Model Tests and Numerical Simulations of Grouted Connections in Offshore Wind Turbines Under Low Circumferential Repeated Loads

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Research Article

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Abstract

**Background:** Grouted connection sections are widely used to connect the support structure of offshore wind turbines to the foundation, and their mechanical performance is crucial to the reliability of the whole wind turbine. In order to find a suitable stress evaluation method for the grouted connection section, finite element simulation analysis is conducted in this paper.

**Methods:** The stress analysis of the grouted connection section under different frequency loads was explored by establishing a scaled-down model and numerical analysis, and the influence of various parameters on the mechanical properties of the connection section was investigated and its engineering applicability was evaluated.

**Results:** The results of scaling tests and numerical analysis showed that the specimens without shear keys in the axial direction had the worst engineering practicality, and the specimens with shear keys in the taper had the best engineering applicability.

**Conclusions:** The results of the reduced-scale tests and numerical analysis can provide a reference for the design of grouted joint sections, and the relationship between them can be applied to the preliminary evaluation of the mechanical properties of grouted joint sections under low circumferential repeated loads.

1. Introduction

As our country becomes rich and powerful and our people become richer, we gradually realize and pay more attention to the health of our living environment while improving our living standard. Therefore, renewable resources such as wind, solar and hydro energy are gradually gaining attention [1-4]. Offshore wind energy is a clean renewable energy source, and the promotion of offshore wind farms in Europe has achieved great economic value [5-8]. The marine platform and foundation connection part supporting the wind turbine is one of the key parts to ensure the normal operation of the wind farm [9-12]. At present, many scholars at home and abroad have used numerical simulation to study the stress state near the shear keys of grouted connection sections and formed clear design specifications to guide the design [13-17]. However, this is not applicable to the actual engineering design and construction, therefore, it is necessary to conduct experimental studies on grouted connection sections [20-24]. Based on this study, low circumferential reciprocal cycle tests and numerical simulations of offshore joints with high performance grout were conducted based on the actual needs of some offshore wind farm development projects in China. The experimental results can provide a reference for the design of similar projects.

2. Low Circumferential Repeated Load Test

2.1. Experiment Overview
This experiment is based on the numerical simulation of a typical connection design specimen, a total of 8 specimens, divided into two groups, respectively: the first group: axially short specimen without shear key, axially short specimen with shear key, axially long specimen with shear key, tapered specimen with shear key, a total of 4 specimens, cyclic loading and unloading rate of 2kN/s; the second group: axially short specimen without shear key, axially long specimen with shear key, tapered specimen with shear key, a total of 4 specimens, cyclic loading and unloading rate of 6kN/s. The second group: 4 specimens with short axial non-shear bond, long axial shear bond, and tapered shear bond, with a cyclic loading and unloading rate of 6 kN/s. The axial repeated load was applied directly. The scale of the model was taken as 1:10, mainly considering the specific size and range requirements of the laboratory experimental equipment, and the detailed dimensions were set with reference to the relevant DNV specifications. The model is designed with reference to DNV specifications.

2.2. Test piece design

The experimental grouting connection section is two pipes set together and grouted between the two pipes, the height difference between the inner and outer pipe ends is set at 100 mm. the grouting material is selected through research and MASTERFLOW 9500 from BASF is chosen. the steel is selected, considering the large size of the test piece, the seamless steel pipe with better overall performance cannot be used (there is no suitable size), finally the suitable steel plate is selected as Q345, rolled and welded into a steel pipe that meets the requirements. Shear key material selection, taking into account the consistency of deformation performance, the same material as the steel, according to the design dimensions will be cut into rectangular section of the steel bar. Welding rod selected J422-3.2 ordinary welding rod, manual welding. The design parameters of the test piece are shown in Table 1.

