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Interfacial shear behavior of a high-strength pile to sleeve grouted connection

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ABSTRACT

A grouted connection is a type of structural composite connection member produced from two different-sized steel tubes and a grout annulus between them. The grouted connection has been widely used in offshore oil and gas platforms and wind turbine structures by simply grouting between the pile and sleeves. In general, the axial compression strength of the connection is known to be affected by the grout strength, shear-key spacing and radial stiffness parameters of the composite section. In this study, concentric and eccentric loading tests were performed to investigate the interfacial shear behavior of the high-strength grouted connections according to the shear-key spacings. The interface shear behaviors, focusing on the strength, failure mode, and strain of the grout and steel tubes, were evaluated by tests and finite element (FE) analysis. The test results showed that the primary strength of the connection was mainly affected by the grout strength, whereas the ultimate strength was affected by the yield strength of the sleeves and the friction coefficient between the steel tubes and grout. It was also concluded that the test results on the high-strength grouted connections were similar to those of previous studies on normal-strength grouted connections, and the eccentric loading did not reduce the axial capacity of the connection. Although the ultimate failure modes of the connections could not be considered in the current design equations, they may contribute to the safe design of high-strength grouted connections.

1. Introduction

Grouted connections have been widely used in offshore oil and gas platforms and wind turbine structures, such as mono-pile and jacket structures. The grouted connections consist of two different sizes of steel tubes with or without shear-keys and a grout annulus between them. Recently, shear-keyed grouted connections, which are more efficient with respect to the strength than plain pipe grouted connections, have been widely used in offshore structures because the strength of the shear-keyed grouted connection is enhanced by the compression strut behavior between the shear-keys on the pile and the sleeves. In general, the typical failure modes that occur in the shear-keyed grouted connections involve diagonal cracks between the shear-keys and slippage between the steel tubes and grout accompanied by crushing near the shear-keys under axial loads. These types of failure may be accompanied by the hoop yielding of the sleeve or pile, because of the confinement of the grout annulus from compression struts and crushing near the shear-keys. And grout shear failure may be occurred in the cylindrical surface when so many shear-keys are used in the connection (see Fig. 1).

To determine the strength of the grouted connections, various experimental tests and failure mechanisms were evaluated. In the late 1970s and 1980s, a number of experimental tests were performed on both plain pipe and shear-keyed grouted connections. Billington and Lewis [1] reviewed over 400 tests of grouted connections with and without shear-keys to evaluate the effects of the surface conditions of the steel, radial stiffness, grout compressive strength and length-to-diameter ratio. Tebbett and Billington [2] and Tebbett [3] reviewed some previous studies performed at Wimpey Laboratories and performed additional extended tests. This stream of works generally concluded that the strength of the grouted connections for normal grout strength specimens was affected by the influence of the grout strength, ratio of shear-key height to spacing and radial stiffness factor (k) of the

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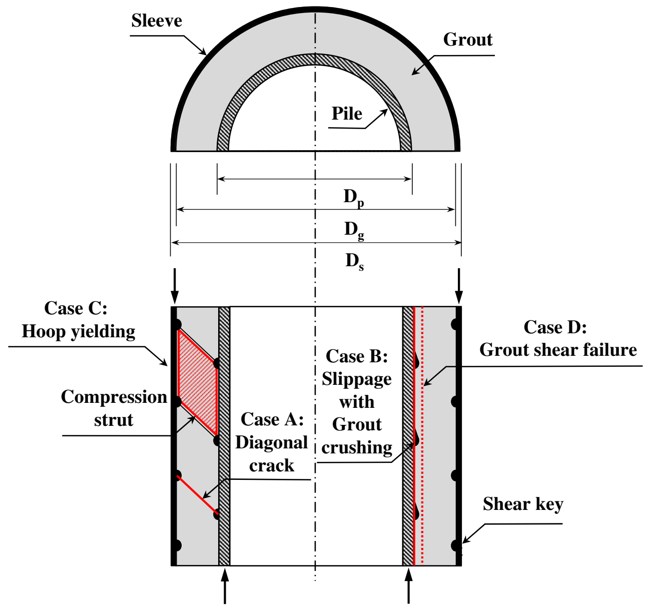

Fig. 1. Typical failure modes of a shear-keyed grouted connection.

composite section on the ultimate capacity of the connections. Their studies were based on tests on specimens with grout strengths within the range of 2–110 MPa. Aritenang et al. [4] studied the failure mechanisms of weld-beaded grouted connections based on concentric loading tests results on six grouted connections with variations of the pile thickness and shear-key height. The test results indicated that an increase in the shear-key height increased the ultimate strength more than the design prediction. The failure of the connection was affected by the hoop yielding of the pile, which led to a sudden decrease in the confining effects. They explained that a shear-key at a pile end did not contribute to the ultimate strength but rather the primary strength of the connections, which was called the end effects. Lamport et al. [5] performed experimental tests on the connections to evaluate the influence of the bending moment on the axial strength (i.e., eccentric loading), the relative position of the shear-key between the sleeves and piles, and the eccentricity of the installation of the piles and sleeves. In the case of the loading condition, the eccentricity of the load to pile diameter ratio (e/D_p) was established between 0.1 and 0.5 as realistic bounds for eccentric loading. The experimental results showed that there was no reduction in the ultimate strength by the eccentric loading conditions. The tests were mainly conducted within the grout strength range of 27–73 MPa.

