Use of Carbon Fibre Reinforced Polymer (CFRP) as an alternative material in permanent ground anchors

Matthew Sentry[1,2], Abdelmalek Bouazza[2], Riadh Al-Mahaidi[3], Darren Loidl[4], Chris Bluff[5], Len Carrigan[6]
[1, 2, 3] Department of Civil Engineering, Building 60, Monash University, VIC, 3800, Australia
[1, 4, 5, 6] Geotechnical Engineering, 68 Springbank St, Tullamarine, VIC, 3043 Australia

ABSTRACT

Steel tendon ground anchors are an integral construction technique for numerous civil engineering applications ranging from deep excavation support to resistance of structural uplift and overturning of superstructures. Failures of steel strand ground anchor systems are rare, but when they occur, corrosion and human error are the primary reason. Several methods of minimising anchor system corrosion have been adopted over time to minimise ingress of corrosive substances. However, anchors are still failing due to corrosion. Advancement in the development of corrosion resistant materials has been at the forefront of materials research. In this respect, research and development of FRP materials is enabling the progress of providing the industry with a more potentially robust anchor system aimed at eliminating current limitations encountered with steel strand ground anchors.

This paper provides an overview of current best practices for the application of permanent ground anchors and investigates the current developments in FRP materials for ground anchor applications as an alternative to conventional steel tendon ground anchors. The paper also provides insight into known areas where further research is required to assist the introduction of FRP ground anchors into standards.

1. INTRODUCTION AND BACKGROUND

Ground anchors can be classified as a substructural members that transmits 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).

With the exception of the development of the single-bore-multi-strand ground anchor system developed by Tony Barley (Barley, 1995, 1997), ground anchor design has not changed dramatically since the works carried out by Littlejohn and Bruce (1977) and Hanna (1982). Current international ground anchor standards and guidelines (EN, 2000; RTA, 1999; Standards, 2002) refer only to the use of the well established stressed relieved steel strand system (Sentry et al., 2007a). Although these permanent ground anchor systems utilise the rugged steel tendons with readily available hardware for anchor applications, they are still vulnerable to corrosive attack from aggressive environments. Recent research has focused on improvements to anchor corrosion protection. Current permanent ground anchor standards require the use of double corrosion protection systems encapsulating the steel strands, to ensure a serviceable design life (Sentry et al., 2007b).

Technological advancements of fibre reinforced polymers (FRP) for applications in civil construction has allowed new products such as glass fibre (GFRP), aramid fibre (AFRP) and carbon fibre (CFRP) to pave the way for research into further improvements to the currently favoured steel strand ground anchor system.

FRP's are characterised by their perceived superior resistance to aggressive ground environments, compared to steel. Where steel reinforcement has been restricted due to aggressive ground conditions, minimal alternatives have been available for industry use until FRP reinforcement was developed and successfully used as a durable construction alternative. Extensive research has been conducted on FRP as a substitute for conventional steel reinforcement; however there is minimal knowledge on FRP limitations, especially its behaviour over prolonged exposure to aggressive ground environments.

2. GROUND ANCHOR LIMITATIONS

In recent times, 35 known cases where permanent ground anchors were identified as having failed during their design lives due to corrosion related failures of the steel strands (Littlejohn, 1987; Littlejohn and Mothersille, 2008a, b). The report concluded that 60% of these failures were a result of corrosion in the free length, 34% occurred at the anchorage head and only 6% were within the fixed anchor length. The small number of failures within the fixed anchor length were contributed to inadequate grouting techniques (Littlejohn, 1987). Ground anchor failure due to corrosion can lead to catastrophic structural failure (Figure 1).

Steel tendon corrosion can occur locally where a strand intersects a crack in the surrounding grout, or as a result of damage to the corrosion protective sheaths (Weerasinghe and Adams, 1997). Grout cracks occur as a result of either shrinkage strains during curing or tensile loading of the anchor. Due to grout micro cracking, the majority of standards do not permit grout to be considered as one of the two means for corrosion protection. Mothersille (2006), Littlejohn and Mothersille (2008b) and Weerasinghe and Anson (1997) provide project examples where corrosion occurred above and below the anchor head, resulting in anchor strength reduction (Figure 1).

