

Modeling and Monitoring of Damage in Grouted Joints

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ABSTRACT

The present contribution is directed towards the concept of a reliable SHM system for grouted joints of the offshore wind turbines. It focuses on static and dynamic tests of a laboratory structure with a grouted joint, on a proper finite element modelling of its behaviour and damage progress. The entire structure as well as the joint itself is subjected to static and dynamic tests.

The material and structural model is validated by comparison with experimental data and non-destructive testing of the joint. Then, suitable physical parameters to be monitored are identified and introduced into the structural model. Their real values are finally determined from the measurement data of static and dynamic laboratory tests by means of suitable identification techniques.

INTRODUCTION

Offshore wind turbines are often founded on monopiles with grouted joints. Due to wind, wave and operation loads, grouted joints of this kind are subjected to extreme fatigue stresses with bending, shear and axial components. In contrast to grouted joints in the bore platforms, the ratio of bending to axial stresses is here much higher. As a result, the stress and strain state of tubes and grout material is more complex. It has already been reported that wind turbines in several offshore wind parks experienced settlements of grouted joints. In order to guarantee the target service life of 20 years, the permission authority in Germany, for example, requires installing condition monitoring systems on each 10th wind turbine in a wind park.

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Instead of diverse laboratory investigations, the deformation and damage processes in grouted joints are still not completely understood. This fact makes the development of suitable monitoring systems and the interpretation of measurements on grouted joints difficult.

A number of the offshore wind parks in the North Sea and Baltic Sea have already experienced damages of grouted joints. The same failure mode in the foundations of various manufacturers and operators indicates a common structural deficit. This specific type of connection has already been a subject of intensive research in the last years, e.g. reported in [1], [2]. In addition, measures to strengthen the existing joint type have also been discussed.

Although the progress of computer and measurement technology makes it a comparably easy task to measure a large number of structural parameters, the interpretation of that measured data demands a deep insight into the material and structural behaviour. Especially decisions on damage and failure as well as predictions of residual lifetime can hardly be done without reliable structural models. They can be successfully developed by use of experimental data, numerical simulation tools and suitable identification techniques.

However, decisions on the necessity of any action, structural as well as operational, require a system of information in which the measured data (e.g. strains or vibrations) is mapped onto the structural parameters. This task has to be done by a proper Condition Monitoring System.

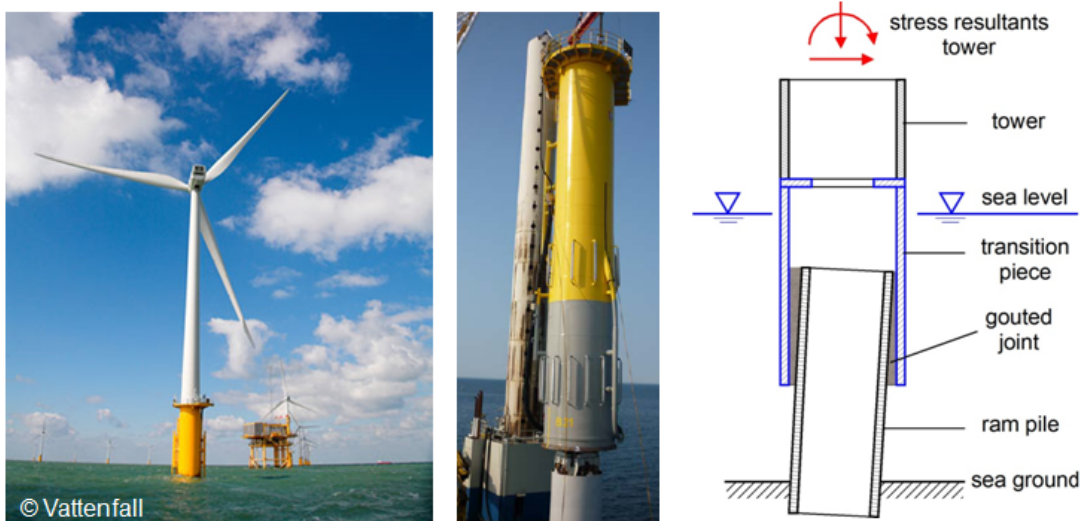


Figure 1. Monopile offshore foundation: Wind turbine, mounting, principle.