Since the grouted connection with the shear-key is subjected to long-term random loading under environmental conditions, high-performance grout materials are efficient for designing the grouted connections in the offshore wind energy industry. Krahl and Karsan [6] conducted tests on grouted connections and suggested failure mechanisms that consider the confinement effects of the grout. The design equations in the API design code are based on their researches and consider grout strengths less than 110 MPa. To study high-strength grouted connections, Schaumann et al. [7] conducted four-point bending fatigue tests and evaluated the fatigue life of large-diameter hybrid connections grouted with high-performance concrete with compressive strengths within the range of 70–130 MPa. Sørensen [8] performed fatigue tests and evaluated the fatigue life of a high-performance cement-based grout with a compressive strength of 141 MPa by the dynamic compressive loading of cylindrical specimens at varying levels of cyclic frequency and different load ratios. Anders and Lohaus [9] conducted concentric loading tests on small-sized static and fatigue test specimens with grout strengths within the range of 110–150 MPa. However, there were still lack of knowledges on the interfacial shear behavior of high-strength grouted connections under axial loading conditions.

In this study, the interfacial shear behavior and strength of the shear-keyed high-strength grouted connections were evaluated using axial loading tests and finite element analysis, and the results were discussed. Five test specimens with different shear-key spacings were tested under two different loading conditions, i.e., concentric loading and eccentric loading. The interfacial shear behavior was evaluated by the strength, failure mode, and strains of the grout and steel tubes on the test results. The strengths were compared to those found in conventional design codes and test results found in the literature.

2. Design of grouted connections under concentric loading conditions

There are several design standards, such as DNV [10], NORSOK [11], ISO [12] and API [13], that are related to the design of connections for concentric loading conditions. In these codes, the design equations were based on analytical approaches and experimental tests of members with various sizes, compressive strengths of the grout, shear-key spacings and radial stiffness factors (k) in the concentric loading condition.

The DNV [10] and NORSOK [11] design codes contain equations according to two failure modes, Eq. (1) and Eq. (2), under the concentric loading. These equations were related to the interfacial shear strength for the grout-steel interface sliding and grout matrix shear failure capacity. The interface shear strength for sliding between the grout and steel tubes in Eq. (1) is dependent on the diameter of the pile (D_p), shear-key height to spacing ratio (h/s), radial stiffness factor (k) of the connection and compressive strength of the structural grout (f_{ck}). Another equation for the grout matrix shear failure is determined by the shear-key height to spacing ratio (h/s) and the compressive strength of the structural grout (f_{ck}). However, these are limited to grout compressive strength of less than 80 MPa.

For interfacial shear strength by sliding

$$f_{bk} = \left[\frac{800}{D_p} + 140\left(\frac{h}{s}\right)^{0.8}\right] k^{0.6} f_{ck}^{0.3} \tag{1}$$

$$k = \left[\left(\frac{D_p}{t_p}\right) + \left(\frac{D_s}{t_s}\right)\right]^{-1} + \frac{E_g}{E_s}\left(\frac{D_g}{t_g}\right)^{-1}$$

For interfacial shear strength by grout matrix shear failure

$$f_{bk} = \left[0.75 - 1.4\left(\frac{h}{s}\right)\right] f_{ck}^{0.5} \tag{2}$$

where f_{bk} is the interfacial shear strength, D_p is the diameter of the pile, h is the shear-key height, s is the shear-key spacing, k is the radial stiffness factor, f_{ck} is the compressive strength of the grout, t_p is the thickness of the pile, D_s is the diameter of the sleeve, t_s is the thickness of the sleeve, E_g is the modulus of elasticity of the grout, E_s is the modulus of elasticity of the steel tube, D_g is the outer diameter of the grout and t_g is the thickness of the grout.

In the ISO [12] code, the interfacial shear strength of the connection was based on the research of Harwood et al. [14]. The strength equations in this code consider the shear-key spacing, strength of the grout and rigidity in the radial direction (see Eqs. (3) and (4)). The design strength of the grout was specified within the range of 20–80 MPa, and it had a coefficient, C_p, considering the pile diameter.