Experimental study on flexural behavior of micro circular steel pipe with grouting

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Abstract. In order to study the bending resistance of grouted micro circular steel tube, pure bending tests on 9 grouted steel tubes were carried out with different grouting materials and three kinds of diameter steel tube. Through the analysis of deflection, surface strain and internal steel bar strain during the test, the deformation characteristics and load-strain relationship of members under load are studied. The ultimate bending capacity and bending stiffness test results are compared with the calculated values of different codes. The results show that the ultimate bearing capacity calculated by different codes is quite different from the test results, and the calculated values of Fujian Provincial Standard DBJ13-51-2010 are in good agreement with the test results and are safe. The bending stiffness at the initial stage calculated by different codes and the bending stiffness at the service stage are also quite different from the test results. The calculation results of AIJ (2002) are in good agreement with the test results and can be used for design calculation after revision.

1. Introduction

Grouting micro-steel tube is widely used as micro-pile in recent years, but the bending mechanical properties of grouting micro-circular steel tube members are still in its infancy at home and abroad, lacking relevant design theory and specifications [1]. Sun [2] thinks pointed out that the flexural bearing capacity of the micro-pile should be calculated as the control index, and the flexural bearing capacity of the micro-pile should be determined by the corresponding test. Ji [3] through the test of flexural behaviour of lightweight aggregate concrete filling in circular steel tube members, the results show that the effect of filling materials on the flexural behaviour of lifting members is remarkable.

Similarly, domestic and foreign scholars have not done much research on the bending design parameters of grouted steel tube members, namely bending stiffness. Varma [4] through the experimental study of high strength concrete filled square steel tubular beams and columns, proposed that the bending stiffness of $M = 0.2Mu$ is the initial stiffness, and the stiffness of $M = 0.6Mu$ is the service stiffness; Lu Hui [5] through the variation law of the initial bending stiffness and service stiffness of concrete filling in circular steel tubular is studied by experiment, and the calculation method of the initial bending stiffness is discussed. Axial compression, instability and bending behaviour of short columns of steel concrete filled circular steel tubular are verified by ABAQUS finite element software[6]. The results are in good agreement with the experimental results.
As a kind of micro-pile, the mechanical properties of grouted micro-steel tubular pile are less studied at home and abroad. The design is still based on the relevant parameters of ordinary concrete filled steel tubular. Because of the large difference in size between the ordinary concrete filling in the steel tubular members and the grouted micro-steel tubular piles, the properties of the grouted filling materials are not the same. The difference of the material properties and the influence of the size effect need to be determined by comparing the test with the theoretical calculation. In this paper, the pure bending tests of 9 miniature steel tube piles are carried out, and the data are analyzed and compared with the calculation methods of concrete filling in steel tube.

2. Bending test

2.1 Design and manufacture of specimens

In the design of the specimen, the diameter of the steel tube, Q235 seamless steel tubes, is 57 mm, 89 mm and 108 mm. The length of the steel pipe is 1350 mm, one end of which is welded with a 8 mm thickness steel plate. The strength of the steel is determined by the tensile test according to the standard of room temperature tensile test method for metallic materials (GB/T228-2002). The yield strength ($f_y$), yield strain, tensile strength ($f_u$), modulus of elasticity ($E_s$) and Poisson's ratio ($u_s$) of the steel are 298 MPa, 1500 $\mu$e, 438.7 MPa, 2.02x105 MPa and 0.28, respectively.

In the test, the core material of steel pipe grouting is pure water slurry or mortar. The cement is Yufeng brand ordinary Portland cement, the sand uses the middle sand, the mixing water is the tap water. When pouring, the slurry is poured into the steel pipe by layers and vibrated. After the vibration is completed, the surface of the specimen is smeared with some cement (mortar) to be even with the steel pipe. After 28 days of curing under the same conditions of indoor watering, the compressive strength of the mortar cube and the modulus of elasticity of the mortar cube are measured to be 40 MPa and 32500 MPa, respectively. The compressive strength of the cement paste cube is 39.5 MPa and the modulus of elasticity is 32300 MPa, respectively. The basic data of each specimen are shown in Table 1.

