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Structural Performance of Prestressed Grouted Pile-to-Sleeve Connections

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Abstract

This paper summarizes the recent development in grouted pile-to-sleeve connections that have been widely used in offshore structures, wind turbine towers and building structures. Parameters affecting the performance of prestressed grouted pile-to-sleeve connection are also discussed according to the test results. Different failure modes with different configurations are compared. The mechanical properties of the connection under axial load, combined loads and cycling load are presented. Relevant design equations proposed by different organizations are also given in this paper. Finally, the possibility of prestressed grouted pile-to-sleeve connection used as a new energy dissipative brace is also presented

Keywords: grouted pile-to-sleeve connection；structural performance；failure mode.

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1. INTRODUCTION

Grouted pile-to-sleeve connection is firstly applied in connections between the piled foundation and steel jackets in offshore platforms (Fig. 1). The annulus between the pile and sleeve is filled with cement grout as a means to reduce horizontal deflection and inhibiting corrosion (Tebbett 1982). However, it is indicated in mechanical tests that there is also considerable enhancement in joint strength and fatigue performance due to composite action contributed by grout. High load-bearing capacity, ductility and flexible forms makes the connection a common way of maintenance and reinforcement in tubes.

Because of the shrinkage of cement grout, prestress is usually introduced. Shear connectors are also used to increase the load bearing capacity if set reasonably. The behavior of the connection under static, fatigue and high amplitude dynamic loads are include in performed researches. Design guides have been provided by several organizations, like HSE (Health & Safe Excutive), API (American Petroleum Institute) and DNV (Det Norske Veritas), etc.

There are increasing applications of this innovative connection in both offshore and on-land structures these years: 1) connections in foundation of offshore platforms and wind turbine towers (see Fig. 2); 2) maintenance and reinforcement in tube structures; 3) connections between tubes in building structures. More recently, X.L. Zhao (Zhao 2002) and S.C Jiang (Zhao 2009) have studied the connection's energy dissipation capacity and pointed out the possibility to use this connection as a new energy dissipative brace which can be applied in building structures. This paper aims to summarize the recent development in this field.

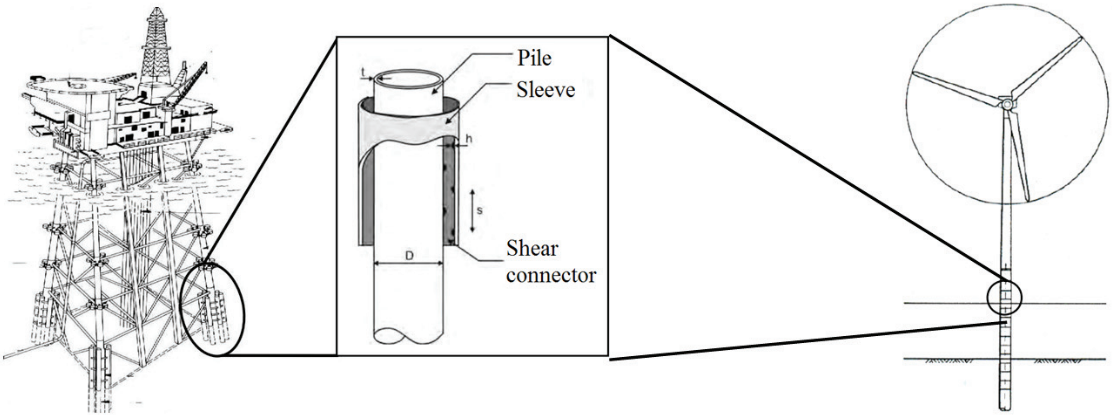


Fig 1 The connection in offshore structures Fig 2 The connection in wind turbine towers

2. LOAD-BEARING MECHANISM

For connection without shear connectors, the uniaxial load is mainly transferred in following forms: (1)bond between steel tube and grout, due to friction, adhesion respectively or both; (2)mechanical interlock due to roughness of the contact interface. For connection with shear connectors, however, the force contributed by shear connectors can't be ignored.

The force in the connection is more complex when used in offshore wind turbine towers. Overturning moment generated by wind and wave load is the governing load and can be transferred as a force-couple in the top and bottom of grouted region. In this case, torsion, moment and axial force will exist in the connection, and shear connector is not necessary anymore.

In cyclic loading tests, energy is dissipated by friction between tube and cement. So the prestress and friction coefficient are the key factors affecting the performance and the friction force can be increased by surface treatment on tubes and increasing expansive prestress between tubes and grout.

