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Experimental study on grouted connections under static lateral loading with various axial load ratios

Tao Chen[a,b,*], Zican Xia[a,b], Xian Wang[a,b], Qi Zhao[a,b], Guokai Yuan[c], Jinchao Liu[c]

[a] Key Laboratory of Performance Evolution and Control for Engineering Structures (Tongji University), Ministry of Education, Shanghai 200092, China
[b] Department of Structural Engineering, Tongji University, Shanghai 200092, China
[c] China Energy Engineering Group Guangdong Electric Power Design Institute Co., Ltd., Guangzhou 510663, China

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ABSTRACT

Grouted connections are critical parts of the integrity of offshore wind turbine structures since they transfer the upper loads to the lower foundations. In this paper, grouted connection specimens were experimentally studied to investigate the interaction between bending moment and axial load. They were subjected to a horizontal loading with various axial load ratios. The mechanical behavior of these specimens such as bearing capacity, ductility and failure mode was investigated. Furthermore, strain distributions on steel tubes of grouted connection were evaluated to learn the load transferring mechanism. Experimental results showed that grouted connection specimens had good ductility and sufficient bearing capacity. With the increasing of the axial compression level, the lateral bearing capacity and ductility of grouted connection decreased.

1. Introduction

Wind energy at sea regions is enormous to be harvested and it seems to be an efficient technology considering the higher wind speed [1]. In contrast, onshore wind turbines may occupy precious land resource and make unendurable noise in heavily populated locations. Therefore, offshore wind turbines are becoming an increasingly important source of clean and renewable energy. Several types of offshore wind supporting structures, such as a jacket, tripod and monopile, have been employed in engineering practice [2–4]. The supporting structures undergo severe actions of wind, wave and dead loads. These loads are predominantly transferred to foundations through grouted connections [5–7]. For that reason, the mechanical behavior of grouted connections is critical to the integrity of the whole offshore wind turbine systems.

A typical grouted connection usually includes two steel tubes with different diameters and the grouting material filling their gap. The smaller diameter steel tube is concentrically inserted into the larger one. Shear keys are normally welded to the outer surface of the smaller tube and inner surface of the larger tube to increase the interaction between steel and grout. There is a trend that the offshore wind industry tends to locate wind farm towards deeper waters with larger wind turbines to get more power from the less turbulent wind. This imposes heavier dead load and stronger bending moment on support structures. Therefore, the mechanical behavior of grouted connections has drawn more attention in recent decades.

The grouted connections were initially adopted to connect offshore gas and oil structures to their foundations and they were mainly subjected to axial load [5,8–10]. Extensive research has been conducted on axially loaded grouted connections [11–14]. Billington and Tebbett [13] reported a comprehensive design approach for grouted connections under static axial loading. The ultimate bearing capacity was correlated to several parameters, such as radial stiffness of steel tubes and grout, diameter ratio, grout compressive strength, surface roughness, dimensions of shear keys and its arrangements. Lamport et al. [10] conducted axial loading test on grouted connections with shear keys. Compression struts in grout were observed. Similar failure patterns, diagonal cracking and crushing, were also observed for high-strength grouted connection specimens [14]. Thereafter, an analytical model and design equations [10,15,16] were proposed for axial loading capacity that mainly consists of grout compression struts and friction between grout and steel interface. The model is only applicable to specimens with small diameters and the grout strength is less than 41 MPa [10,17].

Previous research concentrates on the axial capacity of grouted connections and has achieved success in oil and gas industry for decades. The grouted technique has been introduced to offshore wind turbine support structures. Grouted connections were subjected to the

* Corresponding author at: Key Laboratory of Performance Evolution and Control for Engineering Structures (Tongji University), Ministry of Education, Shanghai 200092, China.
E-mail address: t.chen@tongji.edu.cn (T. Chen).

