Experimental and analytical study of novel full-scale square steel tubular-UHPFRC grouted connection

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Abstract. This paper proposes a novel full-scale square tubular-UHPFRC grouted connection for precast column-column connections. This study examines the mechanical properties of four full-scale square tubular columns fully-grouted or partially-grouted with UHPFRC via experimental and theoretical studies. The experimental program explores the ultimate resistance and failure modes of the grouted connection under axial compressive and tensile loads. The test results show that new column-column connections perform well in its resistance and stiffness while three main failure patterns include punching shear failure of end plate, welding fracture and local buckling of steel tube are observed. The theoretical model on resistance prediction explains the failure mechanisms of new connection well and it is instructive for the detail design of such novel grouted connection.

1. Introduction
Off-site construction provides effective construction technique that can improve construction productivity and quality while reducing labour and emission [1]. Research efforts on precast concrete and prefabricated buildings especially the connection studies have been done for a long time. The existing researches mainly focus on the various joints in traditional reinforced concrete structures and steel structures, such as the post-casting concrete joints, the bolted connections and the welded connections. These prefabricated components are normally prepared in factory environment and assembled on-site, which leads to a high requirement for on-site erections. Grouted connection (GC) is a typical “wet-connection” technique which was born from offshore engineering practice with the purpose of making up for the inaccuracy of traditional steel structure on bolting and welding technique. Grouted connection (GC) can be described as a composite connection of two different-diameter steel tubes with grout annul between them. It can simplify the complexity of construction even in a terrible construction environment [2]. Grouting sleeves firstly become widely used in offshore structures for connecting the pile foundations and transition pieces of offshore wind turbines. Billington et al. [3] carried out a large number of grouting sleeve tests and found that the sleeve with shear connectors has a great improvement in the axial bearing capacity compared to the those without shear connectors. Then, offshore industry guidelines such as DNV code [4], evaluated detail suggestions and calculation formula for the grouted connection. Extensive studies have been conducted to examine the mechanical properties of circular pile-sleeve connection [5-6] while the mechanical properties on square section grouted connection remain unclear. Since square hollow sections (SHS) components are widely used in on-shore

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construction, this paper develops a new type of "UHPFRC grouted connection" for the SHS tubular composite column. The new connection has a great superiority in fabrication and construction through removing the welding and bolting technique to decrease on-site requirement. The UHPFRC matrix perform well in tensile behaviour to enhance the shear resistance of the grouted connection. Through combined experimental and analytical studies, this paper reveals the mechanical properties of the innovative connection.

2. Experimental programme

2.1. Material properties

The grout used the Ultra High-Performance Fibre Reinforced Concrete (UHPFRC) consisting of the ultra-fine silica fume, mineral powder, P. II 52.5 R cement, fine sand, sugar calcium retarder and 2% steel fibre. The average compressive strength of Φ100×200 mm concrete cylinders reached around 121 MPa and the average coupon tensile strength had 7.9 MPa at the 28th day [7]. All the tubes and steel plates used the S355 mild steel while HRB 400 rebar were used for shear key. Direct tensile tests on steel/rebar coupons from different locations of both the inner tube and outer tube using a universal test machine were performed. The yield strength of flat coupon obtained 330 MPa while the yield strength of the tube round corner reached 517 MPa. The shear key had a yield strength of 357 MPa.

2.2. Specimen design and test set-up

The experimental program tests four full-scale SHS composite columns, which are classified as two types: partially-grouted connected column and fully-grouted connected column. Each type of column consists of two specimens subjected to axial compression and tension respectively. Figure 1 shows the configuration and dimension of the column connection, which consists of the upper tube and the lower tube. The lower section is fabricated by welding with an inner tube through an end plate and then welded to an outer tube. The upper section is an outer tube with the same size of the outer tube of the lower section. Both the outer surface of the inner tube and the inner surface of the upper section are welded with shear keys. The two sections are finally connected by infilling the UHPFRC grout in between. Figure 2 shows the test set-up for the tubular column connections.

3. Test result

Four specimens were subjected to the axial tensile and compressive loads. Three primary failure modes were shown in Figure 3. Fully-grouted column under axial tension failed due to the punching-shear damage of steel end plate with a wide gap between upper and lower sections (Figure 3 (a)). Partially-grouted column under tension suffered weld tear failure and the column was separated into two pieces (Figure 3 (c)). The sharp tearing noise of steel plate or weld region could be heard while the load was increased. As approaching to the failure load, the steel plate and weld were almost broken. Partially-grouted column under compression failed due to the local buckling (Figure 3 (b)). In the very beginning, the deformation happened at the non-GC area of the upper section. And as the load was increased, local
buckling occurred at the lower tube and the bulging deformation appeared obviously until the load was significantly declined.