3. FACTORS AFFECTING BEHAVIOR OF THE CONNECTION

3.1. Radial stiffness K

The contribution of grout and tube will be considered in form of radial stiffness in design equations. It is indicated by previous researches that radial stiffness gives a direct proportion with ultimate bond stress and decreases the loss of expansive prestress.

3.2. Grout

The influence of grouted strength is usually obtained by test, little theoretical analysis is available in literatures. The axial force is transferred by grout which is under tri-compression, researchers usually use compressive strength f_{cu} to consider the contribution of grout. Because of the discrete of test data, conclusions provided by different researchers are quite different (Lamport 1991): API thinks the ultimate static bond strengthen has a linear relationship with f_{cu} for a connection with shear connectors, but no relationship is found for connection without shear connectors. However, DNV, UK DOE and Billington holds the idea there is nonlinear relationship between ultimate bond strength and f_{cu}. Lamport regards that $f_{\mathrm{cu}}^{1/2}$ may reflect the relationship between ultimate static bond strength and grout strength. When the connection is used to bear the transversal forces, the grout is under compression and f_{cu} gives a direct influence to the ultimate load-bearing capacity.

It is indicates in tests that ultimate load will increase with the thickness of grout annulus. This is probably due to the change of failure mechanism in grout.

3.3. Shear connector

It has been proved by tests that shear connectors will greatly increase the static ultimate capacity of the connection. But for the connection under cyclic loads, the cement grout around the shear connector will crush, which will reduce the capacity of energy dissipation.

Previous tests have shown that there is a linear relationship between shear connector height and the bond strength. Tests performed by Boswell (Boswell 1985) extended the range of this relationship, and found that there could be leveling off of the stress at greater shear connector heights. Boswell (Boswell 1985) also concluded that triangular shape was better than square and the conventional round weld bead.

h/s is the key factor in design of shear connectors, where h and s are the height and space of shear connectors. Theoretical analysis indicates an upper limit to a useful value of h/s of approximately 0.14, but no data are available when h/s reaches this limit. HSE limits $0 \leq h/s \leq 0.04$ and DNV proposes $h/s<0.1$. Some experimental evidence can be found in Anders (2007) where two types of h/s (0.013 and 0.056) were used.

3.4. Grouted length to diameter ratio (L/D_p)

Y.Y. Zhao (Zhao 2009) pointed out that the stress alone the interface of grout and tube is non-uniform, and stress concentration at the ends of the connection will become more serious with the increasing of the connection length. From the strain distributions (Boswell 1985), the stress concentration can be observed obviously. The influence of L/D_p usually takes the form of C_L in design. From Table 1 (Aritenang 1992), it is found that the contribution of L/D_p will become weaker to load bearing capacity when it increases.

Table 1 C_L's different values according to different people

L/D_p	Billington and Lewis	Wimpey	Finite EI	Analytical	Chilvers	DEn	Aritenang and Elnashai			
							Assuming no bottom weld-bead effective		Assuming the bottom weld-bead is ineffective	
							Finite element	Analytical approach	Finite element	Analytical approach
1	0.816	0.732	0.850	0.818	1.200	—	1.050	1.020	0.850	0.818
2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
4	0.877	1.193	1.050	1.016	0.920	0.900	0.902	0.927	1.050	1.016
8	0.947	0.974	0.831	0.905	0.000	0.800	0.675	0.793	0.831	0.905
12	0.840	0.000	0.720	0.885	0.000	0.700	0.567	0.720	0.720	0.885

3.5. Eccentricity

Eccentricity is more practical than centration in use. Lamport (Lamport 1991) found pile-to-sleeve eccentricity did not significantly affect static strength of the grouted connection, and even a little higher strength is obtained with eccentricity, which will be very encouraging for the convenience in practice.

3.6. Surface treatment

Improving the surface condition of tube is considered as an effective way to increase the load-bearing capacity of the connection, such as sand blast. C_s is usually used to consider the influence of surface condition in HSE, while DNV adopts $2\delta/D_p$ in its recommendation. Surface treatment is more useful for energy dissipation of this connection under cyclic loads, considering the integrity of grout. The quality of surface treatment is also important, because failure maybe occurred in the treated surface.

