Developments in ground anchor technology: Carbon Fibre Reinforced Polymer (CFRP)

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ABSTRACT

Anchored structures are one method of ground improvement used in practice. Steel strand ground anchor corrosion issues can restrict long term use of ground anchors. Advances in the development of corrosion resistant materials such as fibre reinforced polymer (FRP) including carbon fibre based reinforced polymer (CFRP) and aramid fibre based reinforced polymer (AFRP) have allowed for research into the development of a more robust anchor system that aims to eliminate the limitations currently encountered with steel strand ground anchors. This paper provides an overview of the development of ground anchors from alternative materials (CFRP and AFRP).

1 INTRODUCTION

Ground anchors are a sub-structural member that transmit a tensile force from the main structure to the surrounding ground (Hanna, 1982). Ground anchors are used in a variety of civil engineering applications to stabilize rock/soil faces and resist uplift and overturning forces acting on structures (Littlejohn and Bruce, 1977, Weerasinghe and Adams, 1997, Xanthakos, 1991). Developments in new age materials such as aramid fibre and carbon fibre have enabled engineers to actively investigate ways of reducing limitations of the current steel strand ground anchors. This article provides an overview of current best practices for steel strand ground anchors and investigates the developments of fibre reinforced products emerging into the market that have potential to replace steel strand anchors.

2 GROUND ANCHORS

2.1 Background

With the exception of the development of the single-bore-multi-strand ground anchor system developed by Tony Barley, ground anchor design has not changed dramatically since the works carried out by Littlejohn and Bruce (1977) and Hanna (1982). Recent research has focused on improvements to anchor corrosion protection. Global standards (IS/BS EN 1537:2000) now require a minimum two levels of corrosion protection system be used for all permanent ground anchors.

2.2 Current ground anchor practices

The publishing of works by Littlejohn and Bruce (1977) and others provided the foundations for the design methods used in current best practices. Since the development of the fundamental design methods numerous standards have been developed. Over the years these standards have been refined based on further work carried out by Hanna (1982), Habib (1989), Littlejohn and Bruce (1977), and Littlejohn and Weerasinghe (1997) to name a few. In the last 10 years the primary areas of anchor improvements have been advancements in installation process, minimisation of risks and hazards, and improvement of corrosion protection. This paper will discuss the advancements made with current corrosion protection systems.

2.2.1 Corrosion Protection System

Corrosion occurs as a consequence of in-homogeneities or impurities in the steel, grout or by the existence of salts such as chlorides within the ground or grout mix (Littlejohn and Bruce, 1977). Permanent steel strand ground anchors require several areas to be corrosion protected, including tendon bond length, tendon free length, transition between anchor head and free length, and the anchor head.

Temporary anchors have a short service life, as such minimal corrosion protection is used, assisting in keeping the economics practicable for most short-term applications. Additional details for corrosion protection of temporary ground anchors are documented by Hanna (1982), MacLeod and Carrigan (2006), Littlejohn and Bruce (1977), and Littlejohn and Weerasinghe (1997).

Double protection must be implemented for all permanent ground anchors, based on the assumption that ground conditions vary over time and the permanent anchor may be affected by an aggressive environment at some stage in its design life. The double protection system (Figure 1) ensures that a minimum of two physical barriers are protecting the steel tendons. The outer barrier will effectively protect the inner barrier during handling and homing. Major advancements have been made in the last 10 years refining this double protection system, especially with respect to materials used and fabrication methods (Weerasinghe and Adams, 1997). Cement grout does not classify as a layer of protection as cracks can form during stressing.

Materials used for current best practises regarding the corrosion protection systems are:

- Outer layer corrugated/smooth sheath – can be either steel or HDPE,
- Inner layer corrugated sheath – HDPE, and
- Greased and sheathed steel strand or epoxy coated steel strand.

(a) (b) (c)

Figure 1: (a) schematic of double protection system for permanent ground anchor; (b) slice from gun barrel trial of double protected steel strand ground anchor; (c) longitudinal section of double corrosion protection with tendon removed (Mothersille, 2006)

It is becoming easier to purchase quality controlled and mass fabricated HDPE sheathing, and pre-greased and sheathed or epoxy coated strand, which improves the overall quality and durability of the permanent ground anchor.