REAL STRUCTURE AND LOADING

In monopile foundations, a single pile is first driven into the seabed and then connected to the tower by a transition piece, to which the tower is flange-mounted (Fig. 1). To receive an imperfection-tolerant and relatively easy-to-fit connection between the driven pile and the transition piece, the pile is designed of smaller diameter and the gap between the outer and the inner tube (i.e. between transition piece and pile) is filled with a special high-strength concrete, the grout material.

The construction principle itself is not new to the offshore industry, but stress states in grouted joints of monopole foundations differ significantly from those of the bore platforms in the oil and gas industry, mainly due to high bending stresses and high-cycle fatigue loading. This causes fatigue failures and leads to progressive stress redistribution within the joint and finally results in the settlements mentioned above.

The number of load cycles in carrying structures of wind turbines is much higher than that of typical civil engineering or mechanical engineering objects. An insufficient database for ultra high-cycle fatigue and a hard offshore environment make Condition Monitoring Systems (CMS) for foundations of the wind turbines almost mandatory. However, there are still no reliable and commercially available CMS in this field.

LABORATORY STRUCTURE

Approach

The possibilities to measure on a real structure are always limited. Costs, space and environmental conditions make it impossible to get a set of data of the size required to profoundly describe the behaviour of the structure. Beyond the measurement problems, a variety of factors such as boundary conditions (e.g. soil properties), random loads due to wind and waves as well as various imperfections affect the structural behaviour. In the author's view, investigations on a lab-size test structure help to isolate various phenomena and to efficiently develop the main elements of the monitoring approach.

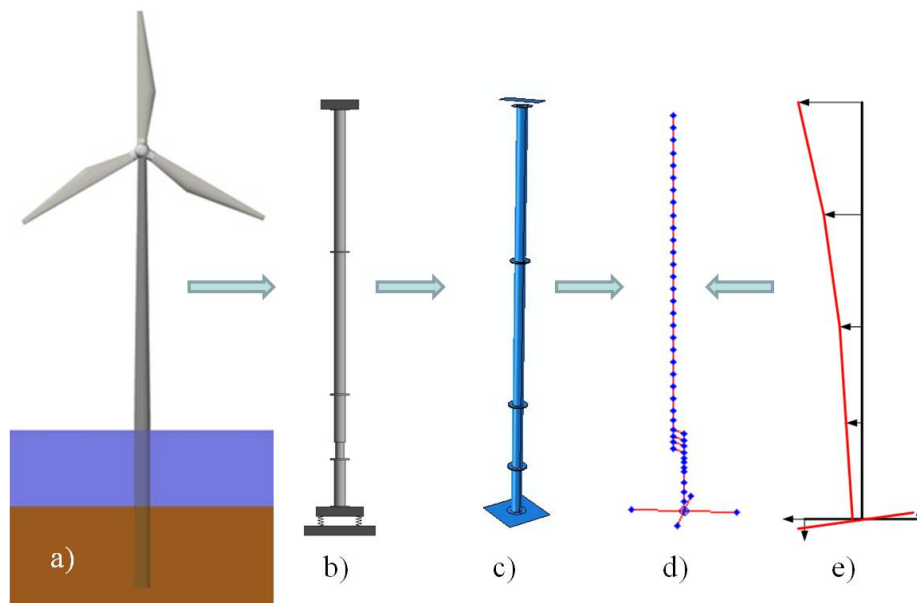


Figure 2. Modeling approach: a) real structure, b) laboratory structure, c) 3D finite element model, d) tie-and strut model, e) reduced set of measured response values

A crucial part is the model development. On the one hand, the model shall be able to accurately reflect the real structural behaviour. On the other hand, it must be as simple as possible in order to become a part of an efficient condition monitoring system. Besides, this model shall include those physical values which can be measured on the structure. Therefore, various models of the test structure can be considered depending on the goals of assessment, as shown in Figures 2 and 3. Details on the model development will be discussed in the conference presentation.