| Specimen number | diameter×t thickness (mm) | $\alpha$  | $\xi$  | $f_y$/ MPa | $f_u$/ MPa | Filled core material | Remark          |
|-----------------|--------------------------|----------|--------|------------|------------|---------------------|-----------------|
| CS57-3.5-A      | 57×3.5                   | 0.300    | 3.761  | 295        | 23.5       | Mortar              | Built-in 22 bar |
| CS57-3.5-B      | 57×3.5                   | 0.300    | 3.310  | 295        | 26.7       | Cement              | Outsourced      |
| CS57-3.5-C      | 57×3.5                   | 0.300    | 3.310  | 295        | 23.5       | Mortar              | Cement slurry   |
| CS89-4.5-A      | 89×4.5                   | 0.238    | 2.599  | 292        | 26.7       | Cement              |                 |
| CS89-4.5-B      | 89×4.5                   | 0.238    | 2.953  | 292        | 23.5       | Mortar              | Built-in 25 rebar|
| CS89-4.5-C      | 89×4.5                   | 0.238    | 2.953  | 292        | 26.7       | Cement              |                 |
| CS108-5.5-A     | 108×5.5                  | 0.240    | 2.666  | 297        | 26.7       | Cement              |                 |
| CS108-5.5-B     | 108×5.5                  | 0.240    | 3.029  | 297        | 23.5       | Mortar              | Built-in 25 Bar |
| CS108-5.5-C     | 108×5.5                  | 0.240    | 2.666  | 297        | 23.5       | Mortar              | Outsourced mortar|

Table 1. Parameters of specimens

Note: 1) steel ratio: $\alpha = A_s / A_e$; 2) the component clamping coefficient: $\xi = af_y / f_u$; 3) The built-in steel bar is located in the steel center, the surface of the steel tube is 20 mm and the slurry is in accordance with the core grouting material.

2.2 Loading mode

The test uses hydraulic jack to load the specimen at three points, and 30 t pressure sensor to measure the loading size of the jack. The longitudinal strain of the steel tube is measured by the resistance strain gauge. Loading system and strain sheet sticking of micro-steel pipe pile members in pure bending test are shown in Fig. 1. Before loading, the members are strictly aligned according to loading schematic diagram.
During the loading process, the initial load gradient is about 1.5 minutes, so that the deformation of the specimen is fully developed. When the specimen is close to the yield load, the gradation of the load is reduced to $\Delta P = 2kN$.

![Diagram](image1.png)

**Fig. 1** Loading of specimens and paste map of strain gauges (unit: mm)

### 3. Analysis of test results

#### 3.1 Load strain relationship

In the pure bending test of the miniature steel tube of the outsourced slurry, the initial load is not obvious. However, the outsourced slurry at the bottom is cracked, and the lower part of the slurry is cracked with the load and continues to expand. When the load is increased to about 60% of the yield load, the compression zone is crushed gradually, but the steel pipe is still not buckling, and can still be deformed, as the deformation of the specimen increases rapidly.

In the pure bending test of a miniature steel tube pile without an outsourced slurry, the cracking noise of the mortar will be continuously emitted when the load is loaded to be close to the damage load. When the specimen is loaded close to the yield load, the vertical deflection of the specimen is increased rapidly, but the load is only slowly changing, and the vertical deflection in the span is too large to stop loading.

Fig. 2 is a typical load-strain curve (CS89-4.5-A). It is shown that the strain growth rate of the specimen is slower than that of the external load at the initial stage of loading, and the readings of the strain gauges (1 and 5). When the maximum fiber strain of steel tube reaches the yield strain of steel, the growth rate of strain gauge reading is faster than that of external load, and the member enters the elastic-plastic stage, but the bearing capacity of the specimen can continue to grow; when the steel yield, the load-strain curve deviates from the original straight line obviously. The strain of the line and the corresponding part of the steel pipe are basically symmetrical to the neutral axis distribution; the analysis of the 3 # and 7 # strain gauges sticking to the center of the steel pipe shows that the change of the two increases and the value is positive. This indicates that the neutral axis of the steel pipe is constantly moving up during the loading process.

![Diagram](image2.png)

**Fig. 2** Load-deflection contrast responses

#### 3.2 Load deflection

The load-deflection (midspan) curves of 9 specimens of miniature steel pipe piles are drawn according to different steel pipe diameters (Fig. 3).
As shown in Fig.3: with increasing the section size, the bending resistance of grouted micro-circular steel tube is improved to a certain extent. However, when the steel content is similar, the effect of increasing section size on the bearing capacity of the component is limited. This indicates that the steel content plays an important role in the bending resistance of grouted micro-steel tube; Materials in the same section of steel tube have an impact on the elasticity of the component. The bending deformation ability of the steel tube in the sexual stage has little influence; the stiffness of the steel tube is not improved by adding an outer layer of slurry on the edge of the steel tube, which plays an important role in anti-corrosion in practical engineering; the bearing capacity of the steel tube can be increased by about 14.5%-31% with increasing specimen size, the increment is even greater. Obviously, it is suggested that steel bar should be added to the tensile zone of the specimen with larger section size. The test results show that the external load acting on the specimen can be increased even if the deflection of the middle section reaches L/30, indicating that the ductility of the grouting micro-steel tube member is better.

