PRELIMINARY EXPERIMENTAL STUDY ON PRESTRESSED GROUTED SLEEVE CONNECTION OF FRP TUBULAR MEMBERS UNDER COMPRESSION

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ABSTRACT

Superior properties of fibre-reinforced-polymer (FRP) composites, such as high specific strength and excellent corrosion resistance, make them as a potential substitute to traditional metallic materials in piping structures. Despite the advantages associated with FRP pipes, their joining methods are still not satisfactory. It is a known fact that joints are the weakest links of such composite piping structures. A new connection method is proposed in this paper, as the prestressed grouted sleeve connection. The connection transmits axial force by shear on the grout and FRP interface. Shear transfer can be enhanced by introducing radial prestress. The prestress is achieved by using an expansive additive (CSA) which expands the grout after setting. This paper investigates the effects of different CSA ratios on the load bearing capacity of the prestressed grouted sleeve connections in compression. It was found pre-load strain developed significantly in hoop direction which indicates the development of radial prestress. Results from compressive experiments indicate that a high CSA ratio enhances the load bearing capacity of the connection. Different failure modes were observed during the compression tests. Possible reasons are discussed based on the interpretation of strain results.

KEYWORDS

FRP pipe joint; Prestress; Grouted sleeve connection; Compression; Failure mode

INTRODUCTION

The fibre-reinforced polymer (FRP) materials possess inherently high strength-to-weight ratios which offer easily handleable components, and also excellent corrosion resistance to a wide range of fluids which can attack metals (Gibson 2000). If glass fibres and pultrusion manufacturing process are used, it further reduces material cost and exhibits advantageous environmental characteristics such as low energy consumption and low carbon dioxide emissions (Halliwell 2010). These special properties make FRP materials as ideal potential substitute to traditional metallic materials in piping structures. The FRP pipes have been applied in civil infrastructure, offshore industries, and oil and gas industries (Ainsworth 1981; Gibson 2000; Liu et al. 2009). The FRP pipework have been installed aboveground, underground and offshore to transport a wide variety of fluids. Typical applications include water transmission pipes, sewage drainage pipes, stormwater drainage pipes, oil and gas transmission pipes and chemical treatment plants (Farshad and Necola 2004). However the joining methods of FRP pipes are still not satisfactory. Connection failure is the most common failure type occurred in FRP piping structures. The pultruded FRP components are not easy to connect due to material inherent brittleness and anisotropic characteristic (Keller 2003). Connection of FRP pipes has been considered as the weakest part in the whole piping structure (Liu et al. 2009).

Different connection types have been developed in current practice, such as mechanical (threaded) joints, laminated (butt and wrap) joints and adhesively bonded joints (Gibson 2000). However the applicabilities of these joint methods are limited. Adhesively bonded connection significantly loses its strength at elevated temperature (even at 60°C), as a result of the adhesive glass transition temperature has been reached (Md et al. 2013). Laminated joints are cheaper than adhesive bonded joints from material viewpoint but they are more labor intensive and difficult to make on-site (Gibson 2000). Guo (2004) has reported that leakage is the major form of screw thread connector failure due to several reasons, such as unqualified thread size, improper selection of thread compound and improper installation. Drawbacks associated with these joining methods of composite tubes divert the research towards creating new solutions. In this paper, a new connection method is proposed for FRP tubular members as the prestressed grouted sleeve connection.

The grouted sleeve connection has been an innovation in the construction of steel tubular structures (Yamasaki et al. 1980; Tebbett 1982; Tebbett and Billington 1985; Elnashia et al. 1986; Foo 1991). There are increasing applications of this innovative connection in both on-land and offshore structures over the last two decades, such as connections between tubular members in building structures; connections in foundation of wind turbine towers and offshore platforms (Jiang 2011). However it has not yet been used in FRP tubular structures. The
grouted sleeve connection transmits axial force by shear on the grout and FRP interface. Shear transfer can be enhanced by introducing radial prestress between the circular sleeve and the through member. The prestress is developed using a cement additive that expands the grout after setting. Calcium-Sulpho-Aluminate compound (CSA) is commonly used as an expanding agent. The connection offers several benefits in fabrication and construction. It uses cost-effective materials including ordinary Portland cement and expansive admixture. In addition, low on-site technology is required for erection which further reduces the cost (Zhao et al. 2006).

