Glass fibre reinforced polymer (GFRP) permanent rock bolts

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ABSTRACT: Glass fibre reinforced polymer (GFRP) is a composite material with many advantages compared to steel – both structurally and in respect of the embodied carbon in the material. Tensile elements like reinforcing bars and rock bolts can be manufactured from GFRP. While they have an excellent tensile strength, because most glass fibres are aligned in the longitudinal direction along the bar, the performance under shearing is less good, particularly the transverse direction due to the anisotropy. Some full scale tests have been performed and these show that the shear capacity of GFRP rock bolts can be higher than steel ones of the same diameter when sheared obliquely. Full scale testing is rarely done because of the cost. To complement this, numerical modelling offers a virtual laboratory in which to explore the behaviour of materials. A new simple design method can evaluate the shear capacity. This paper examines the key concerns regarding GFRP rock bolts in the overall context of the suitability of these bolts for permanent rock support.

KEYWORDS: GFRP, rock bolts, creep, shear, LCA

1. INTRODUCTION

As the tunnelling industry grapples with the competing demands for ever more underground space and the urgent need to reduce the environmental impact of these structures, there is increasing interest in new design methods and low carbon materials. The use of rock bolts for permanent rock support is well-established in Nordic region – as enshrined in the Q-system, for example. Typically, these are steel bolts with some additional form(s) of corrosion protection. Steel is vulnerable to corrosion in wet environments and also the embodied carbon content is high. Attention has been drawn to GFRP as alternative material because of its high tensile strength, excellent durability and its lower embodied carbon content.

This paper will review the current position of GFRP rock bolts and the obstacles to the wider usage of this technology. Shear behaviour has been highlighted as one area of particular concern. This paper will consider this issue in detail, presenting a collection of published data on this subject as well as the results of some recent research at DTU in Copenhagen.

2. PERMANENT GFRP ROCK BOLTS

2.1 Permanent rock bolts

Permanent rock bolts have been used for many years in some countries, most notably in the Nordic region. Elsewhere, rock bolts are treated as temporary. Rock bolts are a very effective element of rock support in blocky rock masses. Neglecting them in the longterm is wasteful in terms of money and the embodied carbon. To reduce both of those, it would be better if permanent rock bolts were more widely used. The only obstacle to this is the durability of the bolts.

2.2 An overview of GFRP rock bolts

GFRP is a composite material – and in the context of rock bolts – it consists of glass fibres embedded in either a polyester, vinylester or epoxy resin matrix. This gives the rod a high tensile strength, especially in the longitudinal direction. The resin matrix fixes and protects the glass fibres. The most durable GFRP uses a vinylester resin matrix matched with a suitable, corrosion-resistant (ECR) glass fibre. The focus of this paper is on high-quality GFRP for use as permanent rock bolts. The fib report (fib 2005) provides an excellent overview of GFRP as a material and in terms of structural design in general.

The advantages of GFRP for rock bolts include:

- Excellent durability
- High tensile strength
- Lower embodied carbon (~30% less than steel)
- Low weight (about a third of a steel bar) – so safer to handle
- No electrical conductivity
- Non-magnetic (so no risk of stray current corrosion)

While automated bolting will become more common in the future, currently there is a lot of manual handling during bolting operations. Since GFRP is much lighter than steel, this reduces the strain on the workers handling the bolts. There is rightly an increasing focus on occupational health in the overall realm of health and safety. GFRP offers one way to reduce the health impacts associated with bolting.

For the best quality, GFRP should be produced in a pultrusion process in a temperature-controlled environment, using high-quality glass fibres, having a high fibre content of about 75%, embedded in a vinylester resin. The remainder of this paper will focus on the application of these high quality GFRP bolts. Most of the bolts on the market these days are designed for temporary applications and they do not have the durability or mechanical properties needed. When choosing a bolt for a permanent application, the datasheets and test reports from the manufacturers should be examined carefully. The variation in quality of products available also presents a challenge when comparing published research.

Thomas (2019a) reviewed the use of GFRP as permanent rock bolts while Thomas (2019b) examined the mechanical performance in detail, including tensile and shear performance. Johansson et al (2020) evaluated the suitability of GFRP for permanent rock bolts and concluded that GFRP is suitable in rock masses of good quality where block instability is the main failure mode and the expected strain in the rock mass is limited. The researchers highlighted some residual concerns of which the most serious centred around durability in alkaline environments, creep and shear capacity. The following sections will look at each of these topics.

