequencies. Based on these test results the main attrition mechanisms introduced by water were identified (cf. [23]) as hydro lubrication in the interface between steel and grout, flushing of crushed grout (cf. [24] and crack initiation caused by water overpressure. Thus far, the transferability of these findings to real-scale structures was questionable due to unknown scale effects. Nevertheless, based on these results [20] Germanischer Lloyd [25] recommends to reduce the number of endurable load cycles for submerged grouted connections by a factor of 10.

The large-scale fatigue tests so far focused on the fatigue behaviour in dry AC for two different grout materials and two different grout layer thicknesses. The resulting damage patterns of the grout section (cf. [26]) confirmed the observations by Karsan et al. [1] and Lamport [2]. Additionally, a lower load bearing capacity and therefore a lower fatigue resistance was identified for a larger grout annulus (cf. [27]).

In the following large-scale fatigue tests in wet AC will be presented and evaluated. Objective of the investigation is to identify the effect of water on the fatigue performance of the large-scale grouted connection and to evaluate the transferability of the small-scale test results to real-scale connections.

2 MATERIALS AND METHODS

2.1 Specimens

To investigate the fatigue behaviour of grouted connections two different large-scale specimen geometries are chosen. Geometry 1 (cf. Figure 2) has a large grout layer thickness of t_g ~ 180 mm and is in scale of ~1:2 to a real jacket structure. In contrast to that, geometry 2 has a larger pile diameter (D_p ~ 600 mm) and therefore a smaller grout layer thickness of t_g ~ 80 mm. The second geometry corresponds to a tripod structure in a scale of ~1:4. Both geometries are equipped with

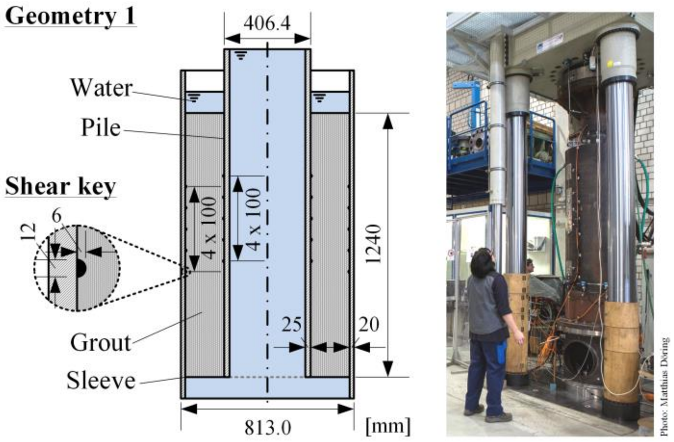

Figure 2: Geometry 1 of large-scale specimens (left) and specimen in test rig (right)

shear keys made of weld beads and positioned in the centre of the connection.

For the following evaluation four tests results from the experimental scope of 'GROWup' are chosen listed in Table 1.

The chosen specimens are filled with an industrial grout product characterised by the following mechanical properties according to the manufacturer:

- f_c = 140.0 N/mm²
- f_t = 8.6 N/mm²
- f_{bt} = 18.4 N/mm²
- E_c = 50'900.0 N/mm²

The steel tubes are standard profiles according to EN 10210-2 with a material strength of S355.

2.2 Ambient Condition (AC)

The specimens tested in wet AC have a steel plug sealing at the lower end of the sleeve and the sleeve tube is extended beyond the grout section forming a water collar. Moreover, the pile has a water outlet which connects the sleeve interior with the water collar. So filling the sleeve with water above the outlet level automatically fills the collar and connects both water columns.

Waargaard [13] investigated different hydrostatic pressures corresponding to surface level (0 bar), 70 m (7 bar) and 140 m (14 bar) water depth. He found only a minor influence for the water pressure. The fatigue behaviour of his specimens was distinctly dominated by local water movement caused by loads acting on the specimens. Consequently, the water pressure of the grouted connection tests is kept comparable to surface level.