Protection for the ground anchor head can be broken down to include the bearing plate, main anchor head, trumpet and the protective cover. The inner anchor head is protected by using a HDPE trumpet sleeve welded to the corrugated sheath (Weerasinghe and Adams, 1997). Grease or polyester resin is used to protect the inner head. The outer anchor head is protected by grease with a steel or plastic cap. Appropriate interlocking between the head cap and bearing plate must ensure no leaking of the grease/resin or ingress of water/air (Habib, 1989, Xanthakos, 1991). Bearing plates are generally painted with bitumastic paint (or similar) for corrosion protection or newer plastics and resins are starting to be used.

(a) (b) (c)

Figure 2: (a) Main anchor head lock off (wedges) and bituminous coated bearing plate (b) Greased protective cover (c) assembled anchor head unit (Mothersille, 2006).

3 ADVANCEMENTS IN GROUND ANCHOR TECHNOLOGY – FIBRE REINFORCED POLYMER (FRP)

There have been in excess of 35 known cases throughout the history of ground anchors where anchor failure has occurred as a direct result of tendon corrosion with many more other cases where drastic remediation works have been required to prevent failure (Littlejohn, 1987, Zhang and Benmokrane, 2005). Research has shifted now into investigating the use of alternative materials to assist in minimising or eliminating risk of anchor failure due to corrosion, including investigations into the use of fibre reinforced polymers (FRP).

3.1 FRP Materials

FRP consist of a group of materials containing aligned continuous organic (aramid or carbon fibre) or inorganic (glass fibre) filaments embedded in a polymer matrix then shaped into a product for use. Organic filaments are the primary choice for ground anchors. The ultimate tensile strength of the FRP compared to prestressed steel indicates that carbon fibre is the superior material (Zhang and Benmokrane, 2005). Benmokrane et al. (2000) discussed the advantages and limitations to the various types of FRP fibres.

The polymetric matrix used to bond the fibres, protect the fibres against environmental effects and assist in the equalization of fibre forces and load transfers in the transverse direction are either an epoxy, polyester or a vinyl-ester resin. Epoxy is the preferred matrix.

FRP properties can vary depending on quality, manufacturer and manufacturing processes (Table 1). Experimental evidence shows that FRP composites have a brittle failure compared to the yielding failure of prestressed steel (Figure 3). This needs to be considered when designing with FRP.

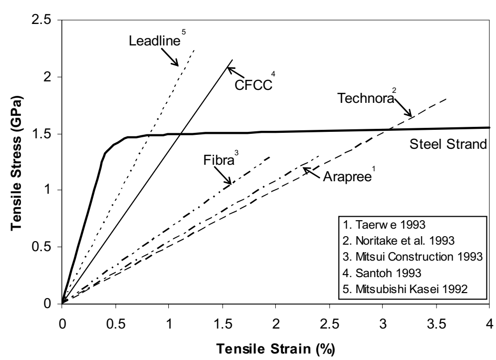

Figure 3: Typical tensile stress-strain behaviour of various FRP products compared to steel strand (after Benmokrane et al., 1997)

Table 1: Properties of FRP composites (after Zhang and Benmokrane, 2005)

Property	GFRP	AFRP	CFRP	Prestressing steel
Minimum fibre volume ratio	0.55	0.6	0.63	-
Density (g/cm^3)	2.1	1.38	1.58	7.85
Longitudinal tensile strength (MPa)	1080	1280	2280	1865
Transverse tensile strength (MPa)	39	30	57	1860
Longnitudinal modulus (GPa)	39	78	142	190
Transverse modulus (GPa)	8.6	5.5	10.3	190
In-plane shear strength (GPa)	89	49	71	
In-plane shear modulus (GPa)	3.8	2.2	7.2	73.1
Maximum longitudinal strain (%)	2.8	1.5	1.5	4
Maximum transverse strain (%)	0.5	0.5	0.6	4
Relaxation ratio (%)			2-3	8

Europe and Asia have taken to using FRP composites over conventional steel in construction where durability has been a serious issue. Numerous projects in Japan alone used FRP ground anchors for slope stabilisation, especially in coastal and snowy environments. Companies such as Tokyo Rope are leading manufactures for the Japanese market, while Sireg is a major contributing company in Europe. CFRP and AFRP have been used for ground anchorage while GFRP has been limited to straight bar soil nails.

