Fatigue Life of High Performance Grout for Wind Turbine Grouted Connection in Wet or Dry Environment

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Publication date:
2011

Document Version
Accepted author manuscript, peer reviewed version

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PO. 178

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Abstract

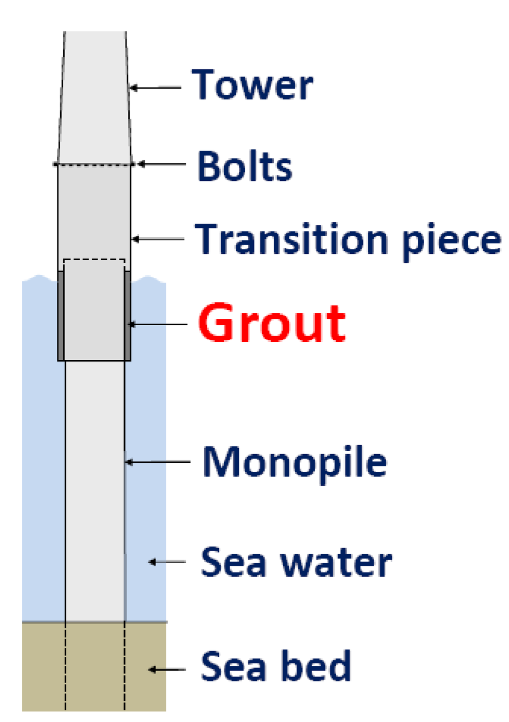
Grouted connections of monopile supported offshore wind turbine structures are subjected to loads leading to very high oscillating service stresses in the grout material.

The fatigue capacity of a high performance cement based grout was tested by dynamic compressive loading of cylindrical specimens at varying levels of cyclic frequency and load. The fatigue tests were performed in two series: one with the specimens in air and one with the specimens submerged in water during the test.

The fatigue life of the grout, in terms of the number of cycles to failure, was found to be significantly shorter when tested in water than when tested in air.

Introduction and Objective

The figure to the right shows the principle of a grouted connection, i.e. a grout filled annular space connecting the supporting monopile to the transition piece which is then bolted to the tower of the offshore wind turbine.



Grouted connection

Recently it was found that grouted connections tend to have their load carrying capacity reduced with time when subjected to alternating dynamic bending moments from wind and waves acting on the structure [1].
Such action induces high periodic stresses locally at the grout ends which may lead to local fracture and crumbling of the grout. Furthermore, it has been found that the fatigue capacity of concrete is reduced when the concrete is tested in water rather than in air [1].

The objective of the present study was to investigate the fatigue capacity of a high performance grout material designed for grouted connections, in air as well as in water.

Grout Material

The investigated grout was a commercially available product based on a high performance cementitious binder material, containing microsilica and other mineral additions, and being prepared at an ultra-low water to cementitious material ratio using superplasticizing admixture. The aggregate was natural sand (0 - 4 mm).

Mechanical properties of the grout were measured after 28 days curing in water at 20°C [2] with the following results:

Compressive Strength (Cubes, 100 mm):	**141 MPa**
Flexural Strength (Mortar Bars,40x40x160 mm):	**18.4 MPa**
Splitting Tensile Strength (Cylinders, ø100x200 mm):	**8.6 MPa**
Modulus of Elasticity (Cylinders, ø100x200 mm):	**50.9 GPa**
Poisson's Ratio (Cylinders, ø100x200 mm):	**0.199**

Fatigue Test Procedure

Cylindrical specimens, 60 mm in diameter and 120 mm high were cast and stored in water at 20°C until testing.
First, the static compressive strength was determined using 6 specimens. Then another 6 specimens were tested in cyclic compressive loading, force controlled, with a minimum force of 20 kN, corresponding to a stress of 7.1 MPa, and the specified maximum force/stress, applied sinusoidally at a constant frequency. The cyclic loading was continued until the specimen broke, or until it had passed 2 million loading cycles.