For the tests tap water is used due to several reasons. At first, salt acts as a catalyst for the corrosion process of steel. Nevertheless, this process is to slow to influence the 3 weeks lasting tests, but it might harm the test facility. Secondly, salt affects the chemical reactions of the grout, especially during the first hours of curing. The grout material used for the tests has to be mixed with tap water likewise in an offshore application. Since the grout annulus of the specimens is dry during grouting, salt ingress into the fresh grout is excluded. All further reactions proceed at a similar time scale as the corrosion and therefore can be neglected for the short term tests. Finally, salt increases the density of water. In the North Sea the average salinity amounts 3 % and corresponds to a density increase of ~3 %. This density difference might influence the water ingress. But the necessary effort to protect the test facility against saltwater is not proportional to the assumed influence of saltwater on the fatigue behaviour.

2.3 Load scenario (LS)

Fatigue tests are always a compromise between a realistic loading situation and an acceptable test duration. Aim of the large-scale tests is to cause a fatigue damage in the grout section and identify the damage mechanisms. Since the specimen's geometries exceed the ranges of application of current fatigue design approaches [6,7], it is not possible to pre-identify the moment of failure. Thus, an incremental load increase is chosen where each load level is applied for 100'000 load cycles.

Figure 3 shows the planed load scenarios (LS) as well as the calculated characteristic capacities of the specimens. It is noticeable that the ULS capacity varies distinctively between DNV-OS-J101 [7] and ISO 19902 [6] even though the DNV design method was derived from the ISO method. But the ISO method considers the full grout layer length minus some vague non-structural lengths at the grout layer ends to be load transferring. In contrast to that, the DNV method considers only the shear key spacing length times the number of shear keys to be load transferring. This is also the reason for a lower capacity for tensile loading.

For the Fatigue Limit State (FLS) capacity only the simplified approach according to ISO 19902 [6] is include in Figure 3. The more sophisticated approach of DNV-OS-J101 [7] requires a numerical model and will be part of future investigations. From the calculations a fatigue failure can be expected for the large grout layer in LS 3 and for the thin grout layer in LS 4. Hence, the loading levels seem to be quite high and the number of load cycles quite low compared to real loading situation. Nevertheless, N = 100'000 corresponds to the high cycle fatigue range.

The LS 1-3 with a loading ratio of R = -1 are a worst case scenario since real fatigue loading ratios are mainly in the range of R = -3 to pure compression.

For the specimens tested in dry AC, the loading frequency was varied between 1 and 2 Hz. Both specimens tested in wet AC are loaded at a constant frequency of 1 Hz to exclude effects of the known loading frequency effect for submerged grout connection tests (cf. [22]).

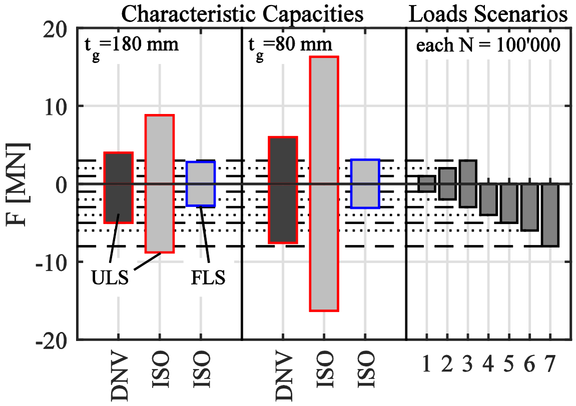

Figure 3: Calculated characteristic capacities of the large-scale specimens according to current design standards and applied load scenarios of the fatigue tests

2.4 Test procedure

Preparation

After the steel tubes are equipped with test rig adapters and shear keys their surfaces are brush cleaned from loose scale. After cleaning the surface quality corresponds to SA2 of ISO

8501-1 which is controlled by several tactile roughness measurements.

Grouting

For the grouting the specimens are completely dry and the lower end of the grout annulus is sealed with a form board. The grout inlet is positioned at about 100 mm above the form board. Thus the annulus is filled from below and the premix is pumped to the top level of the connection. It is assumed that the lower material quality of the premix has little impact at this level because the main loads are transferred in the area of the shear keys. Furthermore the premix is disposed directly from the hose before filling the specimens.