4. Comparison between experimental values and standard calculation values

4.1 Comparison of flexural bearing capacity
In order to further grasp the variation in the steel pipe pile grouting micro bending ultimate bearing capacity, the test results and the calculated part of the design specifications or procedures are listed in Table 2.

| Sample number  | AISC360-10 (2010) | EC4 (2004) | DL/T5085 (1999) | DBJ13-51-2010 |
|----------------|-------------------|------------|-----------------|---------------|
|                | $M_{ue}$ / (kN m) | $M_{ue}$ / (kN m) | $M_{ue}$ / (kN m) | $M_{ue}$ / (kN m) |
| CS57-3.5-A     | 4.89              | 3.67       | 0.751           | 5.44          | 1.112         | 5.47          | 1.119         | 4.31          | 0.881         |
| CS57-3.5-B     | 4.25              | 3.21       | 0.755           | 4.73          | 1.113         | 4.76          | 1.12          | 3.75          | 0.882         |
| CS57-3.5-C     | 4.13              | 3.24       | 0.785           | 4.79          | 1.159         | 4.86          | 1.177         | 3.82          | 0.925         |
| CS89-4.5-A     | 15.96             | 11.67      | 0.731           | 17.26         | 1.081         | 17.01         | 1.066         | 14.78         | 0.926         |
| CS89-4.5-B     | 13.92             | 10.15      | 0.729           | 15.01         | 1.078         | 14.85         | 1.067         | 12.85         | 0.923         |
| CS89-4.5-C     | 12.21             | 10.23      | 0.837           | 15.02         | 1.23          | 15.01         | 1.229         | 11.95         | 0.979         |
| CS108-5.5-A    | 22.54             | 23.08      | 1.024           | 17.42         | 1.54          | 27.51         | 2.129         | 23.86         | 1.058         |
| CS108-5.5-B    | 18.03             | 18.61      | 1.032           | 28.01         | 1.553         | 22.19         | 1.231         | 20.35         | 1.129         |
| CS108-5.5-C    | 18.20             | 18.42      | 1.012           | 28.31         | 1.555         | 22.23         | 1.221         | 20.01         | 1.098         |
| Average        | 0.851             | 1.269      | 1.161           | 0.978         |
| Mean variance  | 0.1329            | 0.215      | 0.069           | 0.094         |
From the analysis and comparison in Table 2, it can be seen that there are obvious deviations in the ultimate flexural bearing capacity calculated by different design codes. The calculation value of AISC360-10 (2010), which neglects the concrete strength, is relatively low, because the contribution of cement mortar to the flexural bearing capacity of micro-steel tube has not been calculated. In addition, the results calculated by Fujian Provincial Standard DBJ13-51-2010 (2010) are in good agreement with the test results and are safe. The results calculated by domestic code DL/T5085 (1999) and European code EC4 (2004) are more than 10% larger than the test results.

4.2 Comparison of flexural rigidity at initial stage

Table 3 shows the initial flexural stiffness $K_{0.2}$ of the micro-steel tubular pile in the time of $0.2M_u$, and compares it with the calculated results obtained from the above four procedures. From the numerical statistics of table 3, it can be concluded that except for the Japanese standard AIJ (2002), the calculated values of the remainder of the rules have a certain gap with the average of the experimental results. The calculated values of the Japanese standard AIJ (2002) are in good agreement with the experimental results, which can meet the engineering calculation requirements.

