TUNNEL HEADWALL SOFTEYES: FIBERGLASS DESIGN APPLICATIONS AND CONSTRUCTABILITY CHALLENGES

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ABSTRACT

This paper outlines the use of tunneling headwall softeyes for transit construction projects in the Greater Toronto Area (GTA) over the past decade. Due to spatial constraints, tunnel boring machines were used to construct the underground tunnels requiring the design of launch and exit shafts with headwall softeyes to facilitate tunneling operations. Variable ground conditions and shaft geometries lead to the development of innovative headwall and tunnel sofeye design applications using fiber reinforced polymer (FRP) elements (beams, reinforcing bars, and tiebacks). This paper outlines the challenges and benefits associated with designing and constructing shafts using various systems. Lessons learned throughout design and construction of more than 20 structures over the past 10 years are outlined. The constructability challenges with using FRP and design performance are also discussed.

Keywords: fiberglass, fiber reinforced polymer, headwall, tunneling, constructability, sofeye, innovation, performance, FRP, GFRP

For over a decade, the City of Toronto has been expanding its metropolitan transit network with a variety of new transit construction projects. Two recent projects in the Greater Toronto Area (GTA) for underground infrastructure include the Toronto York Spadina Subway Extension and the Eglinton Crosstown Light Rail Transit project. These add a total of 31 new stations and 18.6 km (11.5 miles) of underground transit (TTC 2017) (EllisDon 2016).

Due to ground conditions and spatial constraints of existing surface infrastructure, these projects utilized tunnel boring machines (TBMs) to construct the underground tunnels requiring the design of various types of shafts and headwalls to facilitate underground tunneling operations. To allow for tunneling through the headwalls, these shafts were designed with “softeyes” - a section of the wall without metal reinforcement that allows the TBMs to tunnel through.

PURPOSE OF SOFTEYES IN TUNNELING

A sofeye is a wall type which can be drilled through and penetrated by a TBM cutterhead. This can be accomplished in a variety of ways including: mass concrete non-reinforced drilled wall, Fiberglass Reinforced Polymer (FRP) secant pile or slurry wall, jet grout block, or ground freezing (Hunt 2008). In the GTA, we have used FRP secant pile headwalls in the following applications: Launch Shafts, Exit Shafts, Advance Headwalls, Mining Excavation Shafts, and other Access Shafts.

As their names suggest, a Launch Shaft accommodates hoisting, assembly/launch of TBMs, and mucking operations whereas an Exit Shaft is meant to receive, disassemble, and hoist a TBM. Advance Headwalls are typically installed at boundaries of future excavations, such as underground subway stations, to allow the TBM to pass through the headwall prior to excavation of the future shaft. Mining Excavation shafts are access shafts to accommodate mining operations utilizing a Sequential Excavation Method (SEM) or New Austrian Tunneling Method (NATM). Access Shafts are used to proactively provide access to the
TBM for maintenance of cutter heads at some part through the tunnel drive between the Launch and Exit Shafts. Each of these provides unique design challenges and requires design capacities, geometries, and other considerations for the uses of FRP reinforced secant pile headwalls. In Toronto, FRP reinforced softeyes have been designed and used in a wide range of variable ground conditions and adjacent structure geometries, resulting design pressures with K values from 0.25 to 1.0, FRP excavated heights of up to 20 m (65 ft), and unsupported spans of up to 5 m (16 ft).

FRP DESIGN CONSIDERATIONS

Fiber reinforced polymer materials are considered suitable for use in softeyes mainly due to their ‘cuttability’ by the TBM’s cutterhead during tunneling operations. FRP exhibits brittle failure which is different from steel’s ductility. Brittle failure allows the FRP to break into pieces without obstructing the TBM during operation. Brittle failure is also a main consideration in the design of FRP systems, and one of the reasons why current design codes such as the CAN/CSA-S806-02 apply significantly more conservative factors of safety than other design materials. Figure 1 illustrates the significantly different behavior of FRP and Steel anchor bolts.