Table 1. Specimen design parameters
| Group Classification | Short shearless keys | Long shear keys | Short with shear keys | Tapered with shear keys |
|----------------------|----------------------|-----------------|------------------------|-------------------------|
| Outer tube diameter  | 450mm                | 450mm           | 450mm                  | Upper end 450mm         |
|                      |                      |                 |                        | lower end 548mm         |
| Inner tube diameter  | 360mm                | 360mm           | 360mm                  | Upper end 360mm         |
|                      |                      |                 |                        | lower end 482.5mm       |
| Grouting length      | 700mm                | 1050mm          | 700mm                  | Upper end 312.5mm       |
|                      |                      |                 |                        | lower end 387.5mm       |
| Grouting space thickness | 39.5mm            | 39.5mm          | 39.5mm                | Upper end 39.5mm        |
|                      |                      |                 |                        | lower end 27.25mm       |
| Outer tube, inner tube and shear key model | Q345 |                 |                        |                         |
| Shear key spacing    |                      | 125mm           | 125mm                  | 125mm                   |
| Shear key height     |                      | 5mm             | 5mm                    | 5mm                     |
| Shear key width      |                      | 10mm            | 10mm                   | 10mm                    |

The effects of different loading and unloading rates can be compared between the first set of 1 specimens and the second set of 1 specimens.

The effects of different loading and unloading rates can be compared between test piece 2 of group 1 and test piece 2 of group 2.

The effect of different loading and unloading rates can be compared between the first group of 3 specimens and the second group of 3 specimens.

The effects of different loading and unloading rates can be compared between the first group of 4 specimens and the second group of 4 specimens.

2.3. Load Line

The experiment was carried out on a 1000T pressure testing machine in the structural laboratory of Dalian University of Technology, with the experimental apparatus (see Fig. 1), using axially graded
controlled loading, and a sketch of the loading process (see Fig. 2). The experiments were carried out with equal amplitude controlled cyclic loading. Each specimen was divided into 3 load control levels according to 60% of the load carrying capacity, which were 1/3, 2/3 and 60% of the load carrying capacity respectively; each load control level was cyclically loaded and unloaded 5 times according to the equal amplitude loading and unloading rate (2kN/s, 6kN/s) within the control level, and the load and axial displacement during the test were collected by IMC at the same time. Since it is not known whether the specimen will be damaged in the cyclic process, the loading should be stopped after the peak load drops to a certain extent.

2.4. Experimental procedure

In this experiment, the load was loaded in equal-amplitude controlled segmental cycles. Each specimen was divided into 3 load control levels according to 60% of the load carrying capacity, which were 1/3, 2/3 and 60% of the load carrying capacity respectively; each load control level was cyclically loaded and unloaded 5 times according to the equal amplitude loading and unloading rate (2kN/s, 6kN/s) within the control level, and the load and axial displacement during the test were collected by IMC at the same time. Since it is not known whether the specimen will be damaged during the cyclic process, it should be set to stop the loading after the peak load drops to a certain extent.

3. Text Results And Analysis

According to Figure 3, the first cycle of the low-speed cyclic specimen, the displacement is very small, the hysteresis loop becomes narrow and long, and the energy dissipation capacity is very poor; but once the second cyclic loading exceeds the control load of the first cyclic loading, the displacement produces a great change, and with the end of the first cycle, there are already signs of detachment on the contact surface of the relatively large part of the force; once the load is higher than the control load of the first cyclic loading, these contact surfaces are detached and the displacement produces abrupt changes, while the load also produces abrupt changes, and the abrupt changes of displacement and load are not very large; for the specimens with high speed loading and unloading cycles, the load cycle curves of the first two stages are almost parallel to the horizontal axis of the load, which means that the displacement produced by the first two stages of control load is very small, and the displacement produced by the second stage of control load is almost negligible compared with the specimens with low speed cycles. The damage loads of the two loading and unloading rate specimens are almost the same, both are about 60T. In comparison, it can be considered that the low-rate cyclic loading and unloading specimens belong to ductile damage and the high-speed cyclic loading and unloading specimens belong to brittle damage.