### Table 3 Comparison initial bending stiffness with calculated values of standard

| Sample number  | Test value | Mean value $K_{0.2}$ | AIJ(2002) | EC4(2004) | AISC (2010) | DBJ-2010 |
|----------------|------------|----------------------|-----------|-----------|-------------|-----------|
|                | $K_c$      | $K_c/K_{0.2}$        | $K_c$     | $K_c/K_{0.2}$ | $K_c$ | $K_c/K_{0.2}$ |
| CS57-3.5-A     | 44.2       | 45.1                 | 49.5      | 48.6      | 46.1      | 51.3      |
| CS57-3.5-B     | 40.1       | 41.4                 | 45.1      | 49.5      | 48.6      | 51.3      |
| CS57-3.5-C     | 39.9       | 40.1                 | 45.1      | 49.5      | 48.6      | 51.3      |
| CS89-4.5-A     | 259.2      | 249.1                | 230.6     | 259.2     | 255.5     | 272.4     |
| CS89-4.5-B     | 243.2      | 249.1                | 242.6     | 259.2     | 255.5     | 272.4     |
| CS89-4.5-C     | 244.8      | 249.1                | 242.6     | 259.2     | 255.5     | 272.4     |
| CS108-5.5-A    | 534.2      | 523.9                | 518.1     | 582.3     | 573.9     | 612.1     |
| CS108-5.5-B    | 514.2      | 523.9                | 518.1     | 582.3     | 573.9     | 612.1     |
| CS108-5.5-C    | 523.3      | 523.9                | 518.1     | 582.3     | 573.9     | 612.1     |
| Average        |            |                      | 1.05      | 1.11      | 1.09      | 1.17      |
| Mean variance  |            |                      | 0.055     | 0.075     | 0.07      | 0.075     |

4.3 Comparison of the calculation value and the flexural rigidity of the use stage

Table 4 lists the steel pipe pile at $0.6M_u$ micro bending stiffness $K_{0.6}$ use phase member, with the results obtained in the above four procedures for comparison. It is seen from the average value calculated, using the experimental phase gap flexural stiffness of the steel pipe pile micro large and are unsafe. In contrast, the Japanese specification AIJ (2002) calculation agrees well with the experimental results, the average and variance of 1.21 and 0.065, respectively. The obtained calculation result and the remaining specification test results were greater than 30%.

### Table 4 Comparison bending stiffness of work with calculated values of standard

| Sample number  | Test value | Mean value $K_{0.6}$ | AIJ(2002) | EC4(2004) | AISC (2010) | DBJ-2010 |
|----------------|------------|----------------------|-----------|-----------|-------------|-----------|
|                | $K_c$      | $K_c/K_{0.6}$        | $K_c$     | $K_c/K_{0.6}$ | $K_c$ | $K_c/K_{0.6}$ |
| CS57-3.5-A     | 36.1       | 45.1                 | 49.5      | 48.6      | 46.1      | 51.3      |
| CS57-3.5-B     | 35.1       | 45.1                 | 49.5      | 48.6      | 46.1      | 51.3      |
| CS57-3.5-C     | 35.3       | 45.1                 | 49.5      | 48.6      | 46.1      | 51.3      |
| CS89-4.5-A     | 200.1      | 190.6                | 230.6     | 259.2     | 255.5     | 272.4     |
| CS89-4.5-B     | 187.8      | 190.6                | 230.6     | 259.2     | 255.5     | 272.4     |
| CS89-4.5-C     | 184.0      | 190.6                | 230.6     | 259.2     | 255.5     | 272.4     |
| CS109-5.5-A    | 465.1      | 518.1                | 582.3     | 573.9     | 573.9     | 612.1     |
|                |            |                      | 1.45      | 1.43      | 1.35      | 1.35      |
From the theoretical point of view, this may be because the micro-steel tubular pile members from the initial bending stiffness to use the bending stiffness of the obvious degradation phenomenon, and the micro-steel pipe pile and the ordinary concrete-filled steel tubular Members have the effect of size effect.

It can be obtained fit factor calculation 99.97% that the micro bending stiffness value calculated by the Japan Steel Pipe piles specification AIJ (2002) is used, and then multiplied by a correction coefficient of 0.87.

5. Conclusions
1) The load-strain relationship curve of the grouting steel tubular members shows that the top and bottom edge strain gauges (1# and 5#) change the most, and the neutralization axis of the steel pipe is continuously moving up during loading;
2) The loading test shows that the flexural ability of the micro-steel pipe pile increases with the increasing the section size, and the slurry has little influence on the strength of the same section member; the strength of the component can be significantly increased by the built-in rebar;
3) In the calculation of flexural capacity of steel pipe grouting micro-piles, results calculated by the Fujian local standards DBJ13-51-2010 (2010) are in good agreement with the experimental results. This can better meet the accuracy requirements of the project, engineering design reference.
4) The calculation of the initial bending stiffness of the grouted miniature steel tube shows that the calculated value of AIJ (2002) in Japanese code is in good agreement with the experimental results, and the reasonable calculation result can be obtained by multiplying the bending stiffness value of the grouted miniature steel tube by the correction coefficient of 0.87.

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