![Comparison of Material Behavior of FRP and Steel Bolts (Mohanty 2014)](image)

**Fig. 1. Comparison of Material Behavior of FRP and Steel Bolts (Mohanty 2014)**

The manufacturing process used to produce most fiberglass products, called pultrusion, results in an anisotropic material with directional material properties. Therefore, stresses in the transverse and longitudinal directions must be considered in design. Most notably, this results in a significantly smaller allowable shear capacity compared to conventional steel beams. FRP also has a significantly lower modulus of elasticity than steel. This leads to specific design considerations when using a composite steel/FRP system like a Steel/FRP headwall. Table 1 outlines a comparison in material property values between a typical FRP pultruded shape (I-beam) versus the typical steel pile secant wall reinforcing used in the GTA. The contrast in the modulus of elasticity of the two materials needs to be accommodated in the design and can lead to different deformation behavior of the two materials resulting in load redistributions in the system (Schürch 2006). For this reason, the steel/FRP connection is modelled as a hinge since moment transfer is hard to achieve due to strain compatibility issues. This poses a design challenge as the fiberglass beam has low shear capacity. Therefore, the concrete in the secant pile wall acts as additional reinforcing, and the strength should be increased to accommodate shear stresses that exceed the FRP reinforcing capacities. The authors have used concrete strengths ranging from 15 MPa (2200 psi) to 25 MPa (3600 psi) to act as additional shear reinforcing for FRP reinforced secant pile headwalls.
Table 1 – Mechanical Property Comparison of GFRP Beams vs. Steel Beams

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Glass Fiber Reinforced Polymer Shapes</th>
<th>G40.21 Structural Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lengthwise/Crosswise</td>
<td>Fy = 350 MPa (50ksi)</td>
</tr>
<tr>
<td>Ultimate Tensile Strength</td>
<td>207 / 48.3 (30/7)</td>
<td>450 (65)</td>
</tr>
<tr>
<td>MPa (ksi)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultimate Compressive</td>
<td>207 / 110 (30/16)</td>
<td>450 (65)</td>
</tr>
<tr>
<td>Strength MPa (ksi)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultimate Flexural Strength</td>
<td>207 / 68.9 (30/10)</td>
<td>450 (65)</td>
</tr>
<tr>
<td>MPa (ksi)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulus of Elasticity – Full Section MPa (ksi)</td>
<td>19300 (2800)</td>
<td>200000 (29000)</td>
</tr>
<tr>
<td>Shear Modulus – Full Section MPa (ksi)</td>
<td>2930 (425)</td>
<td>77000 (11165)</td>
</tr>
<tr>
<td>Ultimate Shear Strength MPa (ksi)</td>
<td>31 (4.5)</td>
<td>231 (34)</td>
</tr>
<tr>
<td>Unit Weight kN/m³ (pcf)</td>
<td>18 (114)</td>
<td>77 (490)</td>
</tr>
</tbody>
</table>

(Strongwell 2012) (CISC 2010)

It is important to note the properties of FRP materials depend on the material used to reinforce the polymer (glass, aramid, carbon, etc.) and the manufacturing process used. As illustrated by the variability in the preceding examples, design strengths, design recommendations, and material property values from the specific manufacturers should be consulted when designing FRP systems.

FRP IN HEADWALL DESIGNS

A fiber reinforced softee can be accomplished in several ways. In all cases, the steel pile reinforcing typically used for the excavation support system is replaced in the softee zone with FRP reinforcing. This reinforcing can consist of FRP beams bolted to similar depth steel beams or reinforced cages with fiberglass reinforcing bars through the softee zone.