According to Figure 4, the energy consumption capacity of the low-speed cycle is better than the high-speed cycle; the displacement jump at the beginning is due to the leveling stage, due to the test piece and experimental equipment, the displacement jump during the initial loading; as for the reason that the displacement did not recover is still being further explored; it is easy to see from the comparison that the
energy consumption capacity of the active force end is better than that of the passive force end; the test piece is too long due to the test time. In this test, because the test time was too long, the tester could not work continuously for such a long specimen, so we had to suspend the experiment, and the experiment was stopped at the end of the complete cycle of the second level control load, in which we stayed for two hours to make the tester cool down, and then continued the loading experiment of the third pole control load cycle; the final displacement of the specimen loaded by the low-speed cycle was smaller than that of the specimen loaded by the high-speed cycle, which was the same as expected before the experiment. This is the same as expected.

According to Figure 5, firstly, the displacement does not increase exponentially with the load, but more than the load multiplier, indicating that plastic deformation occurs inside the specimen with the increase of the low circumferential load. The final displacement of the lower part of the displacement is larger than the upper part, which is determined by the loading method that we use to apply the load from below.

Secondly, the top final displacement did not change greatly in the case of low-speed loading and unloading and high-speed loading and unloading, but the bottom final displacement produced a great change; the curve at the beginning of each load control level loading when the load rose was basically consistent with the curve at the first loading, but the slope of the curve of the load rise produced considerable changes in the later cyclic loading due to the presence of plastic displacement; the hysteresis loop was basically shuttle-shaped, and the energy dissipation capacity of the shorter specimen without shear bond was significantly improved; both loading rates can be considered as ductile damage.

According to Figure 6, after the first cycle of loading and unloading of the first level of control load, the specimen produces a large plastic displacement inside the specimen, and these plastic displacements are not recovered in the process of subsequent cycles, and are only recovered to a certain extent before the third level of control load loading at low speed; under the same load control level, the axial displacement of the specimen under high speed loading rate is larger than that under low speed loading control when the same size of load is applied.

The axial displacement of the specimen under high speed loading rate is larger than that under low speed loading control. The size of the hysteresis loop reflects the size of the energy dissipation capacity of the specimen, which means that the energy dissipation capacity of the low speed cycle is better than that of the high speed cycle.

4. Numerical Simulation

4.1. Finite element modeling

Using ANSYS modeling, Solid186 unit was used for both the inner and outer steel pipes, and Solid65 unit, an 8-node hexahedral unit, was used for the grouting material, and the William-Warnke five-parameter damage criterion was used for the calculations. The contact slip between the grout material and the outer wall of the steel pipe pile and the inner wall of the conduit frame is simulated by using Contact174 and
Target 170 cells, and the hexahedral mesh is divided. The meshing of the four groups of models is shown in Figure 7:

4.2. Finite element modeling

4.2.1. Finite element modeling

From the above figure 8 and 9, it can be seen that the specimen was damaged at the first cyclic loading of the third load level when low-speed repeated loading was applied. From the hysteresis curve of the displacement-load diagram, it is seen that the specimen has a significant residual deformation at the second load level. When a high-speed repeated load was applied, the specimens were damaged at the first cycle of unloading at the third load level. Since there is no shear bond in this group of specimens, the axial load can only be transmitted by the bond and friction between the grout material and the steel pipe wall. Slip has occurred, resulting in the destruction of the specimen.

4.2.2. Finite element modeling

It can be seen from Fig. 10 that when low-speed repeated loading is applied, the specimen is not damaged in three load levels of cyclic loading, and the displacement changes abruptly in the first load level cycle. Figure 10 represents the cracking of the grouting material, blue color indicates the cracked part of the concrete and red color indicates the intact concrete. From the figure 11, it is seen that the specimen has cracks in the shear bond area at the top of the joint section and there is also severe cracking at the bottom of the joint section.

