Newly Developed GFRP Rebar in Diaphragm Walls of Large Tunnelling Projects

Dipl.-Ing. Ben Jütte, Dr.-Ing. André Weber
Schöck Bauteile GmbH, Baden-Baden, Germany

ABSTRACT

The acceptance of Glass Fibre Reinforced Polymer (GFRP) rebar is growing continuously in civil engineering. Especially in tunnelling projects, the installation of GFRP rebar in the areas of diaphragm walls which are to be penetrated by the tunnel boring machine (TBM) can lead to substantial savings in the overall construction cost and the total construction time.

A newly developed GFRP rebar system is presented here. The most significant issues when designing a concrete member, such as a diaphragm wall, which is to be reinforced with this material, are discussed, followed by a review of several recent applications in tunnelling projects.

1. INTRODUCTION

When new underground lines or sewers are built in the often congested down-town areas of larger cities, the stations are often built in open construction pits. To minimise traffic disturbances during construction, the tunnels between the stations are built underground using tunnel boring machines (TBMs). When tunnels are built in sands, clays or other unstable soils, the construction pits for the future stations are often secured with reinforced concrete diaphragm walls.

In conventional steel reinforced diaphragm walls the area of the wall, which is to be penetrated by the TBM, the so called soft-eye, has to be manually removed, as the TBM can not cut steel. To stabilise the soil behind the soft-eye and to prevent water inflow into the pit, soil stabilisation measures (such as high pressure soil injections) are required behind the wall. These can be time-consuming and expensive. Often spatial restrictions, for instance due to nearby buildings and roadways, make soil stabilisation measures from the existing ground surface very difficult.

The total project cost as well as the time required to build the project can be significantly reduced, if GFRP rebar is installed in the soft-eyes, instead of steel reinforcement. As the TBM can then penetrate the diaphragm walls, the tunnel can be bored in one continuous process. The costly soil stabilisation measures behind the walls are no longer necessary. Comparatively simple waterproofing measures are installed inside the dry construction pit.

2. DESIGN OF GFRP REINFORCED DIAPHRAGM WALLS

The physical and mechanical properties of GFRP rebar differ significantly from those of reinforcing steel. Furthermore the material properties of the various GFRP materials available on the market vary significantly.
In any design of GFRP reinforced concrete members these facts need to be taken into consideration. If this is done, the design of a GFRP reinforced member is in principle analogous to that outlined in the codes for the design of steel reinforced concrete elements.

2.1 Modulus of Elasticity and concrete strength

Unlike reinforcing steel, GFRPs are linearly elastic to failure. Essentially no yielding is observed. Whereas the ultimate tensile strength of most GFRPs is significantly greater than that of steel, the modulus of elasticity is significantly less (between one fifth and one third of reinforcing steel).

Because of the comparatively low modulus of elasticity the cracks in a GFRP reinforced section will penetrate deeper into the member. The concrete compression zone is shallower, implying a greater compressive stress in the concrete. As the concrete grade in diaphragm walls needs to be relatively low - to allow the TBM to cut the concrete – concrete compression becomes the critical factor in the design of GFRP reinforced concrete diaphragm walls.

New subway and sewer tunnels are often located below the ground water table. Accordingly the soft-eyes in the diaphragm walls are likewise below the ground water table. As a result, the water tightness of the wall has to be insured in the design. This is usually done by limiting the depth of the compression zone to 100 mm or more. As the crack depth, and therefore the depth of the compression zone, depends on the stiffness of the reinforcement used, the modulus of elasticity is, especially in the application of a GFRP rebar, critical. The diagram in Figure 1 shows that the GFRP material presented here has a modulus of elasticity of about 60,000 N/mm².

2.2 Bond GFRP - concrete

In several pull-out tests the bond properties of the GFRP material introduced herein were tested and compared to the bond properties of steel rebar. In concretes of grades customary to civil engineering projects the bond behaviour of the GFRP bars is superior to that of steel rebar. As a result, embedment lengths and splice lengths can be (conservatively) determined according to the respective code or design guideline for steel reinforced concrete sections.

Figure 2. Evaluation of bond strength
2.3 Concrete cover

Among other factors, the required concrete cover on any reinforcing bar depends on the tensile splitting action at the surface of the bar. Due to the specially developed geometry of their ribs, the GFRP bars presented here exhibit very low tensile splitting forces. As a result, the sole function of the concrete cover is to insure the proper load transfer between the GFRP bar and the surrounding concrete. Typically a concrete cover of $d_s$ (bar diameter) + 10 mm is entirely sufficient, independent of the chemical environment.

Due to this shallow concrete cover, the GFRP reinforced concrete section can be designed very efficiently. The internal lever arm is much greater than that of the equivalent steel reinforced section. High bending moment capacities can therefore be achieved. In diaphragm walls of tunnelling projects, where the soft-eyes are well below the surface, and the ground water pressure on the wall can be very large, a high bending moment capacity can be indispensable. The maximum allowable / possible reinforcement ration can be exceeded, if the applied GFRP is not strong enough.

2.4 Durability

Durability of the reinforcement is an issue of great significance in concrete construction, independent of the reinforcing material. As concrete structures are designed for increasingly longer life-spans the durability of steel reinforcement can become critical.

A significant advantage of most GFRPs is their corrosion resistance to most chemicals found in soils and in ground waters. However, most glass fibres are vulnerable to alkaline environments. To insure the long-term durability of GFRP rebar, the resistance to alkali has to be insured. As this resistance depends on the material components used in the production of the bars, it varies greatly between the various GFRP materials available today.