Fiberglass Beams

In the GTA, FRP beams have been more commonly used for softee reinforcing. Figures 2 and 3 illustrate a few iterations of FRP/steel softee splices using either FRP splice plates and bolts or typical steel plates and bolts. Since FRP shapes come in a smaller variety of sizes and thicknesses, special consideration for shim plate sizing and preferred pile layout in the headwall needs to be considered.
Fig. 2. Steel/FRP Splice Details – Steel Plate and Bolts (Left) and FRP Plates and bolts (Right) (Units in mm)

Fig. 3. Fabrication and Installation of FRP/Steel Beam at an Advance Headwall
FRP beams can also be built up using other FRP shapes to create composite design sections for loading cases where single FRP beams lack capacity. Figure 4 shows an example of a built up pile layout used for a FRP reinforced headwall for a TBM exit shaft. Special attention to bracing connection detailing (i.e. walers and corner bracing, etc.) and excavation activities needs to be considered prior to construction when using built up FRP connections. In the project example shown in Figures 4 and 5, the secant pile wall was not trimmed back to the front of the steel pile flanges above the softeye to avoid damage to the built up FRP shape through the softeye.
Fiberglass Reinforced Cages

Using reinforced cages with steel/fiberglass for headwall softeyes provides its own unique set of design challenges. Current fiberglass design codes specify conservative allowable stresses for fiberglass design (allowable = 30% ultimate) due to a number of factors (CSA 2009). These include the failure mode of the material, lack of differentiation between temporary and permanent uses, as well as the lack of historical data for use of FRP as a design material compared to other materials. This results in an increased number of bars in the FRP section of the cage to achieve the same required design capacity as the steel section (illustrated the design example shown in Figure 6). Figure 7 shows the FRP/steel cage assembly on the spine support prior to lifting and installation.

![Fiberglass Reinforced Cages Diagram](image)

**Fig. 6. FRP/Steel Cage Reinforcement Detail and Pile Layout Example (Units in mm)**

![Steel/FRP Cage Assembly on Spine Support Beam prior to Lifting](image)

**Fig. 7. Steel/FRP Cage Assembly on Spine Support Beam prior to Lifting**

Fiberglass Anchors

The other strategy used for design of Launch or SEM shaft headwalls is the addition of fiberglass anchors to decrease bending in the FRP pile section, and decrease the shear at the steel/fiberglass splice connections. Use of these anchors has resulted in simplified pile layouts due to the decrease in required fiberglass material, as well as a decrease in the required concrete strength to resist the shear at the connections. Figure 8 shows the design detail developed for use of the fiberglass anchors. Due to the limited availability of high tensile capacity fiberglass anchors, three 25 mm (1 inch) GFRP bars were used.
per location to achieve the required design capacities. In addition, due to limited availability of FRP anchor plates and other bolt accessories, the secant pile wall had to be further broken around to allow enough room to separate the FRP bars for three separate anchor connections at the face of the wall. These FRP anchor connections were recessed into the secant pile wall to allow the bars to be trimmed back. The recess was filled with concrete prior to launching the TBM to allow for a continuous mining face.

![Diagram of FRP Anchor Connection Design](image)

**Fig. 8. FRP Anchor Connection Detail and Example of use at a Launch Shaft (Units in mm)**

Use of the FRP anchors has also allowed for larger design heights and different shaft geometries since internal bracing of the FRP beams is not required. This has allowed for more open excavations, and sequential mining of SEM headwalls as anchor elevations can be customized to the required geometry. Figure 9 shows a progress photo of the excavation for the SEM access shaft to allow mining for future light rail station using the Sequential Excavation Method.

![Mining Access Shaft Headwall with FRP Anchors](image)

**Fig. 9. Mining Access Shaft Headwall with FRP Anchors – Sequential Mining in Progress**
CONSTRUCTABILITY CHALLENGES

Throughout the design and construction of these FRP reinforced systems, several constructability challenges have been experienced.

General Challenges

**Hoisting/Assembly:** Due to the low modulus of elasticity of the FRP reinforcement, the designer and contractor should work closely to understand the forces which may be encountered during hoisting and placement of the FRP reinforcement to ensure the cage or pile integrity. To minimize these forces, two different systems have been used in the GTA:

- **“Dummy holes”** – Vertical splicing over a sacrificial hole followed by vertical hoisting and placement of the reinforcement into the drilled secant pile wall.
- **Support frames** to act as a rigid spine to support the FRP reinforcement during the lifting process. Once the cage is vertical, the spine is disconnected prior to lowering the cage in the drilled hole.