4.2.3. Force analysis of the third group of models under low circumferential repeated loads

As can be seen from Figure 12, a high-speed repeated load is applied to the specimen and the ANSYS calculation process stops at the last cyclic load of the three load levels without convergence. However, by observing the cracks of the grouting material in Figure 13, where the blue color represents the cracks of the cells, it can be seen that the cracks are not very serious and the specimens cannot be judged to be damaged. By observing the displacement-load curve, it can be found that the plastic displacement of the third group of specimens is larger than the second group.

4.2.4. Force analysis of the third group of models under low circumferential repeated loads

The results of applying repeated loading at low and high speeds to the fourth group of specimens, shown in Figures 14 and 15, show little difference and the same plastic displacements, and similar cracking of the grout material, both with local cracking around the shear bond at the intersection of the straight and tapered sections, and cracks at the bottom of the joint section.

Discussion
Through the above two parts of the test and simulation we can compare the two and come up with the following discussion:

(1). First group of models: The load loading level in the actual test did not reach the third level of load and displacement in the numerical simulation appeared smaller gap, mainly due to the unpredictable and uncontrollable deviation in the process of making the specimen and the uncontrollable experimental error of the testing machine in the loading process; through the actual test and numerical simulation it can be seen that the energy dissipation capacity of the shorter specimen with axial non-shear key is smaller, and there is no very obvious signs before the damage, the applicability in actual engineering is not high.

(2). Second group of models: The displacement of the specimen in the actual test is larger than that in the numerical simulation, due to the unpredictable and uncontrollable deviation in the process of making the specimen and the uncontrollable experimental error of the testing machine during the loading process; the final result in the numerical simulation is not converged, while in the actual test, the displacement of the specimen changes more regularly, which is better than the result of the numerical simulation; the energy dissipation capacity of the axially longer specimen with shear bond is better than that of the shorter specimen. The energy dissipation capacity of the longer shear bond is improved compared with that of the shorter axial specimen, but the improvement is not too obvious; the bearing capacity and deformation displacement of the longer specimen are much better than that of the shorter specimen, and the applicability in actual engineering is higher.

(3). Third group of models: The displacement of the specimen in the actual test is larger than that in the numerical simulation due to the unpredictable and uncontrollable deviation during the fabrication of the specimen and the uncontrollable experimental error of the testing machine during the loading process; the actual test and the numerical simulation can jointly conclude that the energy dissipation capacity of the shorter axial shear bonded specimen is significantly higher than that of the shorter axial non-shear bonded specimen, which is more applicable in the actual engineering.

(4). The displacement of the specimen in the actual test is larger than that in the numerical simulation due to the unpredictable and uncontrollable deviation during the fabrication of the specimen and the uncontrollable experimental error of the testing machine during the loading process; the energy dissipation capacity of the conical specimen is better than that of the shorter axial shear key and the longer axial shear key; the displacement of the conical specimen in the actual test is closer to that in the numerical simulation, which means that the conical specimen has better performance than the above three specimens and has the highest applicability in actual engineering.

**Conclusion**

Through this simulation experiment, we get this conclusion through the experimental comparison and data analysis: the same height of the specimen (axially shorter with shear key and tapered with shear key), we get the bottom space of the specimen (tapered with shear key) has better energy dissipation capacity; the same height of the specimen with or without shear key (axially shorter with shear key and...
axially shorter without shear key), we can get The energy dissipation capacity of the specimen with shear
key is much higher than that of the specimen without shear key, and the low circumferential repeated
cyclic load capacity of the specimen with shear key is higher than that of the specimen without shear key;
the energy dissipation capacity of the longer specimen is better than that of the shorter specimen in the
comparison of the long and short specimens (axially longer with shear key and axially shorter with shear
key); the load displacement curves of the three control load levels of each specimen in the first cyclic
loading stage are basically the same as those of the previous load level. The curve of the first cyclic
loading remains the same, which can be said to be an extension on the basis of the previous level of
loading, but the curve is not the same in the cycle after the first cycle due to the existence of plastic
displacement.

In comparison with the numerical simulation results it is concluded that

(1) The specimen without shear bond in the axial direction mainly relies on frictional bond to provide
shear force (pressure in the axial direction), with low strength and no good energy dissipation capacity,
and low applicability in practical engineering.

