Rapid Development and Application of Prototype Test System of Prefabricated Metro Station Structure Joint

Su Huifeng¹,²*, Liu Weining¹, Yang Xiuren³ and Wang Chen³

¹School of Civil Engineering, Beijing Jiaotong University, Beijing, 100001, P.R. China
²Transportation College, Shandong University of Science and Technology, Qingdao, Shandong, 266590, P.R. China
³Beijing Urban Construction Design & Development Group Co. Limited, Beijing, 100037, P.R. China

Abstract: With the engineering background of Changchun metro line 2 proposed prefabricated metro station named Yuanjiadian station and with the final destination of studying the tenon-groove grouting joint’s mechanical property of fabricated blocks, prototype test system of joint has been developed and stages test has been finished. The test system includes loading system, test and monitoring system, assembling and grouting system, lifting and installation system and so forth which can complete the four-point bending test and four-point shearing test at any axial force of the prototype joint. Afterwards, in different conditions (different grouting ranges, different grouting materials and different tenons) the destructive test of axial force combining with bending moment has been done. Ultimate flexural capacity and flexural rigidity of the certain single tenon-groove joint was got and the safe bending moment of the joint was shown providing guidance for the design and construction.

Keywords: Flexural rigidity, prototype test, test system, ultimate flexural capacity.

1. INTRODUCTION

The proposed metro station named Yuanjiadian station of Changchun city is a vault, upright-wall, single arch without pillar and prefabricated metro station which will be the first total-prefabricated metro station of China. Along the longitudinal direction seven precast blocks form one ring every two meters. One new type joint named tenon-groove type grouting joint will be used between the precast blocks along the longitudinal and circular station. The specific form and size in different position of joint will be determined by the internal force, deformation and the construction need.

For the total-prefabricated structure of metro station the most important feature is the tenon-groove type grouting joint. Study of joint mechanical properties will not enough meet the design requirements if only depending on empirical model or numerical simulation. The existing research of underground construction joint mostly focuses on the segment’s joint which is very different from the new one [1-8]. Given the above, joint prototype test should be taken to study the ultimate flexural capacity, shear bearing capacity and flexural rigidity. One meeting research requirement test system should be set up as soon as possible.

2. DESIGN OF TEST SYSTEM

2.1. Test Requirements

The test requirements are given bellows:

1. Transport and hoisting of the test component should be convenient;
2. Loading space should be provided for the big-size concrete and the component should be installed, loaded, disassembled conveniently;
3. Any axial force combining moment or shear test should be taken separately;
4. The loading process should be controlled easily. That is to say the jacking speed and the loading resolution should meet the requirements to make the test under control;
5. The test can be recorded conveniently;
6. The prototype test of single tenon-groove type joint and double can be done and there should be room for the other related test;
7. There is a highly realistic question, the test system must be built to use as soon as possible.

After the comparison of schemes, one scheme of using existing reacting-force wall and test-bed and the other scheme of using long column tester can only complete partial test and the risk is high, so the two schemes is abandoned and the scheme of building test-pit system in segment factory of Changchun’s eastern suburbs was adopted. It took 50 days from design to erection. The whole test system divides into loading system, test and monitoring system, assembling and grouting system, lifting and installation system and so forth.

2.2. Loading System

The size of test-pit is 7200 mm×5100 mm×1500 mm, wall thick 800 mm and built-in φ25 main bar with pre-
embedded 20 mm thick steel plates. Axial force and moment are provided by one horizontal hydraulic jack separately. At the head of the jack one universal rotating joint is put to prevent the axial force direction migration. Of the jacks, one provides bending moment by the distribution beam and pit pilasters. The distribution beam is made of thick steel plate with rib beam inside to providing enough stiffness and several groups force points is set on the beam. Horizontal and vertical support is a solid steel bar diameter of 100 mm and 200 mm. At the bottom of the component is the base with greased rollers. Between the component and the support is 20 mm thick steel plate to prevent the component crushed partially. Within the range of the load the loading system can meet the four-point bending test and four-point shearing test at any axial force. The loading system sees Fig. (1).

2.2.1. Jack Selection

The jack with hydraulic servo system not only costs too high but also long time buying and installing not be considered. At the condition of the metro station buried depth 3m to 5m in normal, the internal force of the structure based on the guidance of load structure theory is calculated. Multi engineering conditions such as 0 to full-rigidity of the joint stiffness has been considered. By calculation, the axial force is located in 1500 kN and 2500 kN and the largest moment of the joint is 535kN.m. Considering the efficiency of the jack, two hydraulic jacks rated tonnage 4000 kN, stroke 500 mm are selected.