4. FAILURE MODES UNDER STATIC LOAD

4.1. Failure of connections with shear connectors

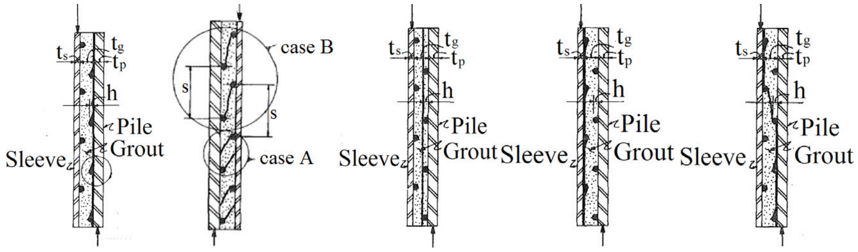
The typical failure occurred in the connection under static load involves slippage between pile and grout (Fig 3(a)) and crush of grout around shear connectors on pile (Fig4), because the bond area between pile and grout is smaller than the area between sleeve and grout. It is indicated in tests that the failure occurs in a ductile manner.

Diagonal cracks are often developed in grout before failure when shear connectors are present. A crack normally involves at least one shear connector, sometimes two. If shear connectors are relatively far apart compared to the width of the annulus, only one connector is likely to be involved, as case A in Fig 3(b). If shear connectors are relatively close, a crack may run from one connector on pile to another on sleeve, as case B in Fig 3(b).

It may be possible to use so many shear connectors that another failure mode occurs. A shear failure through grout occurred on a cylindrical surface, outside of the pile's shear connectors (Fig 3(c)).

However, for different designs, some other possible failure modes should be discussed for completeness. Fig 3(d) shows a slippage failure between grout and sleeve. Obviously, there is greater contact area between grout and sleeve than grout and pile, and greater number of shear connectors on sleeve than on pile, providing that *h* and *s* are the same for pile and sleeve. Therefore, this failure is not likely occurred unless some components at grout-to-sleeve interface are considerably low in strength, or shear connectors on sleeve differ from shear connectors on pile.

Fig 3(e) shows a combined failure characterized by slippage partly between pile and grout and partly between grout and sleeve, and two failure surfaces are joined by a diagonal crack across grout. It would be possible that the diagonal crack might skip over a couple of shear connectors that they would not contribute to the ultimate strength of the joint. However, there is greater surface area of failure once the failure surface reaches the sleeve, which will increase the ultimate strength.



(a) (b) (c) (d) (e)

Fig. 3 Failure mode with shear connector

4.2. Failure around shear connectors

When failure occurred in connections with shear connectors, the grout on compression side will crush while another side will form a void (Fig. 4). The shear connector is under uneven force produced by grout. If the shear connector is stable enough, the failure depends on the strength of grout. Otherwise, failure may be occurred at the root of shear connectors.

4.3. Failure of connections without shear connectors

Failure in connection without shear connectors is mainly the slippage between pile and grout. Sometimes the failure surface is between grout and sleeve when some components at the grout-to-sleeve interface are considerably low in strength or the inner face of sleeve has been done some slippy treatment.

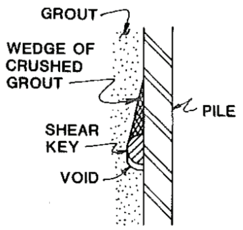


Fig. 4 Failure around shear connector

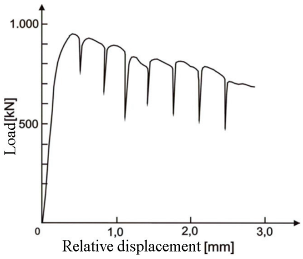


Fig. 5 Typical load-deformation curve

5. MECHANICAL PROPERTY AND THEORETICAL FORMULATION

5.1. Static strength

5.1.1. Axial load

The experiment result (Fig. 5) shows that the bond-slide relation for the interface between steel tube and grout could be simplified as three phase model: bonding phase, sliding phase, and pull-out phase. The bonding phase is an elastic phase with chemical bonding force as main part of interface action, with axial load under about $0.8P_u$. The sliding phase is a non-linear phase with interlock force as main part of interface action, which produced by shear connectors and surface roughness. The pull-out phase is a sawtooth down phase, with friction and shear connectors' interlock force as main parts of interface action.

The prestressed grouted pile-to-sleeve connection is widely used under static uniaxial load, and many corresponding equations are concluded, as shown in Table 2. Most of these equations consist two basic components of strength: One is the bond between pile and grout, due to adhesion, friction respectively or both. The other is due to the contribution from the shear connectors (if shear connectors are present).

