APPLICATION AND PRACTICE OF GFRP BARS IN THE TBM LAUNCHING SHAFT OF METRO IN CHINA

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ABSTRACT

TBM technology has been widely applied in tunnel construction for many years. However, TBMs cannot cut the steel rebar used in reinforcement of concrete. The parts of the station walls where tunnels begin and end need to be removed, before boring could be taken. These procedures are extremely time consuming and may cause delays in the tunnel-boring operations. Therefore, a new material fiber-reinforced polymer bar (FRP Bar) is invented to replace the steel bar. It could be used in the retaining wall construction where "soft-eye" openings are needed for the appliances of tunnel boring machines. Comparing to steel rebar, FRP Bar is easier to cut. This enables the boring machine to penetrate the concrete diaphragm walls in a continuous manner. This will speed up the construction and prolong the service life of the shield machine cutter, possibly leading to significant reduction in project cost. This paper presents an overview and discussion of the applications of FRP bars in metro construction in a city of China, and the details are as follows:

1. The test results of the bonding strength between the GFRP bars and cement
2. The construction of the prefabricated GFRP "cage" located in the TBM Launch shaft
3. The economic and technical analysis of GFRP bar and its application prospects

KEYWORDS

GFRP, anchorage length, lap length, construction

INTRODUCTION

Subway is one of the most important modern public transportation systems, and has been building in many cities. The subway stations are often built in open construction pits. In order to minimize the traffic disturbance during the construction, the tunnels between the stations are built underground by using tunnel-boring machines (TBMs). Since pit floors are often located in unstable soils far below the water table, it is necessary to build reinforced thick concrete retaining walls to prevent groundwater infiltration and cave-ins.

The retaining walls of the launching shaft are cut around the station perimeter. One big limitation is that TBMs cannot cut the steel rebar used to reinforce the concrete. Therefore, the portions of station walls where tunnels begin and end had to be removed by manual operations, before the boring process can begin. In order to prevent water ingress or soil collapse due to water pressure resulting from the manual removal of concrete and rebar, stable soil was often injected before hand, and compacted or a second unreinforced concrete wall was constructed behind the retaining wall. These procedures are time consuming and demand a large work force, and will delay the tunnel-boring operations. The invention of fiber-reinforced polymer bar (FRP Bar) provided a more efficient and effective solution for subway tunnel construction.

A Chinese research institute conducted research on the concrete reinforced schemes in 2006 for the construction of a new Metro line in a Chinese city. The research concluded that the glass fiber-reinforced polymer (GFRP) rebar product, bearing the trademark Road Power, have much better performance against the steel bars. Road Power are easily cut. This enables the boring machine to continuously penetrate station walls, and cut tunnels and bore through the wall to the next station. This continuous process will provide a significant cost saving solution, even though the initial cost of the Road Power is higher than conventional steel rebars.

Scheduled to fulfilling civil work in 2008, the north-south route will run through 11 stations, then descend underground for 16 km, connecting with 11 subsurface stations before leaving the tunnel and entering the line's...
southern terminal. Totally, at least 20 holes needed to be bored through retaining walls. Based on a comparison of retaining structure between diaphragm wall and guard post, the research institute suggested to choose guard post (1.2m) as the main support structure. Walls for the holes are 10m wide. The company owning the subway system planned to fabricate 100 cage sections made of Road Power and insert them into the steel rebar scheme where tunnel openings should be located. Totally, about 400 thousand meters of Road Power will be used.

EXPERIMENT RESEARCH AND DETAILING

The GFRP cage is a very promising technology, and some structural design detailing are discussed as follows:

The Tensile Strength and Shear Strength of GFRP Rebar

The basic property of GFRP is the prerequisite that decides the safety and reliability of its structure. Based on the test methods described in “Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures—ACI 440.3R-04”, the research crews refers to an experimental study on the tensile strength and shear strength on GFRP Rebar. The test result shows that the tensile strength of the main reinforcing bars of Φ25 and Φ22 are above 650Mpa (Figure 1), and the sample deviation of 18 Road Power GFPR rebars is less than 50Mpa. Therefore, it is suggested that the design tensile strength of Φ25 and Φ22 rebar should be calculated as 350Mpa, while the shear strength should be about 150Mpa (Figure 2), which can completely meet the structural design requirements.

![Figure 1. Tension failure of GFRP bar](image1)

![Figure 2. Shear failure of GFRP bar](image2)

Bond Behavior Between GFRP and Surrounding Concrete

Researchers point out that the key to any concrete structure, which is reinforced with rebars, is the bond between the rebar and the surrounding concrete. If cracking develops, then the potential surface damage to GFRP rebar can result in that the rebar becomes compromised, thus increasing the possibility of structural failure. Tests have proved that the ultimate failure load of the GFRP reinforced concrete structure depends on the strength of the concrete. And it can be observed that the slip — the amount the rebar moves in relation to the concrete — is measured up to the point of bond failure.