Due to these known cases, research over the past 15 years has focused heavily on the anchor installation process, hazard risk minimisation during fabrication and installation and the development of an impermeable shield protecting the ground anchor from aggressive foreign environments.


(a) (b) (c)

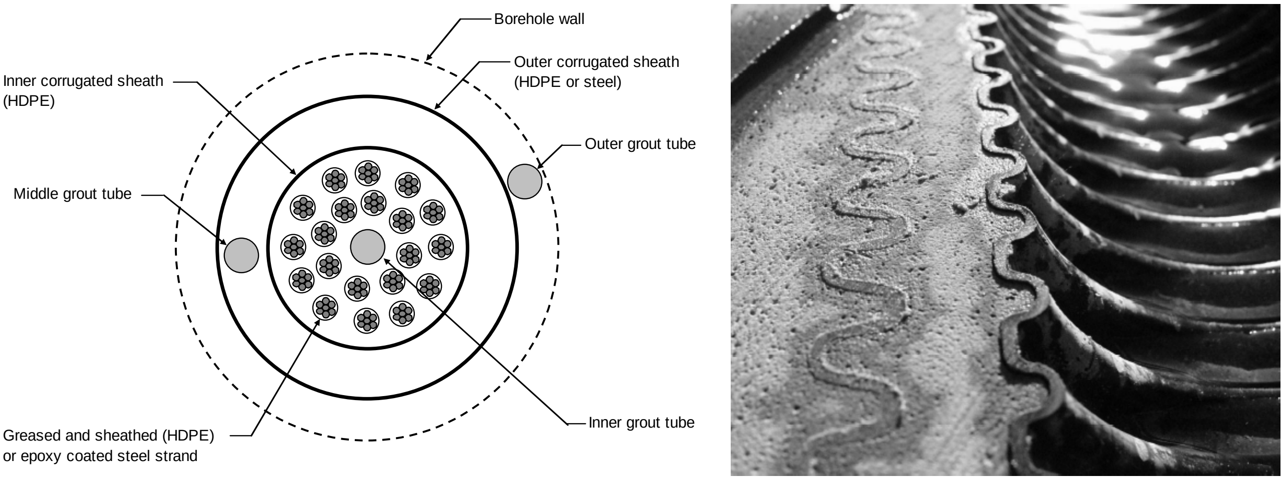
Figure 1: Failure of anchored quay wall (b) corroded barrels and wedges in anchor head (c) lack of corrosion protection behind anchor block (Littlejohn and Mothersille, 2008b; Mothersille, 2006)

3. CURRENT GROUND ANCHOR BEST PRACTICES - 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 (Sentry et al., 2007a).

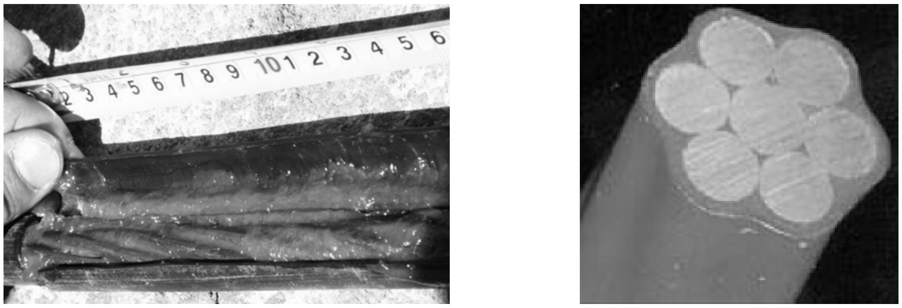
To eliminate the risk of corrosion, international standards including EN1537:2000 (EN, 2000) established a double protection system for all permanent ground anchors, based on the assumption that ground conditions vary over time and the permanent anchor may be affected by an aggressive environment at some stage in its design life (Sentry et al., 2007b). The double protection system (Figure 2a) ensures that a minimum of two physical barriers are protecting the steel tendons. Double corrosion protection must be applied over the tendon bond length, tendon free length, the anchor head and the transition between the anchor head and the tendon free length (Sentry et al., 2007b). 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.