2.2.2. Oil Pump Selection

In order to decrease the jacking speed, small capacity and high-pressure fuel pump with the minimum fuel delivery 2 L/min is selected equipped with constant pressure valve and digital oil pressure gauge. The test indicates that the minimum jacking speed can be 0.28 mm/s stability at the certain fuel delivery.

2.2.3. Force Sensor

In order to accurate measuring and real time recording the jacking force, one high precision axial-force meter is set in jack tail (Brand: MTM, Type:C1-5MN, the maxim range is 5000KN). It can output the practical axial-force real-time to the recorder (Brand: MTM, Type: 2000/CK6).

2.3. Monitor Design

2.3.1. Static Strain Testing System

Test established 2 intelligent circuit data acquisition system DH3816N with each module 60 measuring points and another standby.

2.3.2. Image and Video Collection System

Two high definition cameras have been installed on the wall of the test-pit and outside so as to global and local record the test process. At the same time, digital camera was equipped to take photo whenever.

2.4. Assembling and Grouting System

For the tenon-groove grouting joint, another important thing is the assembling of tenon and groove specimens and the grouting of juncture. All the needing equipment is manual calabash (rated 5ton), grouting pump (the maximum pressure no less than 0.4MPa), level bar, water-proof slab and styrofoam.

2.5. Hoisting and Transportation System

According to the size and weight of the specimens, transportation uses segment factory’s forklift (rated 10ton) and hoisting uses electric hoist wheel-rail gantry crane (rated 10ton, max lifting height 2.7 m).

3. SECMENS SIZE AND MONITORING PROGRAM

3.1. Specimens Size

In the former preliminary design, the widths of the 7 joints per ring are different. The most narrow single tenon-groove joint is 700 mm width and the most wide double tenon-groove joint is 1420 mm width. In order to the
Prototype test will be conducted conveniently in reducing cost, the rest place is simplified to the rectangle section according to the principle of Saint-Venant except a certain range of the joint designed the same to the real prefabricated parts. Among them, the length of the assembling single tenon-groove specimen is 2700 mm and the double tenon-groove specimen is 3600 mm, thickness 500 mm Table 1.

Section size of the single tenon-groove specimen joint’s position sees Fig. (2).

3.2. Joint Splaying Amount Monitoring

Joint splaying amount is one important index of judging the structure waterproofing and the flexural rigidity. Two displacement sensors such as guy wire type and plunger type was used to measuring the joint splaying amount. The guy wire type (Type: LXW-5; Linear accuracy: superior to 1%F.S and resolving precision>0.02 mm) having two measurement range is 50 mm and 100 mm according to the different measurement points. The plunger one (Type: ZY-3770; Measurement range 50 mm; Linear accuracy: superior to 0.5%F.S and resolving precision=0.01 mm) is convenient in measuring the joint splaying amounting reduction. The displacement sensors connect to the DH3816N synchronously with stress and strain and in some palace the two sensors can also check each other.

The displacement sensors see Fig. (3).

3.3. Concrete Strain and Steel Stress Monitoring

Concrete strain and steel stress are all monitored by the strain gage. For the concrete strain monitoring, given that the small joint and the stress complex, if the usual 100 mm strain gages were used, it is difficult to arrange the measuring points. Vice versa, if the strain is too short, the errors will be large. For the above reason, the 50 mm concrete strain was used. For the steel strain, type BX120-80AA were used.

4. TEST APPLICATION

During the first stage, 25 groups single tenon-groove specimens test has been finished including the conditions such as two lengths (tenon length 195 mm and 95 mm), three types of grouting materials (epoxy, cement-based and with no grouting), three types of grouting range (the maximum, the minimum and the designed), five axial forces (0, 500 KN, 1000 KN, 1600 KN, 2000 KN). Through the massive test data and the others the single tenon-groove joint’s flexural behavior was got preliminary.

### Table 1. The number of single tenon-groove specimen strain gages and sensors.

<table>
<thead>
<tr>
<th>Name</th>
<th>Concrete Strain</th>
<th>Steel Strain</th>
<th>Guy Wire (Plunger) Displacement Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tenon Length (mm)</td>
<td>195</td>
<td>95</td>
<td>195</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>65</td>
<td>44</td>
</tr>
<tr>
<td>Number</td>
<td>195, 95</td>
<td>95</td>
<td>195, 95</td>
</tr>
<tr>
<td></td>
<td>9(3)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Fig. (2). Two types of single tenon-groove specimen length (Unit: mm).](image1)

![Fig. (3). Two types of displacement sensor.](image2)

![Table 1. The number of single tenon-groove specimen strain gages and sensors.](image3)
4.1. Study of the Joint Ultimate Flexural Capacity

By comparing the joint surface cracks, concrete strain, steel stress of the key position developing with the axial force and bending moment, the joint flexural capacity can be divided into some stages and the safe moment that the joint can bear is got.