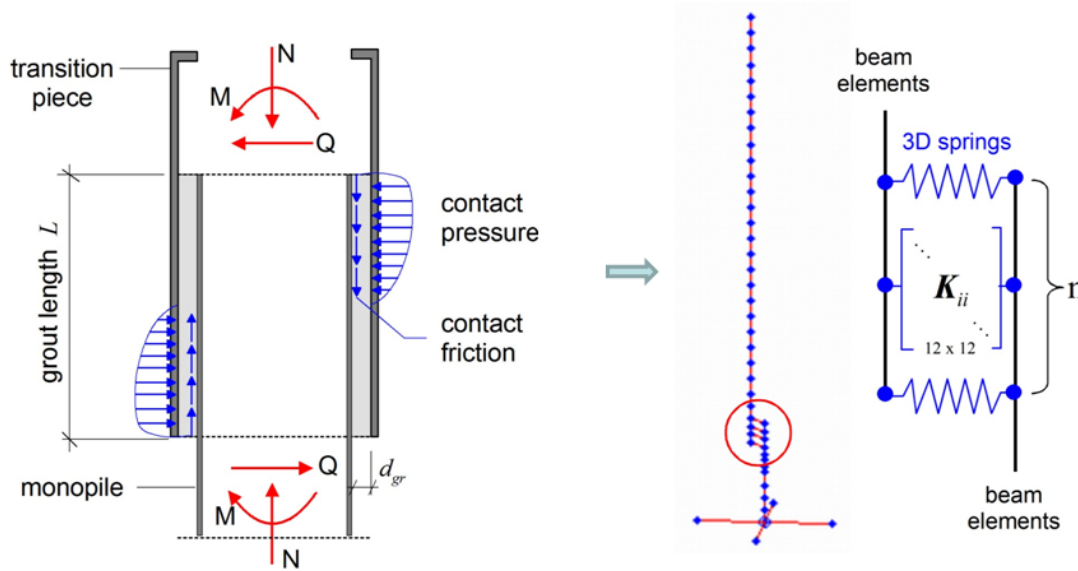


Figure 3. General stiffness terms (3D springs) represent local behavior of grouted connection.

Design

The laboratory structure developed for the present study maps the main properties of a wind turbine with monopile foundation to a scale suitable for laboratory tests (Tables 1,2). It features the possibility to vary structural parameters as well as to apply well-defined static and dynamic loads, which is essential for the validation of the model in a model updating process. The laboratory structure enables measurement on the basis of a large set of degrees of freedom of miscellaneous properties such as strain, force, displacement and velocity. In addition, parts of the structure, e.g. a section with the grouted connection, can be tested separately.

Table 1. Dimensions and scale of structures.

Property	Real struct.	Laborat. struct.	Real/Lab Ratio
Height	83.50 m	4200 mm	19.9
ø Pile	4.30 m	89 mm	48.4
ø Transition Piece	4.61 m	114 mm	40.3
ø Tower	4.20 m	114 mm	36.7
Wall Thickness	55 mm	2.0 mm	27.5
Length of Grouted Joint	6.75 m	120 mm	56.3
Gap of Grouted Joint	0.1 m	10 mm	10.0

Table 2. Properties of applied grout materials in the lab structure.

Grout Material	Young's Modulus	PR
Weicon WR	3000 MPa	0.3
Weicon F2	1750 MPa	0.3
Weicon Urethane UR65	25 MPa	0.5

MODEL UPDATE FOR GROUTED JOINTS

Structural health monitoring includes typically four tasks: objective definition, data acquisition, data processing and prediction of reference values. In context of grouted joints, the corresponding damage identification, assessment and prediction are of interest. Since damage cannot be measured directly, other physical values shall be defined which are suitable to detect and quantify damage. In the present work, we apply the finite element model update to study the changes of stiffness in the grouted joint due to damage and to define a set of measurable parameters for this purpose.

Numerical procedure

Parameter identification in engineering structures is usually related to vibration testing, since it is reasonably cheap and can be executed even under ambient excitation. Vibration testing can also be suitable for the grouted joints of the monopile foundations due to their poor accessibility under water. Parameter identification is possible not only by use of vibration data but also of static response. Although static response measurements are hardly possible for real structures, they are successfully applicable to laboratory tests.

From the mathematical viewpoint, the goal of model update is to minimize the (least square) errors of some reference response values like displacements or frequencies:

$$\boldsymbol{\varepsilon}_s = \mathbf{u}_m - \mathbf{u}_c(\mathbf{p}), \quad (1)$$

$$\boldsymbol{\varepsilon}_d = \boldsymbol{\omega}_m - \boldsymbol{\omega}_c(\mathbf{p}). \quad (2)$$

Here, $\boldsymbol{\varepsilon}_s$ and $\boldsymbol{\varepsilon}_d$ stay for the static and dynamic residual vectors (errors); $\mathbf{u}_m, \boldsymbol{\omega}_m$ indicate the measured displacement and frequency vectors, while $\mathbf{u}_c, \boldsymbol{\omega}_c$ the computed ones which depends on a set \mathbf{p} of physical parameters.