To minimise the risk of corrosion attack, designers require an outer and inner corrugated HDPE duct (Figure 2b). Throughout the free length, steel strand must be fully greased with an approved product then protected from the surrounding grout using a smooth surfaced sheath (Figure 3a). As an alternative, prefabricated epoxy coated systems are also becoming available (Figure 3b). It is becoming easier to purchase quality controlled and mass fabricated materials for ground anchor construction.



(a) (b)

Figure 2: (a) Schematic of double protection system for permanent ground anchor (Sentry et al., 2007b); (b) longitudinal section - double corrosion protection through the bond length of a ground anchor (Mothersille, 2006).



(a) (b)

Figure 3: Methods of minimising corrosion attack to steel strands. (a) Greased and sheathed steel strand (source: Geotechnical Engineering, Australia); (b) Epoxy coated steel strand.

(a) (b) (c)

Figure 4: (a) Main anchor head lock off (wedges) and bituminous coated bearing plate (b) Grease filled protective cover (c) Assembled anchor head unit (Littlejohn and Mothersille, 2008b; Mothersille, 2006).

Ground anchor head components (Figure 4) include the bearing plate, main anchor head, trumpet and the protective cover. Protection immediately below the anchor head is provided by using grease or resin filled HDPE trumpet sleeve which is intended to provide a seal and protect bare strands immediately below the anchor block. The bearing block and anchor block assembly is protected by grease with a steel or plastic cap. Appropriate sealing 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. The need to protect the ground anchor system from corrosion performs an integral element of a permanent ground anchor.

4. ADVANCEMENTS IN GROUND ANCHOR TECHNOLOGY

Due to the 35 known cases where permanent ground anchor failure occurred as a corrosion related issues, leading experts have advised implementing an extensive maintenance testing program for steel strand permanent ground anchors to ensure the life span of the steel ground anchor (Littlejohn and Mothersille, 2008a, b). This monitoring process can become quite costly over the life span of the structure. In addition to the potential maintenance monitoring and testing costs, current complexities of double corrosion protection has shifted research into investigating the use of alternative materials to assist in minimising risk of anchor failure due to corrosion, including investigations into the use of fibre reinforced polymers (FRP).

4.1 FIBRE REINFORCED POLYMER (FRP) MATERIALS

FRP consists of a group of materials containing aligned continuous organic (aramid or carbon fibre) or inorganic (glass fibre) filaments embedded in a polymer matrix and shaped into a product for use (Bakis et al., 2002; Benmokrane and Chennouf, 1997; Benmokrane et al., 2002a; Benmokrane et al., 1997). Organic filaments are the primary choice for ground anchors (Bakis et al., 2002; Zhang et al., 2000). North America is continuously developing and refining the use of inorganic filaments as a substitute for steel in concrete reinforced structures (Tardif et al., 2007; Van der Wal and Boulfiza, 2007), while Japan is constantly evolving the use of organic filament based products for ground anchor applications (Bakis et al., 2002).

FRP filaments consist of various kinds of load bearing fibres of high tensile strength and high modulus of elasticity. Ultimate tensile strengths of carbon fibre reinforced polymer (CFRP) filaments range from 290 to 758GPa, aramid fibre reinforced polymer (AFRP) filaments ranges from 70 to 179GPa compared to prestressed steels tensile strength of 195GPa (Bakis et al., 2002; Benmokrane and Chennouf, 1997; Benmokrane et al., 2002a; Benmokrane et al., 1997; Zhang and Benmokrane, 2004).