4.1.1. Tenon Length 195 mm Specimens

The flexural capacity of the tenon 195 mm can divide into five stages. That are cracks appearance, cracks development, cracks cut-through the tenon, cracks cut-through the structure and losing bearing capacity. Sees Fig. (4). The stages before cracks cut-through the tenon should be defined the safe bearing stages.

For instance, the moment of the different axial force at the condition of minimum grouting range sees Table 2. From Table 2, except the axial force 0kN working condition, the moment of joint tenon cracks cut-through is 2.2 times of cracks appearance. The moment of cracks appearance and the edge of specimens reaching tensile strength can get by simple calculation. The other conditions of the joint are same to the above described and not explained here.

4.1.2. Tenon Length 95 mm Specimens

The flexural capacity of the tenon 95 mm can divide into five stages. That are cracks appearance, cracks development, cracks cut-through the tenon, several parallel fractures appearance in groove, and the final bearing. The stage interval after cracks appearance is too brief even cannot be distinguished (the condition of smaller axial force) which is similar to brittle failure of the rare-reinforced beam even plain concrete beam.

The key bending moment at the condition of minimum grouting range and different axial force is seen in the Table 3.

For the tenon 95 mm length grouting joint, the moment of Cracks appearance should be the maximum safe moment. As it all known by the mechanics, the moment is irrelevant to the reinforcement ratio but the size of the joint tenon.

4.2. Study of the Flexural Rigidity

According to the splaying amount of joints, the flexural rigidity at the different time has been got by the method of segment tangent rigidity. The flexural rigidity test formula of the joint has been fitted also. Results show that flexural rigidity and bending moment satisfying exponential relationship. The relationship equation is

\[ k_p = Ae^{\frac{N}{A}} \]

where

A, B is correlation coefficient which is relate to the joint size, grouting materials, grouting range and the axial force.

For the tenon 195 mm length specimen, the joint flexural rigidity formula at the condition of grouting epoxy and designing grouting range sees Table 4.
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The Open Civil Engineering Journal, 2015, Volume 9

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Fig. (5). Cracks developing at the condition of two axial forces.

Table 3. The key moment at the condition of minimum grouting range of tenon length 95 mm specimens.

<table>
<thead>
<tr>
<th>Axial Force (kN)</th>
<th>Cracks Appearance (kN.m)</th>
<th>Cracks Extension to the Top of the Tenon (kN.m)</th>
<th>Cracks Cut-Through Tenon (kN.m)</th>
<th>Several Parallel Cracks Appearance in Groove (kN.m)</th>
<th>The Final Bearing (kN.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>/</td>
<td>/</td>
<td>140</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>500</td>
<td>/</td>
<td>/</td>
<td>210</td>
<td>213.5</td>
<td>213.5</td>
</tr>
<tr>
<td>1000</td>
<td>/</td>
<td>/</td>
<td>280</td>
<td>280</td>
<td>350</td>
</tr>
<tr>
<td>1600</td>
<td>280</td>
<td>350</td>
<td>410</td>
<td>540</td>
<td>595</td>
</tr>
<tr>
<td>2000</td>
<td>315</td>
<td>385</td>
<td>490</td>
<td>577</td>
<td>665</td>
</tr>
</tbody>
</table>

Table 4. Joint flexural rigidity formula at the condition of grouting epoxy and designing grouting range of tenon length 195 mm specimen.

<table>
<thead>
<tr>
<th>Grouting Material</th>
<th>Axial Force Condition (kN)</th>
<th>Grouting Range</th>
<th>Flexural Rigidity Test Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy</td>
<td>0</td>
<td>Designing</td>
<td>( k_u = 32.78 \frac{M}{L} )</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>Designing</td>
<td>( k_u = 37.03 \frac{M}{L} )</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>Designing</td>
<td>( k_u = 68.04 \frac{M}{L} )</td>
</tr>
<tr>
<td></td>
<td>1600</td>
<td>Designing</td>
<td>( k_u = 76.43 \frac{M}{L} )</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>Designing</td>
<td>( k_u = 101.9 \frac{M}{L} )</td>
</tr>
</tbody>
</table>

Form the Table 4, the flexural rigidity increases with the increasing axial force but decreases with the increasing moment. According to the test formulas, it can been seen that the flexural behavior of 195 mm tenon joint is superior to the 95 mm one. It means that the length of the tenon has influence on the joint flexural rigidity.

CONCLUSION

Some related literatures [9, 10] also describe the segment joint test system. But the loading tonnage and the test items cannot compare to the new system and the system considers more thoroughly, more practically. Up to now, the new test system works well and test precision meets requirements. The test data has offered good reference for designing and also get ready for the subsequent double tenons-grooves test and shear test.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.
ACKNOWLEDGEMENTS

Declared none.

REFERENCES