Based on the test methods described in “Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures—ACI 440.3R-04”, the researchers have carried out an experimental study on bond strength between the GFRP and the surrounding concrete. The test results shows that, compared with bond strength between the steel rebar with the same diameter and concrete, the concrete/GFRP rebar bond is less, and it is about 85% concrete/steel bond (Figure 3), which can completely meet the structural design requirements.
Anchorage Length and Lap Length of GFRP Rebar

Anchorage length

To concrete structure, the tensile forces acting on the main rebar are transferred by the bond to surrounding concrete, and the bond behavior between the GFRP rebar and the concrete is similar to that between the steel rebar and the concrete. The experimental research shows as follows:

- A total of eighteen GFRP samples with the anchorage length of 200 mm have been tested. The failure of some samples was due to the tensile failure of the GFRP rebar, and the corresponding tensile stress is about 661.8 Mpa, which approximate the mean value of the ultimate tensile strength of GFRP rebars. The failure of others was due to concrete damage, and the smallest corresponding tensile stress is 12.67 Mpa, the tensile stress of the GFRP is about 423.6 Mpa, and the mean value of bonding force is about 16.8 Mpa. With the anchorage length of 250 mm, the failure of all samples was due to the tensile failure of the GFRP rebar, and the corresponding tensile stress is about 635.4 Mpa, which is the approximate mean value of the ultimate tensile strength of GFRP rebars. Testing shows that the anchorage length of $\phi 25$ Road Power is about 250 mm (10d).

- To $\phi 22$ GFRP rebar with the anchorage length of 150 mm, all samples were pulled out from the concrete with the corresponding minimum bonding force of 14.63 Mpa. At the anchorage length of 200 mm, the corresponding minimum bonding force is 17.07 Mpa. While the anchorage length increase to 250 mm, the failure of all samples was due to the tensile failure of the GFRP rebar with the corresponding minimum bond force of 611.74Mpa. It can be proved that the anchorage length of $\phi 22$ Road Power is about 250mm (13d).

- The results in the test show that at the same diameter and the same anchorage length of 200mm, all steel bars were pulled out, while the GFRP bars were partly pulled out with the corresponding mean bonding force are 17.3Mpa and 17.07Mpa respectively. That is to say, the anchorage length of Road power is same if compared with a steel bar of the same diameter.

The test results show that at the anchorage length of 15d, the tensile strength of GFRP rebar can be completely exerted. Thus it can be considered as the smallest ultimate value. Considering the difference between the laboratory conditions and project construction, it is necessary to choose the bigger safe coefficient to ensure the reliability of bond between GFRP and concrete.

Based on the Eq. (1) described in Guide for the Design and Construction of Concrete Reinforced with FRP Bars — ACI 440.1R-03, the anchorage length can be calculated as follows:

$$ l_a = \frac{1}{18.5} \times f_{fu} \times d = 420.9 \times \frac{1}{18.5} \times d = 22.8d $$

Where $f_{fu}$ = design tensile strength of FRP, considering reductions for service environment 0.7 (0.7*601 = 420.9Mpa). The ultimate tensile strength of $\phi 25$ Road Power is 693Mpa (18 samples), and its normal value is 601Mpa. In addition, considering the influence of and the concrete cover, the recommended correction coefficient of anchorage length is 1.3~1.5. Thus, the anchorage length of GFRP rebar in concrete is about 29.6d~34.2d, while in actual design it is recommended to choose 40d as the anchorage length.
Lap length

The Guide for the Design and Construction of Concrete Reinforced with FRP Bars—ACI 440.1R-03 shows that limited experimental data are available on the lap length of GFRP rebar in concrete. It is regulated that the stress at the lap length area should not exceed 50% in tensile strength. It is recommended to choose safe coefficient of 1.3 and 40d as the lap length in practice.

Stiffness of Structure

The Young’s modulus of the GFRP rebar is about 40Gpa, which is about 20% of steel rebar. As a result, the stiffness of GFRP cage is obviously less than that of a steel cage. Thus, we should take some measure to increase the reinforcement ratio of GFRP cage. For economic reasons, only the areas of the retaining walls that are to be penetrated by the TBM are reinforced using GFRP-rebars. The remaining areas are conventionally reinforced. Considering the design tensile strength of GFRP rebar is higher than that of steel rebar, in the practice of designing, the spreader bars are assembled to improve the stiffness of the “cage” (Figure 4).

Figure 4. Improve the stiffness of the GFRP “cage” through the spreader bars

Detailing of GFRP Stirrups

Due to GFRP rebar made of thermoset resin all bends must be made at the factory. Testing shows that the tensile strength would be obviously decreased due to the bending of GFRP rebar. Limited research given in ACI400.1R-03 on FRP hooks (Ehsani, Saadatmanesh, and Tao 1995) indicates that the tensile force developed by the bent portion of a GFRP bar is mainly influenced by the ratio of the bend radius to the bar diameter ($r_b/d_b$), the tail length, and to a less extent, the concrete strength. On the condition of $r_b/d_b \leq 14$, there is a decline in tensile strength of GFRP rebar. Therefore, when $r_b$ exceeds 600 mm, there is no significant influence on tensile strength of the stirrup.