Unlike in real application the specimens are kept dry during grouting to exclude the influence of a submerged grouting process from the test results. Investigations within 'GROWup' carried out by the Institute of Building Material Science, Leibniz Universität Hannover are focused on submerged grouting processes (cf. [28]).

After grouting the specimens are stored for at least 28 days to cure. During the first 24 hours the top surface of the grout is kept moisty to reduce dry shrinkage of the material. Additionally the form board is kept in place for at least 7 days.

The process of material preparation as well as grouting is accompanied with typical material property tests such as slump tests for the fresh grout and strength tests on cubes and cylinders for the hardened grout. Moreover, the grouting process is supervised by experts from the material manufacturer.

Testing

The specimen is filled with water 24 h before applying the first LS. This early submerging allows for the water to ingress into the grout surface as well as the interface between steel and grout and lead to a water saturation of the grout comparable to a real submerged application. The specimen is permanently fed with fresh water at a low level to keep a constant water level but not to realize a circulation. The draining water is filtered to identify flushed loose grout. The filter consists of three stages with 250 µm, 106 µm and a sedimentation tank (cf. Figure 7).

While testing the displacement of hydraulic cylinder u, as well as the applied force F is measured and recorded. Further measurements are carried out but they will not be discussed in this paper.

3 RESULTS AND DISCUSSION

3.1 Material properties

As stated before, all tests were accompanied by material property tests. Their results are given in Figure 4, as strength evolution over time on the left hand side and the strength at first day of large-scale tests on the right hand side. All final properties are higher than provided by the manufacturer, but for the prism specimens a large scatter band is visible and the mean values are not steadily increasing over time.

For the first day of test the mean values as well as the 95 % confidence interval (CI) according to student's t-test are shown. Due to the fact that the CIs are overlapping, as favoured a statistically significant difference between the material batches cannot be determined. Therefore, an influence of the real material strength on the large-scale test results is assumed to be of minor relevance.

Table 1: Specimens chosen for evaluation

Specimen	t_g [mm]	AC	Failure
Test 1	~ 180	dry	LS 7 (N~200)
Test 2	~ 80		no failure
Test 5	~ 180	wet	LS 1 (N~95'000)
Test 6	~ 80		LS 2 (N~11'000)

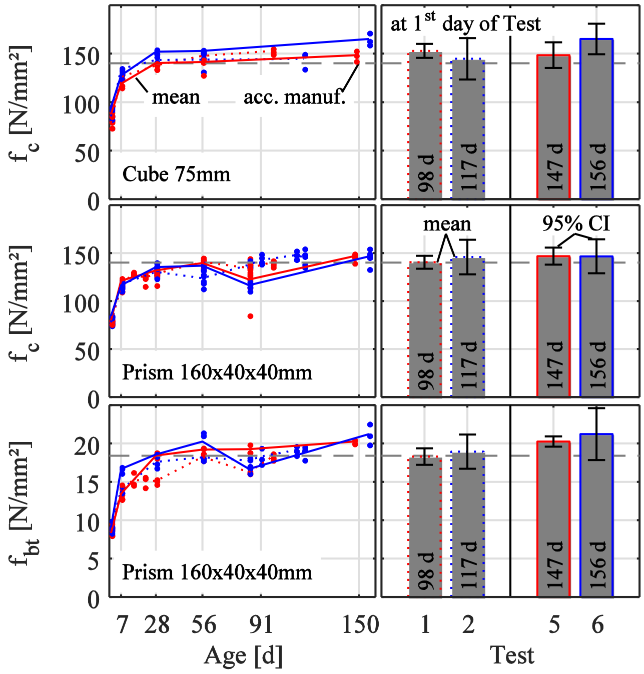

Figure 4: Evolution of material properties (left) and final properties during test (right)

3.2 Number of endurable load cycles

Both specimens tested in wet AC failed at much lower LS compared to their dry counterparts (cf. Table 1). Specimen 5 with large grout annulus failed at N ~ 95'000 of the first LS while the corresponding specimen 1 failed at N ~ 200 of LS 7. Specimen 6 with the small grout annulus failed at N ~ 10'000 of LS 2, while for specimen 2 no definite failure could be detected after LS 7 was applied.