Table 2 Equations for axial load

Proposers	Ultimate bond stress f_{bu}/MPa	Proposers	Ultimate bond stress f_{bu}/MPa
API	$f_{bu}=1.15\text{MPa}+1.72f_{cu}\cdot h/s$	Foo	$f_{bu}=12K_{HSE}C_L C_s f_{cu}{}^{1/2}+\mu P C_L$
HSE(02)	$f_{bu}=K_{HSE}C_L\cdot(9C_s+1100\cdot h/s)\cdot f_{cu}{}^{1/2}$	Aritenang	$f_{bu}=P_u/(2\pi D_p L)$
DNV(86)	$f_{bu}=\mu E_s C_L\left(\frac{2\delta}{D_p}+\frac{h}{16s}\sqrt{\frac{2t_p}{D_p}}f_{cu}^{0.3}\right)/K'$		

Were f_{bu}=ultimate bond stress, μ= static friction coefficient at steel-grout interface, δ= an empirical constant used to represent the roughness of grout-steel interface, C_s=surface roughness coefficient, P=axial force, N=number of shear connectors at sleeve, N'=number of effective shear connectors at pile, C=a parameter representing the effect of radial stress and can be assumed to 4, σ_y=yielding strength of steel, stiffness factor K' is given in DNV(86), for connection without shear connectors $P_u=[9K_{HSE}{}^{1/2}(f_{cu}/35)^{0.25}]\pi D_p L$ ($f_{cu}<35\text{MPa}$) or $P_u=[9K_{HSE}{}^{1/2}]\pi D_p L$ ($f_{cu}>35\text{MPa}$), for connection with shear connectors $P_u=\min\{P_{u1}, P_{u2}\}$: $P_{u1}=[(f_{cu}+2C\sigma_y\ t_p/D_p)N'hC_{hp}+9LK_{HSE}{}^{1/2}]\pi D_p C_L$, $P_{u2}=[(f_{cu}+2C\sigma_y\ t_s/D_s)NhC_{hs}+9LK_{HSE}{}^{1/2}]\pi D_g C_L$.

5.1.2. Combined loads

It is impractical in design only consider the axial force, actually the connection is under combined loads. Lamport (Lamport 1991) found that combination of moment and axial load did not degenerate the load bearing capacity, the mean f_{bu} increases by 14% comparing to f_{bu} only with axial load. This increase partly results from the slightly increase in grout strength of 4%. However, most of the increase can be attributed to a transversal extruding force that developed during loading because of the relative rotation of the vertical axis of the pile to that of the sleeve. The rotation is very obvious for specimen under combined load, and increases grout confinement, thereby increases its shear and friction components.

DNV(2007) also gives its recommendations on grouted pile-to-sleeve connection under torque and axial load and moment and shear load (Table 3).

Table 3 Equations proposed by DNV

Combined load	Different structures		Equations
Axial and torque	With shear connectors		$(\tau_{sa}{}^2+\tau_{st}{}^2)^{1/2}\leq\tau_k/\gamma_m$
	Without shear connectors	If torque cannot be neglected	$\tau_{sa}\leqslant\tau_{ks}/\gamma_m$; $\tau_{st}\leqslant\tau_{kf}/\gamma_m$; $(\tau_{sa}{}^2+\tau_{st}{}^2)^{1/2}\leqslant\tau_{kg}/\gamma_m$
		If torque can be neglected	$\tau_{sa}\leqslant(\tau_{ks}+\tau_{kf})/\gamma_m$
Bending moment and shear loading	Shear connectors are unnecessary		$f_s\leqslant f_{ccu}/\gamma_m$

Where shear stress in axially loaded connection $\tau_{sa}=P/(D_p\pi L)$, shear stress in torsionally loaded connection $\tau_{st}=2M_T/(D_p{}^2\pi L)$, characteristic shear strength of the connection $\tau_k=\min(\tau_{kf},\tau_{kg})$, characteristic interface shear strength due to friction $\tau_{kf}=K_{DNV}\mu E(2\delta/D_p)$, characteristic shear strength of the grout $\tau_{kg}=\kappa\cdot f_{ck}^{0.7}\cdot(1-e^{-4L/D_p})$, characteristic interface shear strength due to shear keys $\tau_{ks}=K_{DNV}\mu E_s\left[(h/21s)f_{ck}^2\sqrt{2\cdot t_p/D_p}\right]sN/L$, κ=early age cycling reduction factor, Tresca stress in the grout $f_s=\sigma_1-\sigma_3$, σ_1/σ_3=maximum/minimum principal stress in the considered point in the grout, γ_m=material factor, M_T=torque, f_{ck}/f_{ccu}=characteristic compressive cube/cylinder strength of the grout.

5.2. Dynamic strength

For connections without shear connectors, the force is transferred by friction between grout and tube, like the principle of friction damper. So the connection is gradually studied as an innovative damper while ensuring the friction. Tests from X.L. Zhao (Fig. 6(a)) and Y.Y. Zhao (Fig. 6(b)) demonstrated that the connection has good energy dissipation ability.