3. DURABILITY

Zhou et al (2011) describe the different mechanisms acting on GFRP, in comparison to steel. In the case of GFRP, carbonation and chloride attack are not relevant whereas diffusion of alkaline ions or water molecules into the resin matrix can cause degradation (fib 2005). A suitable resin must be used to resist this. Closed cell vinylester resin is much more durable than polyester (Robert & Benmokrane 2013). Similarly, alkali-resistant glass fibres should be used. As noted earlier, many of the published studies relate to low quality GFRP, typically using polyester resin so they should not be generally used in the evaluation of permanent GFRP rock bolts.

Test data from high quality products have shown an excellent retention of tensile strength in accelerated ageing tests (e.g. > 75 for unloaded samples over 100 years – Robert & Benmokrane (2013)). The bars in this study were encased in concrete and stored in water or a saline solution. Surprisingly, the salinity of the water did not appear to influence the retention of tensile strength.

GFRP rock bolts are unlikely to be exposed to acidic groundwater but this can occur in certain geological conditions such as alum shale. Zhou et al (2011) compared a samples of plain steel bars with a low quality GFRP, both embedded in concrete and stored in solutions of various acidities. GFRP performed slightly worse than the plain steel. However, it is not clear if these results can be extrapolated to rock bolts.

4. CREEP

GFRP creeps under load so the sustained stress must be limited to avoid creep rupture. Typically, this limit ranges from 40 to 45% for a 100 year design life (fib (2005) – Type B in figure 3.2). The fib guideline describes a method for determining the overall material factor of safety for GFRP, which accounts for creep, based on data from creep tests. The best approach is to use creep data from tests on the specific GFRP product foreseen when determining this safety factor, rather than the general advice. The best quality GFRP bolts have an overall factor of safety of around 2, based on this method. Since the ultimate tensile strength of GFRP is typically twice that of steel, this means that steel bolts can be swapped for GFRP bolts of the same diameter.

5. SHEAR BEHAVIOUR

A common point of discussion is the capacity of GFRP bolts under shear loading. This is a valid issue, even though most designs for rock tunnels do not explicitly calculate shear loads.

Experimental data shows that, while shear capacity of embedded GFRP bolts is generally lower than steel bolts, if the bolt crosses the shearing plane at 90°, GFRP bolts actually have a significantly higher capacity than steel ones at lower angles. In reality, most bolts cross joints obliquely, at these lower angles. Thomas (2019b) presented a collection of published data in a series of figures considering the influence of the most common variables on shear capacity. The variables included hole/bolt diameter, strength of the host rock and strength of the grout.

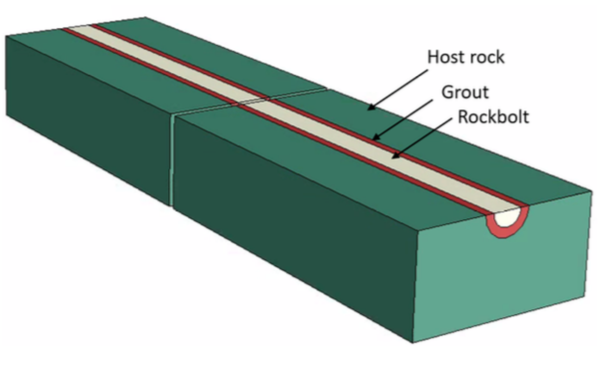

Figure 1 Numerical model of an embedded rock bolt under shearing – discretization omitted for clarity (Christensen 2020)

While there is a reasonable pool of data for shearing at 90°, there is limited published data on the variation of shear capacity with the angle of inclination to the plane of shearing. To address this, a plan for small scale shear testing was developed at DTU. However, due to the COVID-19 pandemic, this laboratory work had to be abandoned and instead a parametric study of this subject using numerical models was performed (Christensen 2020).

In this numerical modelling study, a bolt encased in an annulus of grout, embedded in rock, was simulated using the finite element software, ABAQUS – see Figure 1. The two blocks of rock are sheared past each other and the behaviour of the system analysed. The grout and rock were modelled as elasto-plastic materials while the bolt was simulated as an elastic material, with the failure of the bolt evaluated during post-processing, according to the Azzi-Tsai-Hill failure criterion for an orthotropic material. This approach was deemed to be more appropriate given the anisotropic nature of GFRP.

The parametric study investigated the realistic ranges of key parameters such as host rock strength, joint width, bolt diameter and, most critically, the angle of incidence of the shearing plane to the bolt, ranging from 45° to 90°.