(2) Longer axial shear bond specimens show good load bearing capacity, deformation capacity and
energy dissipation capacity in experiments and numerical simulations, and the specimen performance is
better than shorter axial shear bond specimens, which has higher applicability in actual engineering.

(3) The shorter axial shear key specimen showed good load bearing capacity, deformation capacity and
energy dissipation capacity in both experiments and numerical simulations, and the energy dissipation
capacity of the shorter axial shear key specimen was significantly higher than that of the shorter axial
shear key specimen, but not as good as that of the longer axial shear key specimen, which is more
applicable in actual engineering.

(4) The tapered shear key specimen shows good load bearing capacity, deformation capacity and energy
dissipation capacity in both experiments and numerical simulations. The displacement of the tapered
specimen in the actual test is closer to the numerical simulation results, which indicates that the tapered
specimen has better performance than the above three specimens and has the highest applicability in
actual engineering.

Declarations

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**Tables**

**Table 1.** Specimen design parameters
| Group Classification | Short shearless keys | Long shear keys | Short with shear keys | Tapered with shear keys |
|-----------------------|----------------------|----------------|-----------------------|------------------------|
| Outer tube diameter   | 450mm                | 450mm          | 450mm                 | Upper end 450mm        |
|                       |                      |                |                       | lower end 548mm        |
| Inner tube diameter   | 360mm                | 360mm          | 360mm                 | Upper end 360mm        |
|                       |                      |                |                       | lower end 482.5mm      |
| Grouting length       | 700mm                | 1050mm         | 700mm                 | Upper end 312.5mm      |
|                       |                      |                |                       | lower end 387.5mm      |
| Grouting space thickness | 39.5mm              | 39.5mm         | 39.5mm                | Upper end 39.5mm       |
|                       |                      |                |                       | lower end 27.25mm      |
| Outer tube, inner tube and shear key model | Q345 | | | |
| Shear key spacing     |                     | 125mm          | 125mm                 | 125mm                  |
| Shear key height      | 5mm                  | 5mm            | 5mm                   | 5mm                    |
| Shear key width       | 10mm                 | 10mm           | 10mm                  | 10mm                   |

**Figures**

*Figure 1*

Displacement-load curve.
Figure 2
Displacement-load curve.

- **Shorter non-shear key low speed cycles**
  ![Graph](image1)
  (a) The first group of first specimen cycle curve

- **Shorter non-shear key high speed cycles**
  ![Graph](image2)
  (b) The second group of first specimen cycle curve

Figure 3
The first set of load-displacement cyclic curves.

- **Longer with shear key low speed cycle**
  ![Graph](image3)
  (a) The first group of second specimen cycle curve

- **Longer with shear key high speed cycle**
  ![Graph](image4)
  (b) The second group of second specimen cycle curve
**Figure 4**

The second set of load-displacement cyclic curves.

![Graphs](image)

(a) The first group of third specimen cycle curve  
(b) The second group of third specimen cycle curve

**Figure 5**

The third set of load-displacement cyclic curves.

![Graphs](image)

(a) The first group of forth specimen cycle curve  
(b) The second group of forth specimen cycle curve

**Figure 6**

The forth set of load-displacement cyclic curves.
Figure 7
Meshing of the four groups of models.

(a) First group of model meshing  
(b) Second group of model meshing  
(c) Third group of model meshing  
(d) Fourth group of model meshing

Figure 8
Displacement-load curve.

(a) Low speed  
(b) High speed

Figure 9
The contact state of grouting material and steel pipe wall.

(a) Contact surface between grouting material and inner pipe wall  
(b) Contact surface between grouting material and outer pipe wall
Figure 10

Displacement-load curve at low speed.

Figure 11

Cracking of grouting material.

Figure 12

High-speed displacement-load curve.
Figure 13

Cracking of grouting material.

Figure 14

Displacement-load curve.

Figure 15

The contact state of grouting material and steel pipe wall.