First off all, these results confirm the findings of the small-scale fatigue tests regarding the influence of water reducing the number of endurable load cycles [20,21]. And secondly, the influence of the grout layer thickness reducing the fatigue performance [27] is also valid for tests in wet AC.

To which extent the chronology of the LS and an undetected predamage influences the fatigue performance cannot be evaluated on the basis of these results.

3.3 Displacement behaviour

Figure 6 shows the applied load F_{IST}, the resulting cylinder displacement u_{IST}, the mean displacement u_m as well as the peak to peak value Δu along the number of applied load cycles N, separated for each LS.

Specimens 1, 2 and 6 show a similar displacement behaviour for LS 1. After a slight initial increase u_m decreases during the first ~30’000 load cycles. Afterwards u_m stabilises, which is significantly pronounced for specimen 6. In contrast to that, u_m of specimen 5 decreases constantly until N ~ 80’000 load cycles. Subsequently the decrease elevates and the specimen fails at N ~ 95’000. In LS 2 u_m of specimen 6 shows a similar behaviour as u_m of its counterpart specimen 2. But after N ~ 8’000 load cycles the decrease u_m elevates and the specimen fails at N ~ 11’000.

It has to be emphasized, that Δu remains constant if the specimen does not fail in the current LS. Therefore an increase of Δu can be assumed to be an indicator for an approaching failure.

Besides the presented measurement data, for the tests in wet AC a relative displacement between grout and sleeve in the magnitude of the cylinder displacement was observed during the tests. This leads to the assumption that the main degradation occurs in this contact interface.

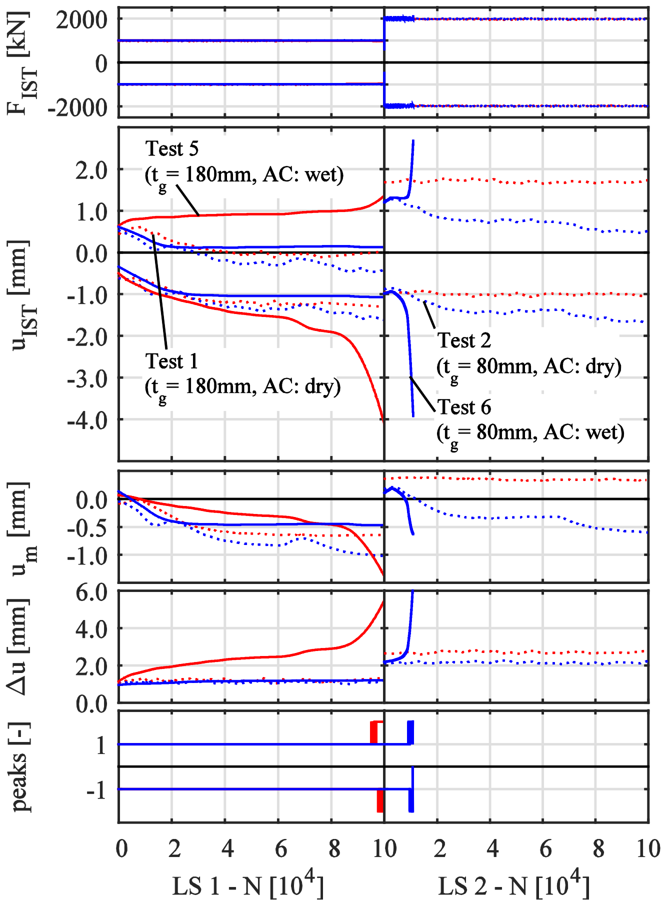

Figure 6: Applied force and resulting displacement of the hydraulic cylinder over number of applied load cycles