The paper examines the effects of different CSA ratios on the pre-load strain developments, load bearing capacities of the prestressed grouted sleeve connections, and the failure modes are also studied. The prestressed grouted sleeve connections were cured for 14 days and strain developments were recorded and analysed associated with radial prestress. After curing, the connections were tested under axial compressive loading. The load displacement responses and the progressive failure modes were recorded and analysed with relation to different CSA ratios and corresponding strain results.

EXPERIMENTAL INVESTIGATION

Materials and Dimensions

The specimen configuration is shown in Figure 1. Glass fibre reinforced polymer (GFRP) tubular members supplied by Bell Composites China were used to prepare specimens (material properties: tensile strength, 206 MPa and tensile modulus, 17.2 GPa). The size of the outer tube was 50mm in outer diameter, 4mm in thickness and 130mm in length. The inner tube had an outer diameter of 31mm, a thickness of 3.2mm and a length of 130mm. The surface treatment for both outer and inner tubes were shot blasted. Grouted sleeve connection requires grouting of the annular gap between the pile (inner tube) and the sleeve (outer tube). V-shaped frames were used to ensure the inner pile was fixed at the centre of the outer sleeve [Figure 1(b)]. The grout length was fixed at 65mm by using cylindrical foam plugged into the sleeve. Expansive grout was used to achieve the prestress level between grout and FRP tube interfaces. The cementitious materials selected for making expansive grout were ordinary Portland cement and Denka CSA #20 (expansive admixture). The ordinary Portland cement was provided by local supplier and Denka CSA #20 was made in Japan (chemical composition: 1.3% MgO, 1.0% ignition loss, 0.06% K₂O, 0.04% Na₂O, 0.03% Cl⁻).

![Figure 1. Specimen configuration (a) Schematic diagram; and (b) Specimen when curing (c) Specimen when loading](Note: Lg = grout length; tg = grout thickness; Do = outer tube diameter; to = outer tube thickness; Di = inner tube diameter; ti = inner tube thickness; SG = strain gauge; SG1, SG2, SG3, SG4, SG8 are in axial direction; and SG5, SG6, SG7 are in hoop direction)
Specimen Preparation

The expansive grout is produced by mixing expansive admixture with ordinary Portland cement and water. Three different mass ratios of OPC/CSA/water were chosen: 0.7/0.3/0.36, 0.9/0.1/0.36 and 1.0/0.0/0.36. Glenium 27 (superplasticiser) was added at 0.5L per 100kg OPC+CSA to enhance flowability. The grout mix design is shown in Table 1. The ordinary Portland cement was blended with expansive admixture, after which water was added. Mixing was performed using a Hobart mixer for duration of two minutes, then the superplasticiser was added and mixed for another two minutes. The mixed grout was poured into the annular gap between the outer and inner tubes. The specimen was vibrated on a vibration table for two minutes to remove any air bubble and sealed immediately after. The grout thickness was 5.5mm and the grout length was 65mm. The specimens were cured at room temperature ($20 ^\circ C \pm 1 ^\circ C$) for 14 days to allow the development of prestress. Two specimens were prepared for each mixture. The average results obtained from two specimens were used for later discussion.

<table>
<thead>
<tr>
<th>Specimen label</th>
<th>Mix portion (weight%)</th>
<th>Superplasticiser</th>
<th>Grout thickness</th>
<th>Grout length</th>
<th>Curing time</th>
</tr>
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<tbody>
<tr>
<td>FF_30_14</td>
<td>0.7 0.3 0.36</td>
<td>0.5</td>
<td>5.5</td>
<td>65</td>
<td>14</td>
</tr>
<tr>
<td>FF_10_14</td>
<td>0.9 0.1 0.36</td>
<td>0.5</td>
<td>5.5</td>
<td>65</td>
<td>14</td>
</tr>
<tr>
<td>FF_0_14</td>
<td>1 0 0.36</td>
<td>0.5</td>
<td>5.5</td>
<td>65</td>
<td>14</td>
</tr>
</tbody>
</table>

Note: FF_30_14: FRP tube joint with 30wt% CSA and 14days curing; FF_10_14: FRP tube joint with 10wt% CSA and 14days curing; FF_0_14: FRP tube joint with no CSA and 14days curing.