Isotropic-based (pitch) and polycrylonitrile-based (PAN) fibres are two types of carbon fibre filaments used in CFRP composites. Carbon fibre filaments are also classified based on their modulus; low modulus ranging between 230-250GPa, medium modulus ranging between 290-300GPa, high modulus ranging between 350-380GPa and ultrahigh modulus ranging between 480-760GPa. Low modulus carbon fibre filaments have a lower density, higher tensile and compressive strengths, higher tensile strain to failure than high modulus carbon fibre filament products and are considered less expensive than other carbon fibres. PAN based carbon fibres compared to Pitch based carbon fibres have a higher ultimate strain, but a lower modulus of elasticity. PAN based carbon fibres are more expensive than Pitch based carbon fibres. The main advantages of carbon fibres over other FRP products are the high strength to weight ratio, high modulus to weight ratio, high fatigue strength, low coefficient of thermal expansion, and excellent moisture and chemical resistance (Mallick, 1993).

FRP fibres are bonded using a polymeric matrix, forming a protection around the fibres against environmental effects and assisting in the equalization of fibre forces and load transfers in the transverse direction. Thermoplastic and thermoset polymers can be applied with FRP fibre filaments to form an FRP composite material.

Thermoplastic polymers including PVC, polyethylene and polypropylene are viscous polymers capable of being modified under temperature and more environmentally friendly than other products, but are difficult to combine with continuous fibres in a production operation (Zhang and Benmokrane, 2005). Thermoset polymers are classified as low viscous, low molecular-weight liquid with thermal stability and chemical resistivity and are said to exhibit reduced creep and stress relaxation when compared to thermoplastic polymers. Thermoset polymers including epoxy, polyester and vinyl ester are preferred resins for FRP material in civil engineering applications (Benmokrane and Chennouf, 1997; Benmokrane et al., 2002a; Sentry et al., 2007b; Zhang and Benmokrane, 2005).

4.2 PROPERTIES OF FRP COMPOSITES

FRP properties can vary depending on quality, manufacturer and manufacturing process (Table 1). FRP composites produce rigid materials compared to the ductile nature of steel strand (Figure 5) (Benmokrane et al., 2002b). Designers need to consider the brittle failure nature of FRP composites when determining the size of the ground anchor required to sustain design working loads.

Tensile strength is dependent on tendon length, implemented anchorage system and loading rate (Benmokrane et al., 1997). CFRP tensile strength ranges between 13-18% higher than steel (Zhang and Benmokrane, 2005). The nature of CFRP materials maintains a linear stress-strain relationship, providing no prior indication of imminent failure, where as steel yields and develops a plastic region prior to failure (Figure 5). The modulus of elasticity for CFRP's to be in the order of 30% lower and AFRP's 65% lower than prestressing steel (Zhang and Benmokrane, 2005). Tensile strain of CFRP ranges between 1.3-1.6% and AFRP ranges between 2.0-3.7%, compared to prestressing steel which can reach up to 4% (Zhang and Benmokrane, 2005).

Fibres used in all FRP materials are weak in transverse loading. As a result, the shear strength of the composite material is almost entirely dependent on the matrix material and is therefore considerably lower than the tensile strength. Santoh (1993) compared AFRP, CFRP and prestressing steel showing lateral shear strength to be 11% (CFRP), 15% (AFRP) and 47% (prestressing steel) of the tensile strength. FRP (CFRP and AFRP in particular) density is approximately 15-20% that of prestressing steel (Benmokrane et al., 1997).