Figure 2 shows the results from this numerical study alongside the prediction using an analytical method proposed by Thomas (2019b) and published data from experimental shear tests of embedded rock bolts. The shear capacity, Q, in Figure 2, has been normalized by the ultimate tensile capacity of the bolts, Nult, so that data from different bolt diameters can be plotted on the same graph. All of the data refers to GFRP bolts, except for Maiolino & Pellet (2015) which are from steel bolts. The tests by Maiolino & Pellet (2015) used blocks with rough surfaces. This additional friction leads to higher apparent shear capacities than the other tests which used smooth blocks, typically made from cast concrete.

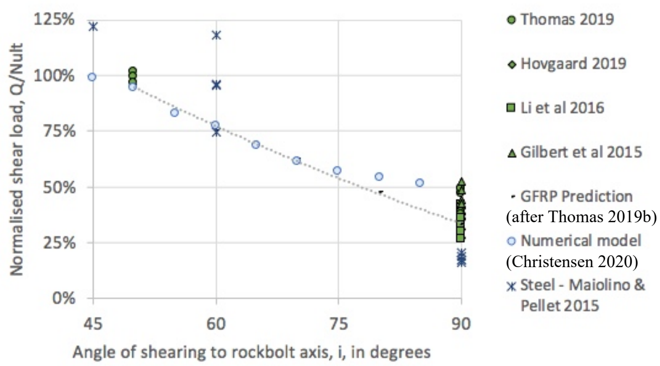

Figure 2 Normalized shear capacity vs angle of inclination

This numerical modelling confirmed the previous theoretical work by Thomas (2019b) and demonstrated that the shear capacity of GFRP increases as the angle of inclination to the shear plane decreases from 90° towards 45° - see Figure 2. The numerical model agreed well with the predicted capacity for a GFRP bolt, sheared under the same conditions, using the simplified analytical method across most of the angles of incidence but less well at angles close to 90°. Again, it should be noted that in reality in most rock tunnels, bolts cross joints at angles closer to 45° to 60°. Thomas (2019b) contains full details of the design method, along with a more thorough discussion of the published data and the key variables.

As importantly, Figure 2 shows that the experimental tests agree reasonably well with both the analytical solution and the numerical model. The picture of an increasing shear capacity as the angle of incidence drops from 90° towards more realistic values is clearly visible in these three independent groups of data.

This can give tunnel designers confidence that, firstly, in practice the capacity of the rock bolts, embedded in the rock under shearing at realistic angles of incidence will be higher than has been previously assumed, in the simplistic approach of assessing the shear capacity of a bolt alone, cut at 90°. Secondly, if it is necessary to evaluate the shear capacity of the embedded bolts in a rock tunnel design, this can be done directly, using either explicitly numerical modelling or the simplified method proposed by Thomas (2019b).

6. EMBODIED CARBON

Steel is one of the biggest contributors to the carbon footprint in a construction project. Hence there is a growing interest in the use of composite materials as low carbon alternatives for steel. Considering reinforced concrete beams, Garg & Shrivastava (2019) compared the moment capacity vs cost ratio as well as the ratios of moment capacity to embodied carbon and energy consumed in production. This study produced the surprising conclusion that carbon fibre bars were the most economic option for reinforcing a beam in a marine environment, despite the fact that Carbon fibre reinforced polymer (CFRP) is much more expensive than steel. However, in terms of sustainability, GFRP was the best option, slightly ahead of Basalt fibre reinforced polymer (BFRP). Both were about 40% better than steel.

There are few studies of this subject in the context of rock support for tunnels. The most relevant one is Kodymova et al (2017), which presented a Life Cycle Analysis (LCA) of the specific case of GFRP rock bolts. Compared to the normal permanent steel bolt, GFRP was found to be significantly better in all categories of environmental impact.

While rock bolts contribute only a small amount to the overall carbon footprint of the rock support in a tunnel (Thomas 2019b), they are one of the few items which can be easily changed. This makes GFRP an attractive choice. In summary, in terms of embodied carbon, GFRP is at least 30% better than the equivalent steel bolt (Thomas 2019b).

7. CONCLUSIONS

Clearly, it would be better for many reasons if the rock bolts used in tunnelling could be regarded as part of the permanent rock support. This is currently normal practice in the Nordic region, using twin corrosion protected steel bolts. This approach could be extended to many other regions in the world.

GFRP is a material which has many advantages in the context of rock support, primarily, its excellent durability, low embodied carbon, high tensile strength and low weight. This paper has demonstrated that GFRP bolts also have excellent shear capacity at the normal angles of shearing in rock support. If required, this can be proven using the simple design method proposed by Thomas (2019b). A recent study for Trafikverket in Sweden supported the use of GFRP for permanent rock bolts but, at the same time, it raised a number of concerns (Johansson et al 2020). This paper has shown that these concerns can be overcome, which opens the path for permanent GFRP rock bolts.

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