By encasing highly corrosion resistant glass fibres in an extremely durable VE hybrid resin a material was developed which promises to fulfil the most stringent durability requirements for long-term applications.

One procedure to test newly developed GFRP bars is to expose them to extreme environments over specified periods of time. After the exposure the residual strength of the bars is tested. The long-term durability is statistically extrapolated on the basis of these test results. In one such test series the bars introduced here were exposed to a pore solution with a ph-value of 13.7 at 60° Celsius for 2000 hours. The mean residual strength of the bars was greater than 900 N/mm².
2.5 Stirrups and transfer of shear loads

It is not possible to bend GFRP bars once they are hardened. Most GFRP bars are produced in a pultrusion process. The ribs of the newly developed GFRP rebar are cut into the bars after they are hardened. In this process it is not possible to produce bent bars with the same material properties as straight bars.

As a result it is recommended that shear forces in GFRP reinforced concrete elements are transferred via double headed bolts and not via stirrups. The bolts are designed for the same strain as steel stirrups. As a result, the commonly accepted truss models for the transfer of shear loads in reinforced concrete can be applied. The shear design can therefore be performed in accordance with the conventional reinforced concrete design codes.

3. APPLICATIONS OF THE NEW GFRP REBAR

The newly developed GFRP rebar is currently being installed in several tunnelling projects worldwide. Some of the larger projects are the new North-South Line of the Amsterdam subway, the Brandenburg Gate station of the new subway line 5 in Berlin, the new North-South Line of the light rail system in Cologne, and the launch and reception shafts of the Durban Harbour Tunnel Crossing in Durban, South Africa.

3.1 North-south line Amsterdam subway

In the course of the construction of the new North-South Line of the Amsterdam underground the GFRP reinforcement is currently being installed in six diaphragm walls in the Dutch capital. A total of 24 cages are to be reinforced with GFRP, covering the twelve soft-eyes of the stations Ceintuurbaan, Vijzelgracht and Rokin.

The diaphragm walls at the Ceintuurbaan station are over forty meters deep. Due to spatial restrictions the two tunnels for the subway are built on top of each other at this station. The bottom of the lower tunnel is 29 meters below ground and nearly 28 meters below the ground water level. Nearly 80 tonnes of the GFRP-reinforcement will be installed on the project.

Bending moments of up to 4000 kNm/m and shear forces of 2000 kN/m have to be transferred by the diaphragm walls in Amsterdam. The walls are 1200 mm thick. Individual panels of the walls are up to three meters wide. The reinforcement cages are 1050 mm thick and up to 2800 mm wide. Several GFRP-reinforced cage sections are designed for the maximum possible moment capacity. For longitudinal reinforcement 32 mm diameter GFRP bars are combined in bundles of two or three bars each, placed in two layers.
on both faces of the diaphragm wall. The bundles are placed at a spacing of 200 mm.

The allowable tensile stress in the longitudinal bars was defined to be 250 N/mm². The design of the diaphragm walls in Amsterdam was carried out according to ACI 440. Design criteria specified in the Dutch VBC-code NEN 6720-1995 were taken into consideration.

Shear forces in the diaphragm walls are transferred using double headed bolts. In Amsterdam up to 18 double headed bolts with 32mm bar diameter are installed in each square meter of the reinforcement cage. The bolts are spaced according to EN 1538.

In Amsterdam most rebar cages are built in three sections. These are connected at the site using so-called fish plates. The bottom, steel-reinforced, section of the cage is lowered into the bentonite-filled trench and then suspended off the guide walls of the trench. The middle, ComBAR-reinforced, section of the cage is lowered on top of the bottom section. The longitudinal steel bars of the bottom cage section are threaded into the ComBAR-reinforced cage section until the two steel plates of the connection are aligned. The steel plates are bolted together with conventional steel bolts. The two cage sections are then lowered into the trench. The top, steel reinforced, section is attached to the cage in a similar manner.

3.2 Applications in Berlin, Cologne, Rotterdam and Durban, South Africa

In Berlin the new subway line number 5 is being built below the famous road Unter den Linden. During construction the tunnel will be secured by soil icing. At the Brandenburg Gate station the newly developed GFRP reinforcement was installed in twenty soft-eyes that will be penetrated by a micro tunnelling machine used to drill the tunnels for the soil icing.

In Rotterdam the material was installed at the Randstad Rail Project in both head walls (diaphragm walls) of the Statenweg station. As in Amsterdam, the unstable soils and high water table lead to a high reinforcement ratio in the GFRP reinforced areas.

The unusual geometry of the diaphragm walls and, as a result, the reinforcement cages in the launch and reception shaft of the Durban Harbour Tunnel Crossing in Durban, South Africa, mandated a custom-made design and lay-out of the GFRP reinforcement.
4. CONCLUSIONS

The installation of GFRP rebar in the diaphragm walls of launch and reception shafts of large tunnelling projects can lead to substantial savings in the overall construction cost.

In the design of GFRP reinforced concrete diaphragm walls the material properties of the specific GFRP rebar material have to be considered. While the design is similar to that of steel reinforced walls, the load bearing capacity of a GFRP reinforced diaphragm wall is controlled by the concrete strength. The stiffness of the GFRP bars used is critical in the design. The superior material characteristics of the newly developed GFRP rebar system presented in this paper ensure an efficient design.

The material has already been applied on several large infrastructure projects world wide. Several projects are under planning where the material is to be used as reinforcement in concrete pile walls.

REFERENCES