GFRP Soft-Eye for TBM Breakthrough: Possibilities with a Modern Construction Material

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ABSTRACT

Building tunnels with Tunnel Boring Machines (TBM) is today state of the art in different ground conditions. Launching and receiving the TBM in shafts and station boxes has in earlier years required a considerable construction effort. Breaking through the steel reinforced walls of the excavation shaft with a TBM required extensive measurements and preparation works. Using modern construction materials as Glass Fibre Reinforced Plastic (GFRP) allows the designer and contractor today to find innovative solutions for the well known situation and save time and costs on site. The following article discusses the relevant material characteristics of GFRP and their influences on the design and construction of alternative TBM breakthroughs and shows possible solutions for the mentioned situation.

1. INTRODUCTION

For several decades TBM’s have been used for the construction of tunnels. Depending on the local situation the TBM can start or end its drive for example in a precut in the open terrain or by lowering it into an excavation shaft down to the tunnel level. This latter technique is used mostly in congested city areas. A few years ago starting and receiving a TBM in an excavation shaft required extensive measures for breaking through the walls of the shaft, which is secured out of steel reinforced concrete. This preparation work needed time and has been expensive. In recent years however the use of Soft-Eyes in these areas is becoming more and more popular. A Soft-Eye may for example be a diaphragm wall or bore piles reinforced with Glass Fibre Reinforced Plastic bars (GFRP) instead of reinforcement out of steel. Also an anchored tunnel face with GFRP anchors will not obstruct the TBM head driving through. The use of GFRP products in tunnelling is getting more and more common in Southeast Asia and is widely applied in Europe and Japan nowadays.

2. ADVANTAGES

In the last few years the use of GFRP bars and anchors on construction site has become more and more customary. For special applications GFRP material are used today to build tailor made solution for demanding situations. The material cost might still be higher compared to the costs of conventional steel products, but this fact is more than compensated with the lesser work involved in preparing the shaft constructions for the TBM launch/receive for example. On the technical level, GFRP products have important advantages. Besides flexibility, elasticity and the minimal environmental impact the following points are key advantages compared to steel:

- Corrosion Resistance:
  GFRP is a durable material which is not affected by corrosion. Therefore GFRP bars/anchors can be used also for example as part of the final lining in a tunnel supporting the structure during its
whole life span. No excessive measurements for the protection of the anchor against corrosion are required as is necessary with steel anchors.

- **High Tensile Strength:**
  GFRP bars can bear very high tensile loads. The commonly used fibre bars in the construction industry have a breaking load which is nearly double as high as the one of a steel bar with same diameter.

- **Cuttability:**
  GFRP material can be cut with working tools like saws, piling/drilling equipment and TBM tools. This avoids damages to cutter heads and does not delay the work progress as piling or cutting through GFRP bars is unproblematic. The fibre bars are split in small pieces which do not harm slurry pipes.

- **Low Weight:**
  The weight of a GFRP bar is only a fourth of its steel counterpart, having the same dimensions. Combined with the flexibility of the bars this allows an easy installation even in confined working space or where the support of lifting equipment is not available.

There are many different GFRP bars on the market today with their own specific advantages and disadvantages. Even some products with a thread over the whole length of the bars are available. These bars together with a wide range of available accessories like nuts or couplers allow the GFRP to be used on site as flexible as the classical steel products. The thread ensures also a superb bonding behaviour between the GFRP bar and the surrounding concrete or grout. However in opposition to steel products welding is not possible with GFRP. It is important to understand that the properties of the GFRP depend strongly on the type of fibres, resin and additives used and is also influenced by the production process. General technical values valid for all GFRP material can therefore not be given, as the technical properties vary in a wide spectrum. For specific details product information from different suppliers are valuable sources of information.

### 3. GFRP MATERIAL

Most glassfibre products are manufactured in a so called pulltrusion process. Single fibres or fabrics of glass fibres are impregnated with a resin and shaped into the required form. Before the resin is cured the bars get a surface treatment for improving the bonding properties between the bars and the concrete for example when they are used as reinforcement. The surface treatment can be different for each supplier. It can for example be a roughening of the surface, forming a continuous thread on the whole surface or also sand coating the bars. After the surface treatment the resin is cured and the bars cut to length. A final step in the production can be a surface coating for giving the fibres, besides the encapsuling in resin, an additional protection against alkaline degradation.