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
Major Poisson's ratio	0.28	0.34	0.27	0.3
Minor Poisson's ratio	0.06	0.02	0.02	0.3
Maximum longitudinal strain (%)	2.8	1.5	1.5	4
Maximum transverse strain (%)	0.5	0.5	0.6	4
Longitudinal CTE ($10^{-6}/^{o}C$)	7.0	-2.0	0	11.7
Transverse CTE ($10^{-6}/^{o}C$)	21	60	27	11.7
Relaxation ratio (%)			2-3	8

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

Creep rupture (or stress rupture) is the phenomenon where strands may suddenly fail after a period of time when exposed to adverse environments under sustained load. This phenomenon can occur in FRP and steel strands (Benmokrane et al., 1997; Zhang and Benmokrane, 2005). Creep stain of CFCC strands is approximately 0.007% after 1000 hours under an initial stress of 65%f_{pu} (f_{pu} = ultimate load) (Benmokrane et al., 1997). Fibres have a better resistance to creep than the resins used in the composites, as such the orientation and fibre volume have a significant influence on the overall creep behaviour of FRP strand (Benmokrane et al., 1997).

Relaxation is the change in stress as a function of time at a constant strain. Zhang et al. (2005) reported that the relaxation for AFRP was 12% after 1000 hours (under load of 0.6f_{pu}), while CFRP ranged between 0.48% and 0.96% (0.5f_{pu} – 0.8f_{pu}) compared to prestressing steel relaxation rate of 1.02% to 7.35% (0.5f_{pu} – 0.8f_{pu}). Tests on CFRP materials have proven that they can sustain 2 million cycles under a mean tensile strength of 0.69f_{pu} with a load amplitude of 0.16f_{pu} (Benmokrane et al., 1997).

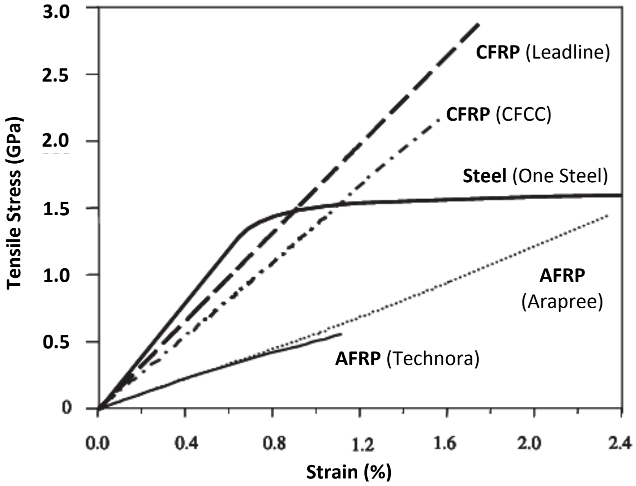


Figure 5: Typical tensile stress-strain behaviour of various FRP products (after Benmokrane et al., 1997) (steel information sourced from One Steel – Australia)

4.3 FRP GROUND ANCHORAGE DESIGN

FRP strand ground anchors must consider the same design criteria and procedures as with conventional steel tendon ground anchors. Several quality standards are available to assist designing with FRP tendons (EN, 2000). In addition to standards, government organisations have established rigorous guidelines complementing local and international recommendations (ACI, 2004; ASTM, 2000; RTA, 1999). Adjustments to current standards and guidelines are required when replacing steel tendons with FRP tendons. Current documentation relevant to ground anchorage construction and for application of FRP tendons in ground anchors includes (but is not limited to) EN 1537:2002–Execution of special geotechnical works–Ground Anchors; BS 8081:1989–Ground Anchorages (EN, 2000); ACI 440.4R-04-Prestressing Concrete Structures with FRP Tendons (ACI, 2004); CAN/CSA S806–Design and Construction of Building Components with Reinforced Polymers (CAN/CSA, 2002); ISIS Canada-Educational Modules No. 6 and 8 (ISIS-Canada, 2006a, b); Post Tensioning Institute (USA)-Recommendations for Prestressed Rock and Soil Anchors (PTI, 2004) and RTA QA Specification B114 Ed 2/Rev 3 1999 (RTA, 1999).