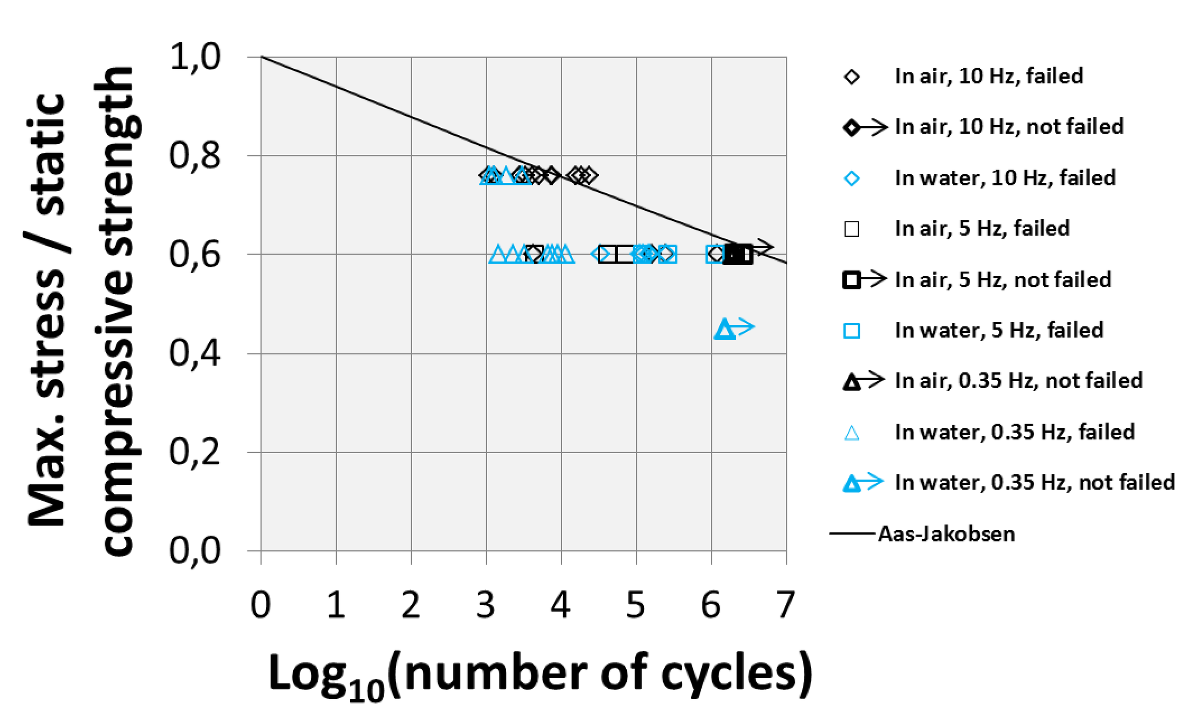
During the test the free (curved) surface of the specimen was surrounded by either the ambient air or by water held in a container surrounding the specimen. Tests were run at constant frequency at three levels: 0.35 Hz (simulating real-time wave action), 5 Hz, and 10 Hz, and at three load levels: 45%, 60%, and 76% of the static compressive strength. At the time of test the specimens were between 4 and 26 months old and had a static compressive strength of about 170 MPa

Results and Discussion

The result for each individual specimen is shown in the table below. In general, each test series comprised 6 specimens. However, at 0.35 Hz it takes more than two months to reach two million cycles, for which reason such test series were limited to a few specimens.
At the 60% stress level all combinations of test environment and load frequency were investigated.

Max. stress level (% of stat. compr. str.)	Environment	Max. number of cycles at frequency: 0.35 Hz	5 Hz	10 Hz
45%	In water	>1,537,229		
60%	In air	>2,000,000 >2,000,000	>2,666,547 >2,042,980 >2,039,759 71,161 41,554 4,364	>2,000,007 >2,000,007 1,223,862 247,247 164,451 4,212
60%	In water	11,640 9,158 7,714 6,744 3,248 2,287	260,964 135,153 119,684	260,243 151,062 148,605 123,141 113,094 33,324
76%	In air			23,535 15,554 7,486 5,076 4,180 2,823
76%	In air			18,496 7,787 3,337 2,853 1,300 1,096
76%	In water	3,012 1,843 1,491 1,264 1,261 1,133		

When the general scatter of fatigue results is taken into account the figure below shows that the results for the specimens tested in **air** (shown in **black colour**) are in agreement with similar results for ordinary concrete which in turn are well represented by the relationship proposed by Aas-Jakobsen [5].