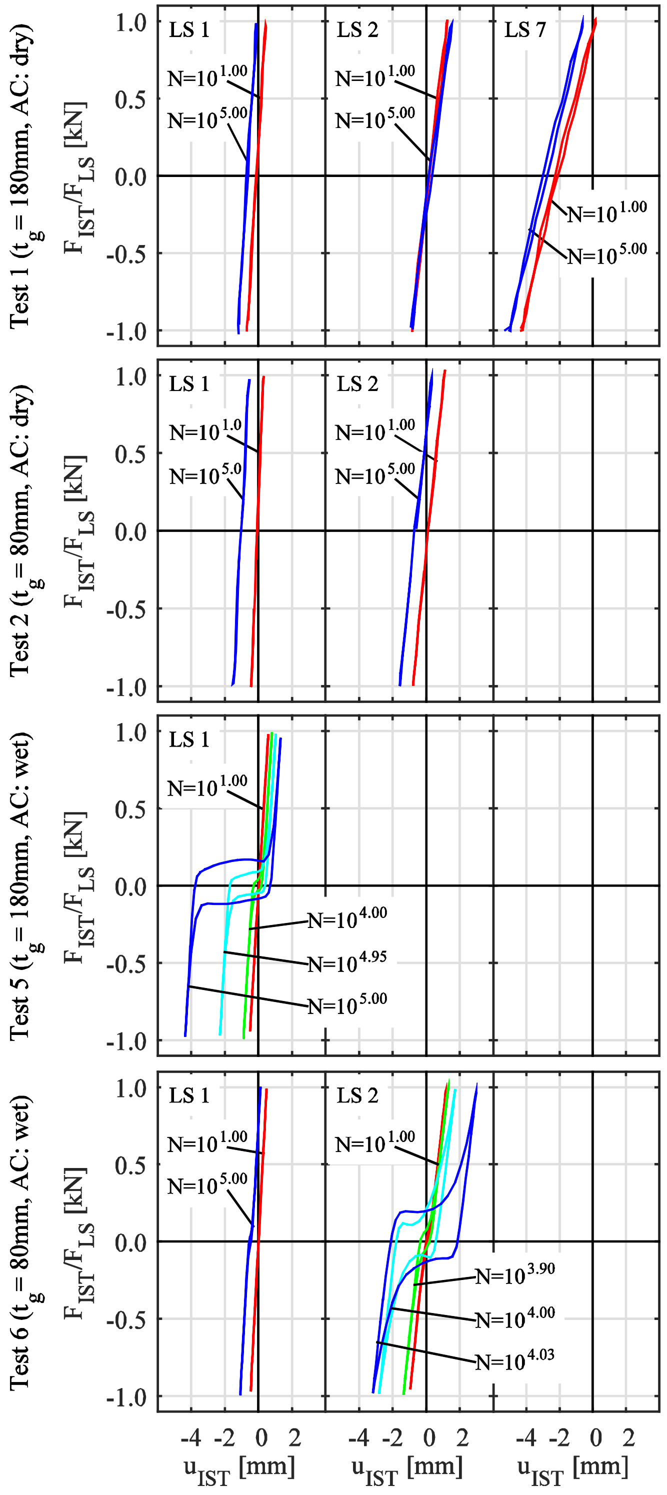

Figure 5: Force-displacement hysteresis evolution of all specimens for selected load cycles of LS 1, LS 2 and LS 7

3.4 Stiffness degradation

A hysteresis loop shows the stiffness behaviour of a specimen. For the tests carried out in dry AC one of the first and one of the last hysteresis loops of LS 1, 2 and 7 are plotted in Figure 5. Besides the previously described mean displacement offset both specimens show no significant stiffness degradation. The slight inclination between the LS is caused by the diagrams normalised axis scaling.

For specimens 5 and 6 an opening of the hysteresis loop can be detected. Especially close to the moment of failure Δu increases distinctively. Interestingly, this displacement is concentrated around the neutral point of the applied load and will be described as slack in the further reflection. For specimen 6 a slight kink at the neutral point is already visible at the end of LS 1. But during the LS of failure this displacement increases significantly. Usually a hysteresis loop has two peak values, the lower and the upper end. For the opened hysteresis loops of specimen 5 and 6 two additional (cf. Figure 5, blue lines) peaks can be detected. The lowest diagram of Figure 6 shows the number of peaks detect for each hysteresis loop of specimen 5 and 6 and separated between tension (positive) and compression (negative). The peak detection shows a correlation between number of peaks and failure of the specimen. Moreover, it shows the lower capacity of the specimens for tensile loading, since the number of peaks increases at first in the tensile direction. It should be highlighted, that after the neutral point slack is passed through the specimen's stiffness remains comparable to its initial stiffness.