Other means of lifting, such as the use of multiple pick points with the use of strong backs and rolling blocks, have been used in other jurisdictions.

**Excavation/Shaving:** Secant Pile walls in the GTA are typically reinforced with steel I-Beams in low strength concrete (4 MPa/ 580 psi) whereas FRP reinforced headwalls can have concrete strengths of up to 25 MPa (3600 psi). Excavators are used to trim the rounds of the secant pile walls to accommodate bracing/support connections and the proposed permanent wall locations, where applicable. Due to the different geometries of the FRP sections and weaker material strength, damage to the FRP materials from the excavator was experienced, such as over-excavation through FRP pile sections and bolted splice connections being sheared off during excavation to the pile face as seen in Figure 10.

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**Fig. 10. Broken FRP bolts (Left) and Over-excavation through FRP Piles (Right)**
**TBM Forces:** The Shoring wall designer must understand the temporary supernormal loading pressures, which may occur when the TBM is approaching the back of the shoring headwall prior to breakthrough. Earth Pressure Balance Machine's used in the GTA can impose a pressure of up to 200 kPa (30 psi) on the back of the shoring headwall. To ensure adequate FRP Exit Shaft Headwall performance, removable internal bracing can remain in place until TBM makes contact with the back of the headwall and earth pressure forces are negated.

**Softeye Placement Accuracy:** Placement of the FRP/steel reinforcing requires coordinating installation of the FRP within tolerances necessary for tunneling by the headwall Shoring Contractor. This can be particularly challenging when trying to mimic the circular tunnel liner shape with the FRP softeye.

**Monitoring Programme:** Based on the design challenges mentioned above, a quality monitoring programme for the temporary FRP walls in softeye applications is prudent. On these projects, a combination of 3D Precision Survey Monitoring, Inclinometers, and Load Cells on the anchors between the tunnels were successfully used.

**FRP Reinforced Cages**

Although our experience in the use of FRP reinforced cages is limited, several important lessons were learned through the construction process. During installation of the 33 m (108 ft) long reinforced cages, several of the cages broke in the FRP section resulting in the top section of the steel cage falling into the required softeye clearance zone. Upon review of each of these occurrences, two main modes of failure were determined after cage recovery.

Initially, the bars were fixed together with binding wire and scattered U-bolts at the FRP/steel splice location. After the initial splice failure, additional U-bolt reinforcing was added to the splice connections shown in Figure 11, a recommendation also reinforced by Schürch and Jost in their 2006 paper.

After the initial failure mechanism was resolved, some of the cages began to break within the FRP only section during drill casing extraction. This was determined to be a result of the small 50 mm (2 inch) cover between the inside of the drill casing and the outside of the cage. To resolve this issue, additional FRP ties were added to the cage, and an oscillator was used for liner extraction of the remaining piles to limit the torque applied to the cages from continuous rotation in one direction.

![Fig. 11. Reinforced FRP/Steel Splice Connection](image)
Future recommendations for design of FRP cages include:

- Increased cover between drill casing and cage reinforcing;
- Additional U-bolt reinforcing at splice connections where large forces are transferred;
- Use of reverse spiral shear reinforcing on the inside and outside of the cage in lieu of single tie shear reinforcing to limit shear forces applied to the cage during liner extraction; and
- Special attention to concrete mix design and forces on cages during construction.

CONCLUSIONS

Underground transit infrastructure projects in metropolitan areas provide an excellent opportunity for use of Tunnel Boring Machines (TBMs) to minimize impacts to existing surface and shallow infrastructure and surrounding communities. Use of TBMs requires construction of various Launch, Exit, and Auxiliary Shafts to facilitate tunneling operations requiring the design of shaft headwall softeyes. The use of FRP reinforcement and bracing has proven to be an effective and efficient means of providing structural support of the shaft and suitability for accommodating tunneling operations. The design of FRP systems provides unique construction challenges compared to more common construction materials; therefore, special attention needs to be given to material properties and constructability challenges. Overall, use of FRP has been found to be the most effective solution for softeyes in large diameter tunneling applications in various soil conditions in the Greater Toronto Area.

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REFERENCES