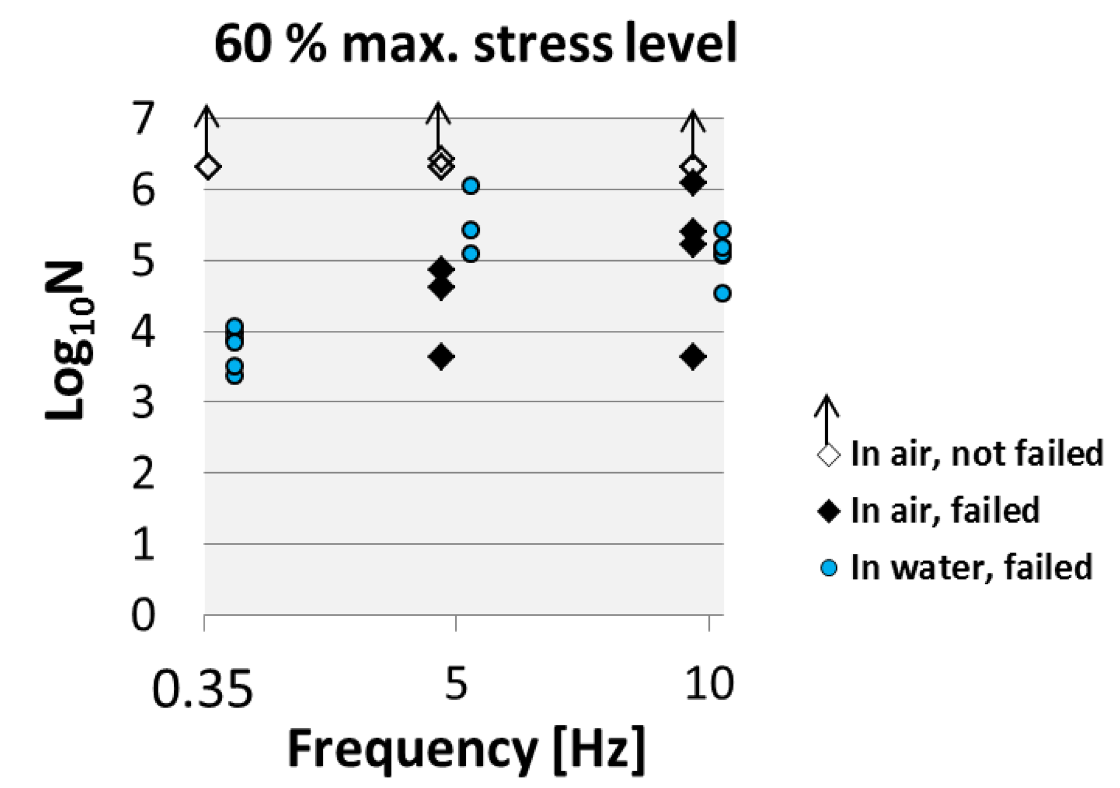


However, the specimens tested in **water** (shown in **blue colour**) exhibit markedly lower fatigue strengths. This can also be seen in the succeeding figure showing the fatigue results at the 60% maximum stress level. At all frequencies, testing in water led to lower fatigue strengths than in air, where several of the specimens in each series survived more than 2 million cycles.

The fatigue life in air is almost independent of the loading frequency, as expected [4]. In water, however, the specimens showed significantly lower fatigue strength at 0.35 Hz than at either 5 Hz or 10 Hz.

Possible differential strains induced by moisture gradients in the partially dried specimens in air [3] would not be able to explain the phenomenon, since the saturated specimens exhibit the lower fatigue capacity.

It has also been suggested that the reduced capacity of wet specimens was the result of a wedging action of water trapped in cracks [6].



The general mechanism leading to failure of concrete under loading is the progressive formation of micro cracks. If water is trapped in the microstructure and in the larger pores during compression it may exert pressures high enough to contribute to crack opening and further crack formation. As more micro cracks are formed they will tend to merge and ease the ingress of the surrounding water. This should be expected to be particularly pronounced for a high performance grout due to its more brittle nature.

Also, water pumping back and forth in the micro cracks and the pores could be suspected to cause degrading erosion – although no evidence to that effect could be observed by visual inspection after the test.

The fact that the greatest reduction of fatigue life in water compared to air was observed at the (very) low frequency of 0.35 Hz might be explained by the lower frequency providing more time during each load cycle for sufficient water ingress and pressure build-up to cause damage.

Conclusions

When tested in air it has been found that the high performance cement based grout investigated had a fatigue life comparable to that of ordinary concrete.

When tested in water, however, the grout exhibits drastically shorter fatigue life at stress levels of 60% of the static compressive strength and above.

In air, the frequency of the loading (0.35 Hz, 5 Hz, and 10 Hz) has no influence on the fatigue strength.
In water, however, the fatigue capacity is substantially lower at 0.35 Hz than at either 5 Hz or 10 Hz.
Thus, the reduction of the fatigue life by testing in water is particularly severe at the lowest frequency of 0.35 Hz.

It is suggested that the reduced fatigue capacity is due to water being trapped during the cyclic loading, exerting pressures high enough to cause progressive crack formation. This effect is more pronounced at low loading frequency with longer time available for water ingress and pressure build-up in each load cycle.

The fatigue life reduction in water was not observed at the lowest stress level investigated (45% of the static compressive strength).

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