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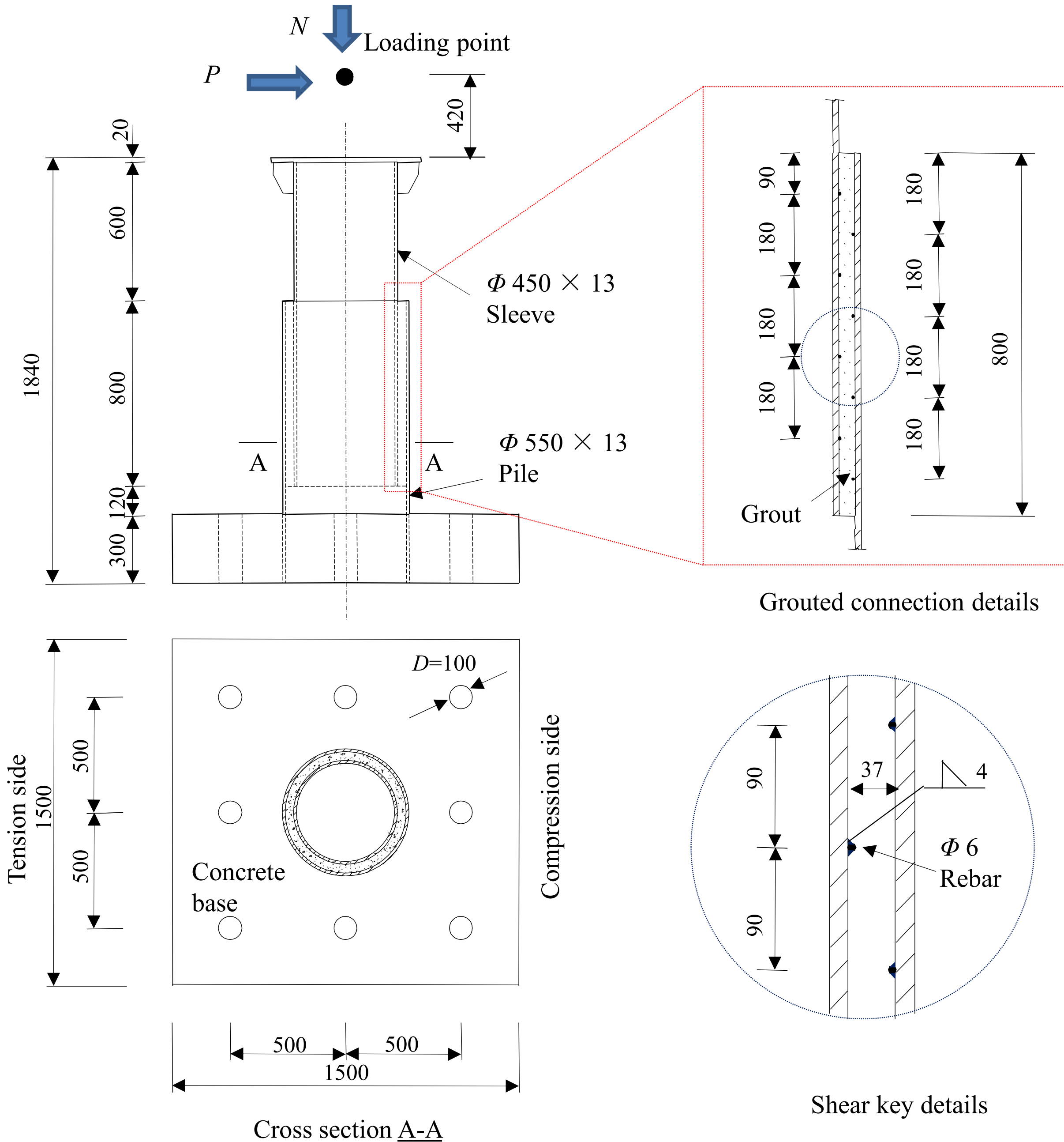

Fig. 1. Geometry configurations (unit: mm).

combination of bending moment and axial load, the load transferring mechanism of which is different from that of axial loading. However, limited data are available for the complex loadings. Lamport et al. [10] conducted series tests of eccentric loading patterns to investigate the interaction between axial loading and bending moment. Experimental results of three specimens indicated that moment had no detrimental effect on the ultimate axial bearing capacities. It should be noted that axial loads changed during test. This is not true in engineering practice since dead loads are usually constant. Their conclusions can lead to inaccurate predictions of bearing capacity when specimens were subjected to high axial load ratios [17–20]. Andersen and Petersen [21] performed numerical analysis and conducted bending tests on grouted connections. The results showed that bending capacity can be obtained without shear keys and they were adopted in the design of several wind farms in Europe. However, unexpected slippage was reported between the grout and the steel tubes [22].

Following joint industry project revealed the low long-term axial capacity of grouted connections without shear keys [5,23] could not withstand the external actions. Lotsberg [5,23,24] investigated the interaction between axial loading and bending moment. For specimens under pure bending moment, it is transferred by contact compression and interface shear stresses. They are generalized as horizontal contact compression force, the horizontal shear force, the vertical shear force due to contact pressure and friction and the vertical shear force