It is the fibres which give the bars their high tensile strength. The resin is just holding the fibres together and protecting them also from damages and alkaline degradation. For reaching high tensile capacities of the bars it is therefore desirable to have a high glass content in the GFRP product. Typical values for this glass content are around 75% of the weight of the bar, but can reach even over 80%. The resin itself is normally a thermosetting resin cured in a heater, but also curing with microwaves is used today. This means also that once the polymerisation of the resin has taken place it can not be reversed. Necessary bends for example for shear reinforcement bars have therefore to be made during the production process in the factory. Here any shape required can be manufactured according to the requirements of the project. Bending of bars on site is not yet possible. However with further development of the resins this step might be taken in the next few years.

The type of fibre, the resin used and also the details of the production process vary from manufacturer to manufacturer. All the bars used in the construction industry have in common the parallel fibre alignment within the cross-section and their complete enclosure in the resin matrix. Picture 1 shows some detailed photographs of the fibres in a GFRP bar made with a scanning electron microscope. The parallel alignment of the fibres can be clearly seen in the longitudinal section while the embedment of the fibres in the resin can be observed in the cross section.
4. TECHNICAL PERFORMANCE

GFRP reinforcement bars have a very high tensile strength which can reach far over 1000 N/mm². But as the values are different for the bars of different manufacturer, a general value for all bars cannot be given. Furthermore the tensile strength of a reinforcement bar out of glass fibres depends also on the diameter of the bar. Bars with a smaller diameter have a higher tensile strength than bigger ones. More informative for GFRP bars is therefore the bearing capacity. As the bars are produced in a wide range of qualities and diameters, the right product for a specific application with the requested bearing capacity can easily be found in the market today. Bars with a bearing capacity well over 700 kN are available today in Singapore.

GFRP bars have some typical material behaviours which distinguishes them from the more commonly used steel bars. First and most significantly of all is the lack of yielding of the material. GFRP is linear elastic till failure which can be clearly seen in Figure 2. This is the reason why GFRP bars are used as reinforcement in Soft-Eye areas. The brittle failure behaviour allows the TBM to drill through the concrete and the reinforcement bars. Steel reinforcements would obstruct the TBM due to its yielding behaviour. Locally high loads introduced onto the tunnel face by the tools on the TBM cutter head are transformed into a yielding deformation of the steel reinforcement. This may prevent the TBM from passing trough the steel reinforced concrete structure and may result in damaging the cutting tools.

The mentioned linear elastic behaviour of the GFRP bars is caused by their load bearing element, the fibres in the bar. The properties of the fibres can be described with a linear elastic stress-strain relationship until failure. Therefore the deformation behaviour of the bars under tensile loads is explained with the specific behaviour of the fibres used in the bar. GFRP bars have for example a typical elastic modulus around 40,000 N/mm². This low elastic modulus is generally a disadvantage of the material as it can lead to big deformations and therefore to open cracks in concrete structures. In special situations however this low elastic modulus of the GFRP bars can also be advantageous. In case the GFRP bars are used as prestressed anchors for example, moderate deformations of the ground will just result...
in small adjustments in the anchor load. A strong loss of the prestress force for example due to concrete shrinkage can therefore be avoided.

Figure 2. Typical stress-strain behaviour of a FRP bar compared with a steel bar.

Although the modulus of elasticity for GFRP is much smaller and the breaking load is almost double than the one of steel, the resulting deformations before failure of the GFRP bars are moderate due to the lack of a yielding behaviour of the glass fibres. As a result failure of a construction element reinforced with GFRP bars has to be judged as brittle and considerable care should be taken during the design process to ensure that an overloading of the element can be excluded.

