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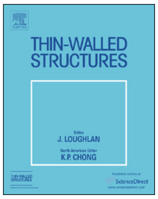

Full length article

Experimental study on ultimate bending performance of grouted connections in offshore wind turbine support structures

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ABSTRACT

This paper investigated six grouted connection specimens under ultimate four point bending test. The different eccentricity values of pile tube, overlap length and thickness of transition piece (TP) tube has been studied. It was found that all the specimens failed in a similar ductile mode. The eccentricity values had little effect on bending capacity, stiffness and ductility. However, the increased eccentricity values would aggravate the radial and inner cracks in grout material. Meanwhile, the overlap length and the thickness of the TP tube had apparent effect on bending behavior. Moreover, the effects of the eccentricity were studied and discussed by theories of composite beams in material mechanics.

1. Introduction

A number of offshore wind farms have been built or proposed in China's coastal areas, reflecting the country's decision to divert its energy supply from traditional fossil fuels to new resources. After the installation of some wind farms with gravity base foundations and high-rise pile cap foundations, monopile foundations (Fig. 1) with more challenges have been put on agenda.

Grouted sleeve connections have already been widely used in offshore platforms and buildings for many years [1–4]. They normally have two types, i.e. connections with or without shear keys. This paper focus on a relatively new application, i.e. grouted sleeve connections with shear keys for offshore wind turbines structure, more specifically monopile structures to join transition piece (TP) and driven pile with different diameters. They transfer loadings from turbine tower to foundation, including self-weight of the wind turbine, wind and wave effects on the tower, etc. Also, they can correct the imperfections of the pile introduced during the hammering process into the seabed [5,6]. In contrast to their traditional application in jacket structures for the oil and gas industry, grouted connections (GCs) in monopile structures are under predominating bending moments due to the slenderness of the structure and the load from wind and wave [7,8].

In engineering practice, imperfections in the relative position of the TP and pile are inevitable following the hammering process. The imperfections can be divided into two main types—vertical misalignment and the eccentricity of the longitudinal axis of the two tubes [9]. The former would introduce decreased effective grouted thickness at the end of the GC; this has been considered in some specifications [10,11]. On the contrary, few attentions and researches have been implemented on the eccentricity. Lamport and Jirsa [12] firstly studied imperfections in the axial capacity of the GCs through experimental testing, including the relative shear key location between the two tubes and the eccentricity. It was found that neither of them have an apparent effect on the axial capacity. Similar conclusions have been drawn by Schaumann et al. [13], who carried out linear finite element (FE) analysis to study the effect of grout thickness and eccentricity on the stress distributions in the connection under mainly axial load. Conclusions have been drawn that large grout thicknesses led to local stress concentrations at the shear keys, while eccentricity had almost no influence on the stress distribution. Although these studies have proved that eccentricity had little effect on axial capacity and stress distributions, there exists a knowledge gap regarding the influence of the eccentricity on the bending capacity of the GCs.

In contrast to the scarcity of studies on the influence of eccentricity, the bending behavior of GCs and other similar joints have been researched since the 1980s. Billington [14] presented the results of tests carried out by British Petroleum on grouted T-shaped joints under axial compressive, tensile and in-plane bending loading conditions. The tests focused on the strength improvements compared to ungrouted joints. Significant improvements in strength due to the presence of the grout