3.2 FRP Ground Anchors

3.2.1 Advantages and Limitations of FRP

The advantages of using FRP composites for ground anchors compared to the conventional prestressing steel tendon ground anchor include (Benmokrane et al., 2000, Zhang et al., 2000):

- High axial tensile strength (generally equal to or greater than prestressing steel),
- Highly corrosion resistance,
- Lightweight; FRP is approximately 15% - 20% lighter than prestressing steel tendons, and
- Optical fibres can be integrated into FRP strands allowing for real time monitoring of ground anchor performance.

The limitations of FRP tendons are yet to be fully determined as minimal long term research has been conducted. Restrictions with anchorage and cost of material currently limit works to very specific projects where the environment is known to be aggressive and there is adequate space for bond-type anchor heads.

3.2.2 Ground Anchor design using AFRP and CFRP tendons

Designing ground anchors using FRP tendons must consider the same design criterion and procedure as with steel strand ground anchors. ACI 440.4R-04 – Prestressing Concrete Structures with FRP Tendons and IS/BS EN 1537:2000 – Execution of special geotechnical works (Ground Anchors) are quality documents available to assist in designing with FRP tendons. Other state road authorities throughout Australia, Europe and Asia are commencing establishing standards for FRP anchor construction.

Due to the difference in material characteristics between steel and FRP, some modifications to the design methods need to occur. For high capacity ground anchors Benmokrane et al. (1997) recommends to design for a working load of $0.6f_{pu}$. Design working loads that have been employed in field applications for FRP anchors generally vary between $0.22f_{pu}$ to $0.66f_{pu}$ due to the brittle nature of composites (Figure 3). Table 2 lists field applications of AFRP and CFRP ground anchors in Japan.

Table 2: Field application of CFRP ground anchors in Japan (after Benmokrane et al., 1997)

Project	Competed Year	Anchor number	Rock type	Tendon Size	Ultimate Load, Pu (kN)	Design Load (%Pu)	Total anchor length (m)	Bond Length (m)	Hole size (mm)	Reference
Slope stablisation, Hokkaido	1993	22	Volcanic	6ϕ12.5	852	0.58	20.5-24.5	7.5	115	FRP Int. 1995
Slope stabilisation, Niigata	1993	42	Granite	6ϕ12.5	852	0.6	10.5	6.5	115	Koyama 1996
Slope stabilisation, Niigata	1994	4	Mudstone	3ϕ12.5	426	0.46	16.5	3.5	115	Koyama 1996
Retaining wall, Toyama	1995	6	Sandstone	3ϕ12.5	426	0.22	11-17.5	3	115	Koyama 1996
Revetments, Sokusen, Gifu	1995	46	Gravel	3ϕ12.5	426	0.555	9.2-17.5	-	115	Koyama 1996
Slope stabilisation, Ito, Shizuoka	1995	20	Soft Rock	4ϕ12.5	568	0.63	9-11.5	-	115	Koyama 1996
Slope stabilisation, Ishikawa	1995	40	Soft Rock	6ϕ12.5	852	0.57	10-11.5	-	115	Koyama 1996
Slope stabilisation, Yamanashi	1996	10	Soft Rock	3ϕ12.5	426	0.53	7.3	-	115	Koyama 1996
Slope stabilisation, Kyoto	1996	10	Soft Rock	2ϕ12.5	284	0.66	7.3-17.3	-	115	Koyama 1996

3.2.3 Fixed Anchor Design

Calculations for the fixed anchor length of FRP anchors assumed design is for a straight shafted ground anchor into rock, based on uniform bond stress distribution at the ground and grout interface. From these assumptions, Benmokrane et al. (1997) developed this relationship (Equation 1). Fixed anchor length at the grout-tendon interface is represented by equation 2.

$$L = \frac{T_w S_f}{\pi D \tau_{ult-1}} \quad (1)$$

$$L = \frac{T_w S_f}{n \pi d \tau_{ult-2}} \quad (2)$$

Where: L= fixed anchor length, T_w= working load, and $\tau_{ult\text{-}x}$= ult shear strength, D,d= diameter.