5. DESIGNING WITH GFRP

The first GFRP applications in the construction industry go back well over 20 years. These applications have been related to projects, where electrically nonconductive reinforcement was demanded or the construction was exposed to a severe corrosive environment. This was mostly the case where high salt concentrations have been present like on highway bridges and airport runways out of the application of de-icing salts or for seawall construction. GFRP is mostly used in highly industrialized countries like the USA, Japan and Europe, where a lot of research work was conducted in the last decades. These countries, which have the advantages of a long experience of constructions with GFRP, have in the meantime developed standards and guidelines for the design with GFRP material. Most commonly used is the American guideline ACI 440.1R “Guide for the Design and Construction of Concrete Reinforced with FRP bars” published by the American Concrete Institute. Other countries have also established recognised design and construction standards as for example Great Britain with their British Standards and the “Interim guidance on the design of reinforced concrete structures using fibre composite reinforcement (1999)” from the Institution of Structural Engineers, Germany with the DIN Codes and also Japan or Canada.

In comparison to the conventional design of concrete elements with steel reinforcement, designing with GFRP shows some important singularities based on the typical material properties of the material used. The most important one is based on the fact that GFRP shows under tensile load a linear elastic behaviour with no yielding deformations till failure. For the design of GFRP reinforced flexural members out of concrete a different design approach is chosen than that used for steel reinforcement. While the steel reinforcement is commonly designed so that it is overloaded and yields before the concrete starts crushing for assuring a ductile failure behaviour of the element, such preference is not set for the design with GFRP reinforcement. With GFRP both failure modes, the one governed by the crushing of the concrete (concrete crushing failure) and the one governed by the tensile rupture of the
fibre reinforcement (rupture-controlled failure), are acceptable. While the rupture-controlled failure leads to a sudden failure with limited warning, the concrete crushing failure shows a pseudo-plastic behaviour due to the deformations resulting out of the concrete crushing. This results in a higher reliability as a failure will be announced by the appearance of observable deformations. A strength reduction factor of 0.7 for the tensile strength of the bars is therefore recommended by ACI 440.1R for the concrete crushing failure compared with a more conservative factor of 0.5 for the more sudden rupture-controlled failure. A linear interpolation between the factors is chosen in the transition range between the two failure modes.

The absence of a yielding behaviour of the glass fibres affects also the tensile strength in bent areas of the bars. Among other effects like fibre bending and stress concentrations it can not be prevented that the different fibres in the bent parts of the bar are uneven loaded resulting in failure of the first fibres and with it of the bar before all fibres have reached their ultimate tensile strength. The tensile capacity of a bar is therefore reduced in a bent section compared to a straight section. The ACI 440.1R gives a detailed recommendation, how this reduction can be determined.

A similar impact on the design as the lack of a yielding behaviour has the low modulus of elasticity of the GFRP. This is especially the case when serviceability is a design criteria. With a modulus of elasticity about 5 times lower than the one of steel, designing for crack width limitation or limited deflections can require a very high percentage of reinforcement what will similarly increase the material costs. General specifications for the serviceability should therefore be carefully evaluated if they also apply for GFRP reinforced concrete members. When corrosion of the reinforcement is the primary reason for the specified crack width limitation for example, this requirement can be relaxed as the GFRP bars are corrosion resistant. In general it can be stated that for structures with reinforcement out of GFRP with a short life-cycle like Soft-Eyes, crack width limitations can be disregarded if aesthetic criteria is not a concern. However the deformations of GFRP reinforced members have to be considered especially when they are standing in a direct interaction with steel reinforced members. The different deformation behaviour of members can lead among others to considerable load redistributions which have to be considered during the design process.

The overall aim to have a secure design for the Soft-Eye in the excavation shaft is not only a matter of choosing the right bar diameter. It is also a part of the general planning process and involves working together and communication between client, consultant, contractor and specialist supplier.

6. SOFT-EYES

Soft-Eyes consist usually of bore piles or diaphragm walls which are locally reinforced with GFRP bars. The sections below and above the tunnel are reinforced conventionally. Depending on the designer and contractors preferences full rectangular sections are built out of GFRP bars or the fibre reinforcement follows more closely the tunnel section resulting in a circular arrangement of the GFRP links and similar adjustments for the vertical bars. Both possibilities have their advantages. While a rectangular arrangement saves time during the design and assembly of the cages, following more closely the tunnel section is reducing the material costs for the GFRP bars. Often applied is a compromise where the vertical bars are covering a rectangular section while the shear links follow the circular layout. Experience shows that this approach increases the material costs for the GFRP material by less than 5% compared to the minimum possible while the detailed design and assembly of the cages is still efficient. Picture 3 shows such a solution.