We apply a classical gradient-based update procedure for the iterative improvement of the parameter vector \mathbf{p} . Starting from an initial solution \mathbf{p}_0 and corresponding computed values of \mathbf{u}_0 and $\boldsymbol{\omega}_0$, an iterative procedure for the linearly incremented parameter values:

$$\mathbf{u} = \mathbf{u}_0 + \mathbf{G}_s \cdot \Delta \mathbf{p}, \quad (3)$$

$$\boldsymbol{\omega} = \boldsymbol{\omega}_0 + \mathbf{G}_d \cdot \Delta \mathbf{p} \quad (4)$$

with the so-called sensitivity or gradient matrices \mathbf{G}_s and \mathbf{G}_d for static and dynamic response values, respectively

$$\mathbf{G}_s = \frac{\partial \mathbf{u}}{\partial \mathbf{p}}; \quad \mathbf{G}_d = \frac{\partial \boldsymbol{\omega}}{\partial \mathbf{p}} \quad (5)$$

delivers the following update of physical parameters:

$$\Delta \mathbf{p} = \mathbf{G}_s^{-1}(\mathbf{u}_m - \mathbf{u}) \text{ (static),} \quad (6)$$

$$\Delta \mathbf{p} = \mathbf{G}_d^{-1}(\boldsymbol{\omega}_m - \boldsymbol{\omega}) \text{ (dynamic).} \quad (7)$$

Obviously, the convergence rate of the updating procedure differs for static and dynamic cases depending on the corresponding sensitivities \mathbf{G}_s or \mathbf{G}_d , respectively. For complex structural models, multiple finite element simulations are usually necessary at each iterative step to determine the elements of the sensitivity matrices.

The above procedure for parameter identification is a part of the Matfem and Update software developed at the University Kassel [3,4] and applied in the present work.

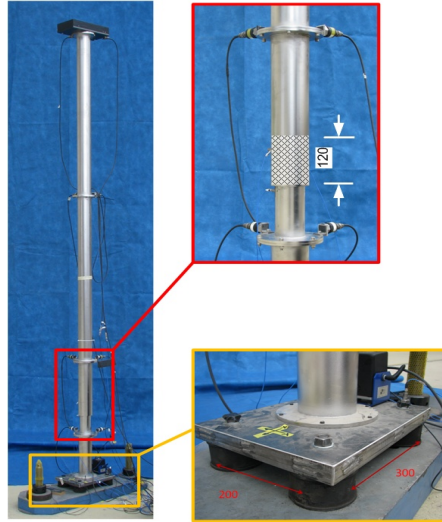


Figure 4. Laboratory structure: Modeling of structural elements.

Vibration testing

For vibration testing, the test structure has been instrumented with 16 sensors capturing accelerations at each flange, the tower top and the basis. The data processing is done with the M+P VibRunner system in combination with the S+O Analyzer software [5]. This setup enables the excitation by an electro-dynamic shaker, which is used for sweeping tests, or an impact hammer. The gained modal data is stored in the UFF file format and transferred to the Update_g2 program for parameter identification.

PARAMETER EVALUATION FROM STATIC TESTS

In addition to dynamic tests, the local deformation mechanisms acting in the grouted joint have been investigated on a four-point bending test (4PBT, Fig. 5) and an axial compression test (ACT). Urethane has been used as grout material for the first test series. Experiments with other materials are currently in progress.