3.5 Grout flushing

Similar to the small-scale fatigue tests [24], grout flushing was observed during the submerged large-scale fatigue tests (cf. Figure 7). The concentrated local load application of the shear keys leads to grout crushing in front of the shear keys. The water pumped through the interface between steel and grout flushes these loose particles out of the connection.

As described before, three sizes of loose grout could be detected. Most of the loose material was found in the specimen after disassembling the water seal. And as the three stages filter of the water hose in Figure 7 shows, the main fraction of the loose material was smaller than 106 µm and hence was caught in the sedimentation tank. It should be assumed that parts of material below this size were flushed through the outlet. Therefore, a reliable volumetric or weight evaluation was not possible.

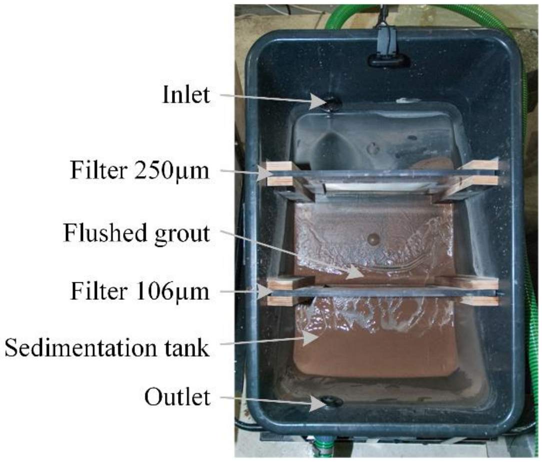

Figure 7: Three stages filter for AC water after Test 5 including flushed grout

For specimen 5 which degraded over the full LS 1 a higher amount of flushed grout was observed compared to specimen 6 which failed mainly degraded within 10'000 load cycles. Accordingly, the failure mechanisms of specimen 5 and 6 are slightly different.

4 CONCLUSIONS

This paper is addressing four large-scale tests on axially loaded grouted connections. The tests revealed significant influences of the grout layer thickness and the ambient condition on the fatigue performance of grouted connections. Independent of the ambient condition (AC), a larger grout layer thickness leads to a lower fatigue capacity. Same counts for a wet AC which reduces the number of endurable load cycles significantly.

The damage behaviour seems to differ between tests in dry or wet AC. Specimens tested in dry AC fail within a few load cycles and without showing a large degradation beforehand. Their failure can be detected as a sudden incapacity of carrying the applied load. In contrast to that, specimens tested in wet AC degrade over a larger number of load cycles and then fail by means of a significant slack between grout and sleeve. This slack leads to an instable state of force transfer, but not to the incapacity as seen for the dry AC tests. This long-term degradation was also observed for small-scale specimens loaded at a low load level [24]. Overall, the submerged large-scale tests show good agreement with the small-scale tests and therefore, the small-scale results seem to be transferable to real-scale structures.

The degradation of the submerged large-scale tests is assumed to consist of the following processes. Autogenous shrinkage of the grout leads to an initial gap between sleeve and grout. The applied full reversal loads lead to local crushing of the grout in front of the shear keys due to a concentrated force transfer. Water invading in the initial gap flushes out the loose grout leaving clearance around the shear keys. This clearance leads to a slack of the connection on a global scale and a hammering effect of the shear key on a local scale. Finally this degradation ends in an instable load transfer and an unreliable connection.

As proposed by Germanischer Lloyd [25] a reduction of the number of endurable load cycles for submerged connections by a factor of 10 seems to be a suitable precaution. Nevertheless, this paper shows the first two results of large-scale tests focusing on the influence of water on the fatigue performance. Thus, for a reliable consideration of these effects in the fatigue design of grouted connections further investigations are needed.

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