Building the corresponding reinforcement cages out of GFRP bars on site requires the same working procedures as for an equal steel cage. The necessary bars are tailor made and delivered to site where the assembly takes place. The bars are fixed together with binding wire, cable binders or similar products. U-bolts are used for clamping bars together when high loads have to be transferred over a connection. This is the case for example in the connection between vertical GFRP bars and the corresponding steel bars which have to carry the dead load of the reinforcement cage during the lifting process and lowering of the cage into the trench. Welding as is commonly done with steel reinforcement in such situations is not possible with GFRP bars.
The use of GFRP reinforcement for diaphragm wall cages does not restrict the designer and the contractor in choosing the most suitable panel size for a specific task. However, as the modulus of elasticity of the fibre reinforcement is relatively low, special measurements should be taken for assuring the cage integrity during the handling and lifting process. Otherwise large deformations of the cage could occur while lifting up and rotating the cage in a vertical position. This could result in displaced bars or even in breaking open of the cage when the bars are not well fixed in place. For preventing such incidences supporting frames or steel beams can be used to stiffen the GFRP cage during handling and lifting. These stiffening elements are normally mounted on the outside of the GFRP reinforcement cage and have to be designed to resist the bending moments acting on the cage during the lifting process. Once the cage is in a vertical position, the stiffening elements are dismantled section after section before the cage is lowered into the trench. Picture 4 shows such a stiffening frame out of steel on the GFRP cage for the diaphragm wall.
6.1 Alternative applications

In case more space is available and the ground conditions are favourable, excavation pits are often secured using sprayed concrete and anchors. In such situations prestressed steel anchors are commonly used for limiting the deformations of the excavation walls. However, such steel anchors in the region of the tunnel would obstruct the tunnelling process and damage the cutter head of a TBM. Also for such a construction method Soft-Eye solutions are possible and have been used successfully. For allowing an unobstructed passage of the TBM the steel anchors in the region of the later TBM face are replaced with GFRP anchors. For such an application GFRP anchors with a continuous thread on the surface are favourable. They are easily installed with an anchor plate and a nut on the anchor shaft with no requirements for special tools. Furthermore such threaded bars allow introducing locally the highest loads into the bars at the anchors head as it is desired. Similar as for standard Soft-Eye, the use of GFRP material in such a way does not obstruct the tunnelling process. Figure 5 shows such an application chosen for the Islisbergtunnel as part of the national highway system in Switzerland.

Figure 5. Sketch of GFRP anchors used as Soft-Eyes in the tunnel face of the Islisbergtunnel, Switzerland

Similar situations can also occur when anchors used for temporary stabilisation of a pilot tunnel or excavation bits penetrate into a tunnel section or further constructions, which are built after the setting of the anchors. In such cases usage of GFRP anchors has the same advantages as discussed above as they can be cut by the working tools of excavation machineries. Picture 6 shows such an example where prestressed GFRP anchors have been used for securing the excavation pit during construction. Cuttability of the anchors was essential for allowing the TBM to start its drive. Alternatively removable steel anchors could have been used. But for such a solution coordinating the advance of the TBM with the removal of the anchors would have been necessary for assuring the structural safety of the excavation pit while at the same time not obstructing the TBM from advancing. Such a solution, while technically possible, would result in higher overall construction cost and was therefore avoided.
7. CONCLUSION

While there are always several ways to start or receive a TBM in an excavation shaft, a solution using GFRP bars as reinforcement in the diaphragm wall or in the bore piles has proven to be the most competitive in many situations. The use of Soft-Eyes saves not only overall construction time and costs, but is also in line with the high safety standards today implicated on construction sites. The demand from the construction industry for GFRP materials is growing steadily and additional applications with GFRP will become more common in the next years as the use of Soft-Eye is already today.

REFERENCES


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