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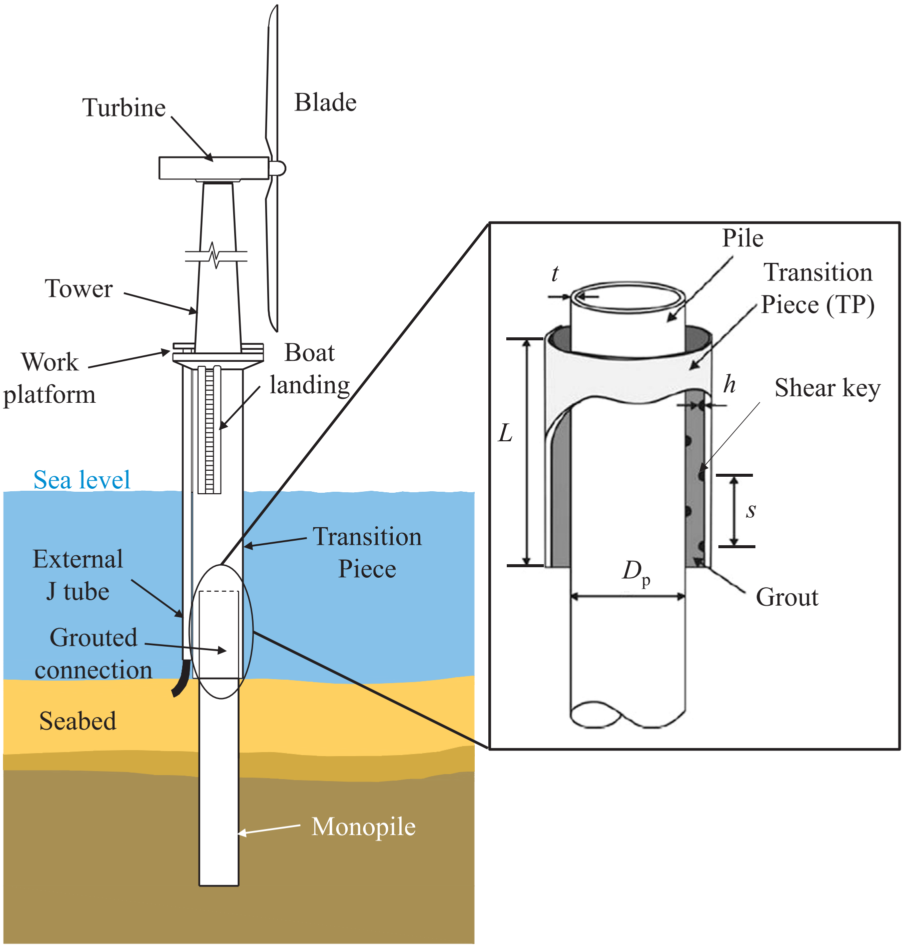

Fig. 1. Monopile offshore wind turbines structure with grouted connection details.

has been proved, which also provided information for grouted repair methods. Sele et al. [15] discussed the results of tests on prestressed grouted clamps under both pure axial load and axial load after the exertion of bending moment. It was found that the considerable bending moments had no influences on the axial capacity. This agreed with the findings of Lamport and Jirsa [12], whose research showed that moment loading had no detrimental effect on the axial capacity of a grouted pile-to-sleeve connection.

The studies above were mainly focused on axial loads, due to GCs were mainly used in jacket structures for the oil and gas industry. Nevertheless, in offshore wind industry, the concept of monopile structures have been wildly approved since it was initially introduced by Lely in 1994 [16]. And until 2016, it has represented 80.8% of total installed substructures in Europe [17]. As mentioned before the GCs were mainly under bending moment in these structures. Thus researchers had paid more attentions on the bending capacity of the GCs since 2000s, due to the widespread usage of monopile.

In 2001, model tests have been carried out by Aalborg University [6,9,18]. The specimens with and without shear keys were tested under both ultimate and fatigue bending. Andersen and Petersen [18] reported the main results of the tests, and gave their own FE calculation of the specimens without shear keys. Klose et al. [6] recorded that the grouted area should include a sufficient overlap length approximately 1.5 times that of the pile diameter, since a specimen with an overlap length equal to the pile diameter led to local buckling of the steel tube outside the grouted region. Wilke [9] presented more details about the shear key arrangement and stress distribution in the test. He also reported that no distinctive differences were found between the specimens with and without shear keys. From then on, this conclusion convinced designers that GCs without shear keys were capable of withstanding the large bending moment, until failures related to grout slippage in about 800 foundations without shear keys were reported in 2010 [19].

From 2007 to 2010, experimental studies on GC under fatigue bending moment was carried out by Germanischer Lloyd (GL) together with Leibniz University Hannover [20]. Specimens without shear keys was tested in 2007 [7]. Meanwhile, additional specimens with shear keys contained different grout material overlap lengths and strengths were tested afterwards [9]. It was found that shear keys could clearly reduce the gap at the end of the GCs. Moreover, a decreased overlap length led to increased gapping distances. Furthermore, the dynamic behaviors of the monopile structures were studied [21]. Conclusions have been made that the reducing overlap length of GCs increased the structural nonlinearities and decreased the connection's stiffness as well as the natural frequency of the structures.

In summary, bending capacity are critical for the GCs in offshore wind turbine structures and shear keys have indispensable contributions on the bending capacity. However, the effects of the inevitable eccentricity on the capacity (especially the bending capacity) of the GCs have been barely studied. Moreover, the overlap length of the GCs was a significant factor for the bending capacity. Thus, this paper designed six shear key GC specimens with two eccentricity values and three kinds of overlap lengths. In addition, the thickness of TP tube has also been studied since it decided the dynamic property and the construction cost of the monopile structures [22]. All the specimens were tested under an ultimate four-point bending moment. The failure modes, stress distribution and load versus deflection relations were recorded. The influence of eccentricity, overlap length and TP tube thickness on the