![Image](a) Punching shear damage of end plate  
(b) Local buckling of steel tube  
(c) Welding fracture

Figure 3. Failure modes

4. Analytical Study

4.1. Buckling of outer tube

For compression cases, outer tube of half-grouted column may suffer nonlinear buckling failure as illustrated in Figure 3. This position is not surrounded by the grout which leads to a very low stiffness. Eurocode 3 provides a formula to evaluate the compressive resistance of the steel tube with a local buckling failure pattern,

\[ N_b = \chi f_{ya} A_g \]  
\[ f_{ya} = f_{yb} + (Cn^2/A_g) \times (f_u - f_{yb}) \]

where \( N_b \) is buckling resistance of the compression member; \( f_{ya} \) is the yield strength which take into account the influence of cold forming; \( \chi \) is the reduction factor for the relevant buckling mode; \( f_{yb} \) and \( f_u \) are the characteristic tensile yielding strength and tensile ultimate strength of the basic material (N/mm\(^2\)); \( t \) is material thickness before cold forming (mm); \( A_g \) is gross cross sectional area (mm\(^2\)); \( C \) is the coefficient as a function of the type of forming; \( C = 7 \) for rolled material and \( C = 5 \) for other methods of forming; and \( n \) is the number of 90° bends in the section with an internal radius < 5\( t \).

4.2. Punching shear of end plate

The connecting end plate is subjected to complex forces, leading to the punching shear failure. Packer [8] explains this failure mechanism using the equation (3),

\[ N_1 \sin \theta_1 = \frac{f_{y0}}{\sqrt{3}} \frac{t_0}{\sin \theta_1} + 2b_{e,p} \]

\[ b_{e,p} = \frac{10}{b_0/b_1}b_1 \text{ but } b_1 \leq b_0 \]

where \( N_1 \) is the ultimate axial load (N); \( f_{y0} \) is yield strength of the plate (N/mm\(^2\)); \( \theta_1 \) is the angle between plate and the inner tube (here \( \theta_1 = 90^\circ \)); \( t_0 \) is material thickness of the plate (mm); \( h_1 \) is external depth of inner tube (mm); \( b_{e,p} \) is effective punching shear width (mm); \( b_0 \) is the external width of the plate (mm); \( b_1 \) is the external width of inner tube (mm).

4.3. Fracture of the welding

Welding fracture, as a possible failure mode of the GC system, occurs due to the initial imperfection of the weld part between inner tube and end plate. Equation (5) gives the formula of the ultimate welding capacity,
\[ N = \sigma_f l_f h_e \]  

where \( N \) is the ultimate axial load (N); \( \sigma_f \) is yield strength of the weld (N/mm\(^2\)); \( l_f \) is the calculating length which \( l_f = l - 2h_f \) (mm); \( h_e \) is effective thickness of fillet weld which \( h_e = 0.7h_f \) (mm); \( h_f \) is the fillet weld height (mm).

### Table 1: Peak load comparison of between test result and proposed equations

| Failure modes          | \( P_{\text{max, Test}} \) | \( P_{\text{max, Prediction (Eq.)}} \) | Prediction /Test |
|------------------------|-----------------------------|----------------------------------------|-----------------|
| Local buckling         | 3267.8                      | 3273.9 (Eq.1)                          | 1.00            |
| Punching shear         | 1214.1                      | 1219.4 (Eq.3)                          | 1.01            |
| Weld fracture          | 1208.5                      | 1326.5 (Eq.5)                          | 1.10            |

### 5. Conclusions

The compression and tensile tests are carried out on the novel square grouted connection. This paper presents the typical failure modes and proposes theoretical model to predict the ultimate strength of the connections. The following conclusions can be obtained:

1. There are three main failure modes: the local buckling of steel tube for partially-grouted column under compression, punching shear failure of fully-grouted column and welding fracture failure of partially-grouted column under tension. Grouted area remains undamaged before the steel tube yielded or welding failure, which indicates that the GC possess high strength as well as high stiffness. Using this new type of GC in prefabricated buildings is feasible.

2. This paper proposes design equations to predict the ultimate resistance of the new GC connection. The comparison between the test result and predictions indicates that the proposed model can give a reliable prediction.

3. Future work on numerical analyses will be done and more significant parameters will be considered. More works are needed to propose a calculation model for design guide of the novel connection.

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