Instrumentation

In order to measure amount of expansion generated during curing period, eight strain gauges were installed on the outer tube of each sample with expansive grout (FF_30_14 and FF_10_14). Strain gauges were installed in both axial and hoop directions and numbered as SG1, SG2 and so on, up to SG8. The positions of strain gauges were shown in Figure 1(a). Four strain gauges were installed on specimens with normal grout (FF_0_14). The positions of the strain gauges were at SG1, SG3, SG6 and SG8. One Data Logger and two Channel Expansion Modules were used to automatically record strain readings every five minutes for 14 days of curing.

Mechanical Loading

After 14 days of curing, specimens underwent axial compression tests using an Instron 4204 50kN capacity testing machine. Two steel plates were installed onto the loading machine. The specimen was put vertically in between the steel plates and compressive load was applied on top of the inner tube using displacement control [Figure 1 (c)]. The loading speed of the test was at 0.4mm/min at the beginning until the connection reached its ultimate load. It was then increased to 2 mm/min when the axial displacement reached 4mm. During compression test, the strain generated on the outer tube of all samples was also measured in order to monitor the load-strain behaviour and strain distribution.

RESULTS AND DISCUSSIONS

Strain Developments before Loading

Figure 2 (a) shows the typical strain developments in hoop direction (SG6) for specimens with different CSA ratios. The strain results in axial direction for all specimens are negligible since the expansion is confined by outer sleeve in hoop direction. Hoop strain increases as the grout expands inside the connection. Hoop strain is used to predict the level of the prestress as it is directly proportional to the prestress. Specimen with 30wt%CSA reaches the maximum hoop strain about 0.4% in 8 days, and then the hoop strain slowly reduces due to shrinkage of the grout. The maximum hoop strain for specimen with 10wt%CSA is less than 0.1%, which is much lower than 30wt%CSA samples. Specimen with no CSA has no hoop strain development since the grout is made of pure OPC so that no expansion is introduced. Therefore an increase in the CSA ratio in the grout causes an increase in the maximum hoop strain achieved, which results in an increase in the prestress. The hoop strain developments for SG5 and SG7 are shown in Figure 2 (b). The hoop strain results are similar as SG6, except a higher reduction of strain was observed on SG5 for both FF_30_14 and FF_10_14 after reaching its
maximum hoop strain. This is because SG5 is on the edge of the grout which exposed to air, so that constrain becomes less and shrinkage happens more rapidly.

Figure 2. Hoop strain developments for specimens with different CSA ratios (a) SG6; and (b) SG5 and SG7

Failure Modes

The CSA ratio also influences the failure mode of the specimens. After reach the maximum compressive load, FRP tube joint with 30wt% CSA shows the slip at pile (inner tube)-grout interface as shown in Figure 3 (a). The inner pile was pushed into the sleeve under compression but the grout was still on the surface. However, the failure mode for FRP tube joint with 10wt% CSA is the slip at sleeve (outer tube)-grout interface as shown in Figure 3 (b). The grout moved together with the inner pile into the sleeve. The failure mode for FRP tube joint with no CSA is the same as for FRP tube joint with 10wt% CSA as shown in Figure 3 (c). Large amount of prestress has been generated inside the annular gap when a high CSA ratio is used. A strong bond exists between sleeve and grout since the sleeve confines the expansion of the grout. When a low CSA ratio is used, there is not enough prestress developed inside the joint, which results in a relatively weak bond between sleeve and grout. An even weaker bond exists between sleeve and grout when there is no prestress inside the joint. Therefore slip at pile-grout interface occurred in specimen with 30wt% CSA and slip at sleeve-grout interface occurred in specimen with 10wt% CSA and specimen with no CSA when the connections reach their ultimate capacities.

Figure 3. Failure modes (a) FF_30_14; (b) FF_10_14; and (c) FF_0_14

Load-Displacement curves and Load-Strain curves

Figure 4 shows the axial load versus axial displacement curves for all specimens. In common, all specimens undergo approximately linear elastic deformation up to ultimate load. The stiffness of the connection is almost constant with different CSA ratios. Among these specimens, FRP tube joint with 30wt% CSA shows the highest failure load of 20.1kN. FRP joint with 10wt% CSA only has a failure load of 8.9kN. The failure load is reduced more than 50% when CSA ratio decreased from 30wt% to 10wt%. The FRP tube joint with no CSA has the lowest failure load of 6.5kN. This indicates that prestress enhances the load bearing capacity of the grouted sleeve connection. After failure load, all specimens exhibit the same trend regardless of CSA ratio. The compressive load decreases gradually to a constant value, which is the residual strength of the connection.