4.3.1 Design working loads

Maximum working load of $0.6f_{pu}$ is recommended when designing high capacity ground anchorage systems with FRP (Benmokrane et al., 1997). Various design working loads have been trialled and adopted for a range of project specific FRP ground anchor field applications ranging between $0.22f_{pu}$ to $0.66f_{pu}$ (Table 2).

Project	Year	Anchor number	Rock type	Tendon Size (mm)	Ultimate Load fPu (kN)	Design Load (%fPu)	Total Length (m)	Bond Length (m)
Slope stabilisation, Niigata	1993	42	Granite	6ϕ12.5	852	0.6	10.5	6.5
Slope stabilisation, Ito, Shizuoka	1995	20	Soft Rock	4ϕ12.5	568	0.63	9-11.5	-
Slope stabilisation, Nazusa, Gifu	1995	30	Soft Rock	3ϕ12.5	426	0.43	7.6-10.6	-
Slope stabilisation, Ishikawa	1995	40	Soft Rock	6ϕ12.5	852	0.57	10-11.5	-
Slope stabilisation, Yamanashi	1996	10	Soft Rock	3ϕ12.5	426	0.53	7.3	-
Slope stabilisation, Kyoto	1996	10	Soft Rock	2ϕ12.5	284	0.66	7.3-17.3	-

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

4.3.2 Fixed anchor design

Research to date has established the following relationships for determining fixed anchor lengths for FRP anchors where the design assumes a straight shafted ground anchor into rock, based on uniform bond stress distribution at the ground and grout interface. From these assumptions, Benmokrane (1997) developed a relationship between fixed anchor length and anchor design working loads (Equation 1) and at the grout-tendon interface (Equation 2).

$$L = \frac{T_w S_f}{\pi D \tau_{ult-1}} \tag{1}$$

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

Where: L=fixed anchor length, T_w=working load, and τ_{ult-x}=ult shear strength, D,d=diameter, S_f = Safety factor.

Bond values at the interface for grout and ground used for FRP tendons are coherent with what is currently being established for conventional prestressed steel tendon ground anchors (Littlejohn and Bruce, 1977). The wide variety of surface textures available in FRP tendons still requires a considerable amounts of research to establish various bond values between tendon and grout (Zhang and Benmokrane, 2002). Some results published by Benmokrane et al. (1997) show the relationship of bond values between selected FRP strands and cement grout under field conditions (Table 3).

Tendon Type	Tendon	Design Load (kN)	Bond length (m)	Working Bond Strength (MPa)
CFCC	6ϕ12.5	490.0	7.5	0.28
	6ϕ12.5	510.0	6.5	0.33
Technora	9ϕ7.4	400.0	6.5	0.44
	9ϕ7.4	400.0	3.0	0.96

Table 3: Working bond values back-calculated from field applications of FRP ground anchors (after Benmokrane et al., 1997)

4.3.3 FRP anchorage systems

Tensile forces for FRP anchorage systems are transferred from the grout-ground bond to the anchor head in the same manner as steel tendon anchor systems. 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). Sensitivity to lateral stresses and any notch or defect can limit its performance during stressing.

Standard steel tendon based wedge type anchorage systems, when used on FRP materials, are currently inefficient and can cause premature failure of the FRP tendon at the wedge interface. This is due to the concentrated transverse stresses at the wedge-FRP strand interface (Sentry et al., 2007b). To accommodate for the transverse material property limitations of FRP at the anchor block, research into different methods for anchorage has taken place over the past ten years (Campbell et al., 2000; Zhang and Benmokrane, 2004). There is no single method of anchorage to suit a wide variety of FRP materials and their unique profiles, but several anchorage methods have been developed including soft metal wedges and soft metal swage anchorage systems, plug-in-cone anchorage systems, bond-type anchorage system and soft cone anchorage systems (Campbell et al., 2000; Reda and Shrive, 2003; Tardif et al., 2007).