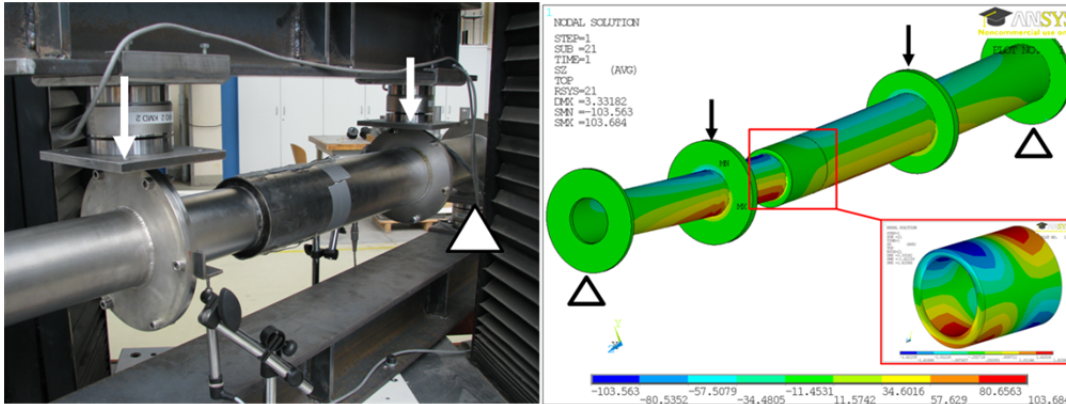


Figure 5. Test setup (left) and numerical stress plot (right) of four-point bending test.

In the bending test, applied forces, resulting displacements and local strains have been measured. The load level is selected in such a way that no damage appears in the first stage and the response remains elastic. The obtained experimental results have been compared to the simulation by use of a 3D model with shell elements for the tubes, continuum elements for the grout material and contact elements for the interface (Fig. 5). All simulations are carried out within the ANSYS software [6].

Figure 6 shows the results of the bending test with a nonlinear relationship between the flange displacements (or integral bending stiffness) and the Young's modulus of the grout material. The intersection points of numerical and experimental curves indicate the real value of the E-modulus.

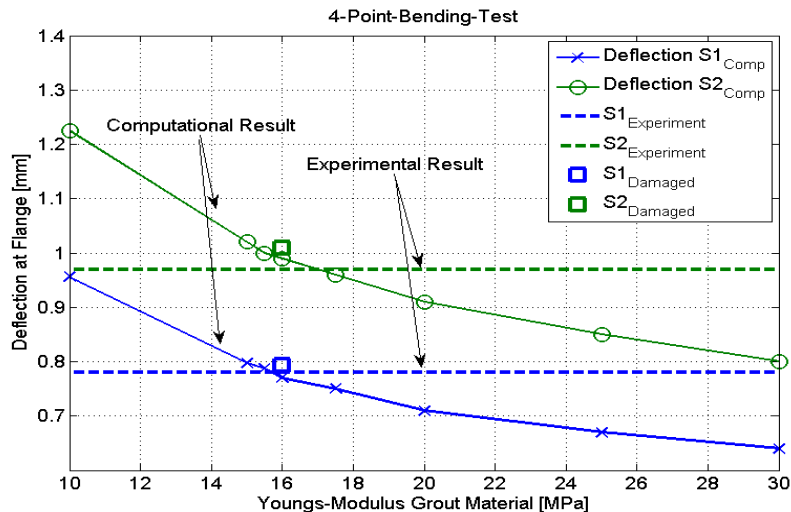


Figure 6. Identification of Young's modulus of grout material in the bending test.

Finally, different damage scenarios have been numerically investigated by use of the updated model. At that, damage effect on the representative springs of the strut-and-tie model has been identified. For instance, the reduction of the Young's modulus to 0.1 MPa in 10 out of approximately 2300 elements results in a loss of the integral bending stiffness of about 3% (Figure 6, square markers).

ONGOING RESEARCH

The work described above is the first step in the development of the Condition Monitoring System for grouted joints. The properties of the grout material determined directly from the static component tests will be then compared to the material tests and vibration tests. The goal of the first stage is to identify the real stiffness of the grout material from vibration testing. The proposed procedure will be further applied to various grout materials including also the high-strength concrete.

In the next step, the damage of grouted joint will be induced by overloading the joint section in static tests, both axial and bending. In addition to strain gauges, the deformation of the joint will be measured by means of the optical metrology system ARAMIS [7], which is able to measure 3D field displacements and strains, both static and dynamic. In addition, several non-destructive techniques will also be applied. They will help to get an insight into the stress distribution over the joint and damage mechanisms. Such information is necessary to define the best structural characteristics and locations to be measured for the state monitoring.

In the final stage, the proposed monitoring procedure will be tested on prototype structures under real conditions.

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