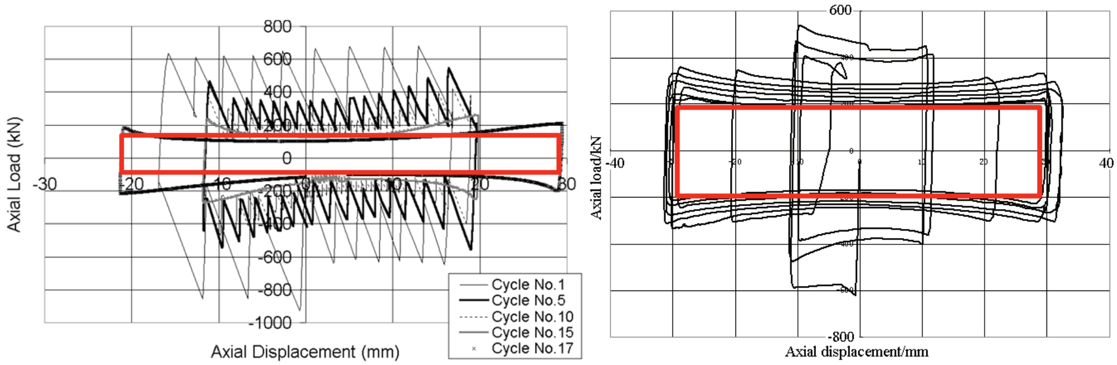


Fig. 6 (a) Hysteresis loop from X.L. Zhao (b) Hysteresis loop from Y.Y. Zhao

6. DURABILITY

The prestress is usually produced by ettringite generated by reaction of expansive agent and cement grout. Ettringite is unstable when temperature reaches 70~80°C. But the environment temperature seldom reaches so high, and this unstableness is beneficial to structures in case of fire because it can release the thermal forces in structures due to the temperature increase.

Shrinkage, especially drying shrinkage of cement grout, must be considered because it may cause the loss of expansive prestress, even separate of grout and tube. The prestress can be guaranteed by adding proper expansive agent or fibers, like carbon fiber, steel fiber, etc.

7. CONCLUSIONS

This paper present a summary of the recent development in grouted pile-to-sleeve connections in terms of key parameters, failure modes, mechanical properties, design equations and prestressed grouted pile-to-sleeve connections as an energy dissipation brace.

REFERENCES

[1] American Petroleum Institute(2000). Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms—Working Stress Design(21st edition). Washington.

[2] United Kingdom Department of Energy (1980). Report of the working party on the strength of grouted pile sleeve connections for offshore structures, Report No.ST41/80C, Wimpey Laboratories, Ltd.

[3] Department of Energy (1988). Grouted and mechanical strengthening and repair of tubular steel offshore structures, Offshore Technology Report (OTH88283).

[4] Health&Security Executives. Assessment of strengthening clamp from the Viking offshore platform: Phase Ⅰ. Offshore Technology Report 2000/057. United Kingdom.

[5] Health&Security Executives (2002). Pile/Sleeve Connections. Offshore Technology Report 2001/016, Norwich.

[6] Det Norske Veritas (2007). DNV-OS-J101-Design of Offshore Wind Turbine Structures. Det Norske Veritas.

[7] Zhao YY (2009). Performance of prestressed grouted sleeve connection. Master’s thesis, Department of Civil Engineering, Tongji University.

[8] Foo J (1991). Prestressed grouted tubular connections. PhD thesis, Monash University.

[9] Anders S (2008), Betontechnologische Einflüsse auf das Tragverhalten von Grouted Joints. PhD thesis, Hannover University.

[10] Zhao XL, Grundy P and Lee YT (2002). Grout sleeve connections under large deformation cyclic loading. Proceedings of fifth international society of offshore and polar engineering conference, vol.IV. Kitakyushu, Japan.

[11] Krahl NW and Karsan DI (1985). Axial strength of grouted pile-sleeve connections. Journal of Structural Engineering, Vol.111, No.4.

[12] Lamport WB, Jirsa JO and Yura JO (1991). Strength and behavior of grouted pile-sleeve connections, Journal of Structural Engineering, Vol.117, No.8.

[13] Aritenang W, Elnashai AS and Dowling PJ (1992). Analysis-based design equations for composite tubular connections. Eng. Struct, Vol.14.

[14] Anders S and Lohaus L (2008). Optimized High-Performance Concrete in Grouted Connections. Tailor Made Concrete Structures-Walraven & Stoelhorst.

[15] Boswell LF and Mello CD (1985), The experimental behavior of grouted connections for construction and repair. Behavior of offshore Structures. Elsevier Science Publishers B.V., Amsterdam.