GFRP CAGE CONSTRUCTION AND APPLICATIONS

For this Metro project, both steel and Road Power cages are assembled offsite and then trucked to the construction site. While steel rebar cages are welded, the Road Power bars are combined into cages using conventional tying wire. It must be noted that these stirrups do not have the same function as steel rebar stirrups. Rather, the Road Power stirrups simply help to stabilize the cage as it is being transported to the construction site. The Road Power stirrups no longer have any structural function once the concrete is poured.

At the job site (Figure 5), steel and Road Power cages are connected using standard lap method commonly used when joining separate sections of steel rebar cage prior to casting. When wall trenches are excavated, the first steel cage, which is placed in the area that are to be cut by tunnel boring machines, is lowered part way into the trench and suspended to allow attachment of the middle Road Power cage, at the point in the wall where the tunnel will be bored. The two sections are then lowered into the trench and suspended to permit similar attachment of the top steel cage. When the reinforcement cages are completely connected, the concrete pile is cast.
Comparatively simple waterproofing measures are installed inside the construction pit to keep the pit dry. Because the TBM can cut directly through the Road Power reinforced wall, soil stabilization and secondary concrete walls are no longer necessary, which can efficiently shorten the construction period.

THE ECONOMIC ANALYSIS AND APPLICATION PROSPECTS

The economic effect analysis is a complex process, this paper only provide an alternative method (Table 1). Compared with the conventional supporting methods, such as secondary supporting at starting excavation, refrigerant method at the soft soil area, the “soft eye” technique can reduce the total construction cost. Of course, we cannot provide a quantified calculation method, only can this paper give a reference.

Table 1. The economic analysis between Soft eye technology and conventional technology

<table>
<thead>
<tr>
<th>Item</th>
<th>GFRP reinforced diaphragm walls and guard post</th>
<th>Conventional steel reinforced diaphragm walls and guard pile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material costs Ø25 10000~20000m</td>
<td>¥ 6250 /0.25t</td>
<td>¥ 3300 /t</td>
</tr>
<tr>
<td></td>
<td>¥ 250,000~500,000</td>
<td>¥ 121,000~242,000</td>
</tr>
<tr>
<td>Costs due to removing steel rebar manually ①</td>
<td>— —</td>
<td>+ ¥ 27,000~45,000 (Going though openings)</td>
</tr>
<tr>
<td>Costs due to laying aside the machine ②</td>
<td>— —</td>
<td>+ ¥ 30,000 ~ 100,000 (Going though openings)</td>
</tr>
<tr>
<td>Cost due to postponing the date ③</td>
<td>— —</td>
<td>+ ¥ 15,000 ~ 37,500</td>
</tr>
<tr>
<td>Cost of temporary supporting structure ④</td>
<td>— —</td>
<td>¥ 380,000</td>
</tr>
<tr>
<td>Total amount</td>
<td>¥ 250,000~500,000</td>
<td>¥ 573,000~804,500</td>
</tr>
<tr>
<td>Cost saving</td>
<td>¥ 323,000~554,500</td>
<td></td>
</tr>
<tr>
<td>Damage for the boring machine due to the steel bar</td>
<td>— —</td>
<td>Cannot estimate</td>
</tr>
<tr>
<td>Conclusions</td>
<td>“Soft eye” technique is a new solution for tunnel, which is worthy of popularization.</td>
<td>Time- and labor- consuming, even can cause damage to the boring machine.</td>
</tr>
</tbody>
</table>

From the above analysis, it is proved that using GFRP rebar in replace of steel rebar in supporting structure of launching shaft not only can reduce the construction cost, but also can provide safe and time-effective construction. The contractor also benefits from significant cost and time saving by the construction of soft eyes. Placing GFRP bars would be carried out in the same manner as fixing traditional steel bars and due to the lightweight of GFRPs (¼ that of steel) the task would only be made easier.

Typically, a hand breakout would add several days to the construction program depending on the depth of the
shaft, accessibility, safety considerations, availability of manpower and resources required to carry out the works etc, just like a system engineering. If the soft eye technique new is applied, personal safety involved in such an undertaking is greatly improved, as no manual effort is required to access the shaft prior to placing the TBM in the launching shaft or ahead of a breakout. In addition, it can avoid the soil reinforcement through pouring concrete before a hand breakout. Given these unique advantages of soft eye openings, more and more tunneling contractors are adopting this technique, and the future of soft eye openings looks positive for the time to come.

CONCLUSIONS

The “soft eye” technique has been extensively studied in the last decades, and it has been applied in more than one hundred successful construction projects over the world. However, its application in China is not popular. Based on the successful applications of Road power in metro construction of the Chinese mainland, this paper has the following conclusions:

① Road power can match the performance of the similar material, which can completely meet the structural requirements.
② The design and the construction of GFRP cage are significantly different from that of the conventional steel cage. The national standard or specifications on this aspect is yet blank in China and needs to be developed.
③ Using GFRP rebar to replace steel rebar in supporting structure of launching shaft can reduce the construction cost, leading to a safe and time-consuming construction.

REFERENCES

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