The load-strain relationship was investigated from compression tests using strain gauges. Specimens with different CSA ratios exhibit similar load-strain behaviours. For illustration purpose, load-strain curves for specimen FF_30_14 is shown in Figure 5. Results are shown only up to the ultimate load as the subsequent
strain readings were no longer a reliable reflection of load-strain relationships. SG1 presents maximum compressive strain since it is on the inner tube which has smaller area than the outer tube. Axial strain value increases from SG2 to SG3, then to SG4. This is because compressive load applied on top of inner tube was transferred by the expansive grout through shear to the outer tube. As contact area of grout and sleeve increases along the length of the sleeve, more shear stress is resulted on the sleeve to balance axial stress, therefore the strain results increase accordingly. It is noted that SG4 has very close strain result as SG8. The location of SG4 is at the end of grout connected to the outer tube and SG8 is on the part of outer tube out of the joint region. They should have similar stress values as a result of the load balance, which leads to similar strain values. When SG2 is in compression, SG5 is in tension. This is due to Poisson’s Ratio effect as SG2 is in axial direction while SG5 is in hoop direction. Similar results are shown for other paired strain gauges including SG3 and SG6; SG4 and SG7.

![Figure 4. Axial load versus axial displacement curves for all specimens](image)

**Figure 4.** Axial load versus axial displacement curves for all specimens

**Figure 5.** Load-strain curves for FF_30_14

**Load Bearing Capacity and Residual Strength**

Figure 6 shows the ultimate capacity and residual strength of the connection in term of CSA ratio. The maximum compressive load increases as the percentage of CSA increases. With increased amount of CSA, more prestress at grout-FRP interface has been produced due to expansion of the grout. Shear bond strength increases as prestress increases, which results in an increase in the ultimate capacity of the connection. The residual strength for sample with 30wt% CSA is 5.4kN. The residual strength for sample with 10wt% CSA is 4.2kN. The residual strength for sample with no CSA is 3.7kN. Even though the load bearing capacity for 30wt% CSA sample is much larger than that for other two samples, the residual strengths appear close for all three samples. This indicates that CSA ratio has large influence on the ultimate capacity of connection but little influence on the residual strength. According to Zhao et al. (2002), the ultimate capacity depends on both the adhesion and friction resistances of the grout-FRP interface. The adhesion bond is lost on the first sudden dynamic slip just after failure and the load capacity of the connection thereafter depends mainly upon the friction resistance. This leads to a rational conclusion that prestress has a major contribution to the initial adhesive between grout and FRP tube. After connection reaches its failure load, the adhesion is lost and the load drops to a constant value contributed by the friction resistance between grout and FRP tube.

**CONCLUSIONS**

In this research paper, the effects of different CSA ratios on the pre-load strain developments, load bearing capacities and failure modes of the prestressed grouted sleeve connections are studied. Axial compression tests have been conducted on the connections with different CSA ratios. The following observations and conclusions are made based on the test results and analysis. (1) Pre-load strain increases significantly as the CSA ratio increases which results in an increase in radial prestress. 0.4% of pre-load strain developed in 8 days for
specimen with 30wt% CSA. By comparison, less than 0.1% of pre-load strain developed for specimen with 10wt% CSA. (2) Prestress enhances the load bearing capacity of the connection. Specimen with 30wt% CSA showed the highest failure load of 20.1kN whereas specimen with 10wt% CSA only had a failure load of 8.9kN. In contrast to prestressed connection, the non-prestressed connection experienced the lowest failure load of 6.5kN. (3) Different failure modes appear on the connection incorporated with different CSA ratios. Failure mechanism for connection with high CSA ratio is the slip at pile-grout interface. Both connection with low CSA ratio and non-prestressed connection have the same failure mechanism, which is the slip at sleeve-grout interface. (4) It is interesting to note that for both prestressed and non-prestressed connections, residual strength exist after the connections reach their ultimate capacities.

FUTURE RESEARCH

It should be noted that only two specimens were examined for each mixture, more specimens will be prepared and tested in order to obtain more reliable conclusions. In addition, only one bond length (65 mm) and only three CSA ratios were adopted in the current testing program. Future research is needed to investigate the influence of bond length and different CSA ratios on failure modes and load-deformation behaviour of the prestressed grouted sleeve connections.

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