Bond values at the interface for grout and ground used for FRP tendons are consistant with what is currently being used for standard prestressed steel strand anchors (Littlejohn, 1987). Due to the wide variety of surface textures available in FRP tendons, large amounts of research is still required to establish bond values between tendon and grout for all usable FRP tendons (Zhang and Benmokrane, 2002). Results published by Benmokrane et al. (1997) show the relationship of bond values between FRP tendons and cement grout under laboratory conditions.

3.2.4 FRP Anchorage Systems

As with conventional prestressed anchors, the tensile forces are transferred to the FRP anchor head system by anchorage. This load transfer requires lateral pressure and shear stresses to act on the FRP tendon surface in conjunction with high axial stresses applied to the anchor (Benmokrane et al., 1997). A limitation of FRP tendons is their sensitivity to lateral stresses and any notch or defect caused during anchor fabrication or transport which can affect its performance during stressing.

To cope with the concentrated stresses at the anchor block, research into a modified wedge-type anchorage system is being conducted (Campbell et al., 2000) for FRP ground anchors. FRP wedge-type anchorage systems currently have major limitations due to the brittleness of the FRP products and the damage caused by the wedges to the FRP at the anchor head (Zhang and Benmokrane, 2004, Campbell et al., 2000).

Bond type anchorage systems are common for post tensioning and prestressed FRP-rod ground anchors. FRP rods are generally grouted with expansive grout inside a prepared steel housing, with the outside threaded to allow for external lock-off (Figure 4). If resins are used, resins with a low modulus of elasticity can potentially limit the peak shear stress during load transfer, while resins with a higher modulus of elasticity can generally be more efficient at long-term creep control. Grout selection is extremely critical for bond-type anchorage. Standard Portland type cement based mortars should not be used, but expansive cement grouts are acceptable should adequate trials be carried out.

(a) **(b)**

Figure 4: (a) Carbon fibre flat stand mono wedge (Sireg, 2006); (b) Carbon fibre rod bond-type anchorage system (Benmokrane et al., 1997)

3.2.5 Fabrication and installation techniques specifically for FRP ground anchors

In addition to industry practices and standards for steel ground anchors fabrication and installation, FRP ground anchors must adhere to strict guidelines specified by manufactures.

FRP anchor free length can either be corrugated or smooth (HDPE). The anchor head can be similar to that of prestressed steel ground anchors, where either a wedge-type anchorage or a bond-type anchorage system is used. FRP fixed anchor length can be achieved in various methods. Most FRP ground anchors have some form of grip at the end of the fixed anchor length to ensure all tendons are correctly installed into the borehole un-damaged.

Large capacity long FRP ground anchors can be easily manhandled in comparison to steel strand anchors. Currently only minimal changes have been made to the corrosion protection systems used for CFRP strand anchors compared to the steel strand anchors. Further research into the durability effects and possible simplification of the CFRP anchor protection system needs to be carried out.

4 CONCLUSION

Recent developments have seen not only the improvements to steel strand ground anchors regarding corrosion protection but the increased interest in the developments of using new age materials. Fibre reinforced polymer (FRP) composites have been used in the aeronautical and motor industry for decades, it is only now that these advanced composite materials are becoming available for research into use for construction, especially ground anchors. Large amounts of research still needs to be conducted prior to adoption of standards incorporating CFRP tendons as an alternative to steel strand. Over the next few years the development of FRP composites will see more and more standards incorporate the new advanced composite materials for common project use.

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