Soft metal wedge anchorage systems is dependent on the gripping action of the wedges and/or teeth around the tendon perimeter, accompanied by compression exerted by the wedges onto the FRP tendon (Reda and Shrive, 2003). There is great potential for this system as it is easy to assemble and use on site, but the risk that localised FRP tendons rupture at the wedge/tendon interface by excessive shear stress has restricted this potential (Tardif et al., 2007). Trials using a soft swage system, such as aluminium or copper to minimise the excessive shear stress between the wedge and tendon, have showed promise (Reda and Shrive, 2003; Tardif et al., 2007)(Figure 6(a)). Non metallic wedges are currently being researched as an alternative to soft metal wedges (Sireg, 2007) (Figure 6(c)).

Plug-in-cone anchorage systems accommodate multiple tendons, substituting the wedges with a conical solid cone. Anchorage is dependent on the effects from the inner solid cone pressing the FRP tendon against the teeth of the outer conical socket. Common failure is as result of shear rupture of the tendon at the base of the anchorage system. Limited success has been had using AFRP material (Reda and Shrive, 2003).

Bond type anchorage systems have had large repetitive success (Figure 6(b)). Zhang et al. (2004) developed a bond type anchor using an internally deformed cylindrical metallic shell to host the number of tendons in the anchor. High strength, expansive grouts are commonly used, but resins (epoxy) can also be successful. Resins with low modulus of elasticity can potentially limit the peak shear stress during load transfers, while high modulus resins are more efficient at long-term creep control (Benmokrane et al., 1997). Initial systems utilise the use of lock-off nuts at the anchor block to source the load in stressed strands. As a result, the bond type anchorages are quite large and complex systems, restricting the clearance and tendon extension at the anchor head which could impact on space constraints and minimise additional re-stressing. Due to recent research works, alternative methods of successfully locking applied loads and reducing the overall size of the bond type anchorage system have been developed. The authors believe that further research into the anchorage methods at the anchor block is needed to facilitate the incorporation of FRP strands into future ground anchor standards.

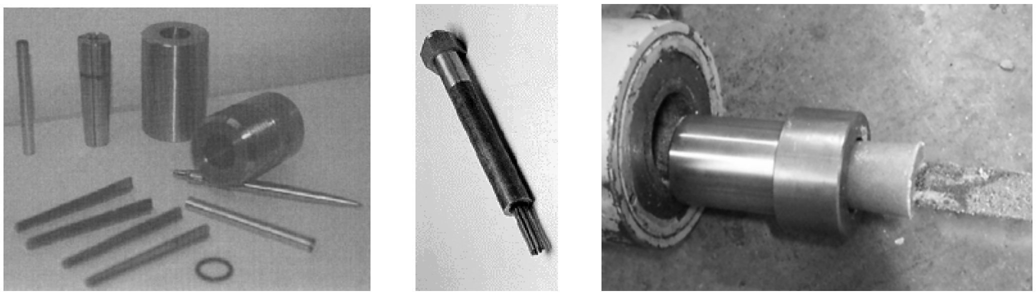

(a) (b) (c)

Figure 6: FRP anchorage systems (a) soft metal swage wedge anchorage system (Campbell et al., 2000) (b) bond type anchorage system with external lock-off nut (Benmokrane et al., 1997) (c) non-metallic wedge anchorage system for flat CFRP tendons (Sireg, 2007)

5. THE FUTURE OF FRP IN GROUND ANCHOR APPLICATIONS

The current corrosion limitations to the prestressed steel strands used in permanent ground anchor applications highlight the necessity for constant attention and research to develop a sound and competent alternative product with performance results equal to or greater than that of the steel strand. Over the years, structural engineers have become more confident in the performance of various FRP products when used to complement or substitute for conventional steel reinforcement. As a result of the knowledge and confidence gained from the use of FRP in civil and structural applications, international standards are beginning to incorporate the use of FRP reinforcement into their standards. With continued extensive research being conducted for the use of FRP’s in ground anchor applications, it is possible for the foundation and ground improvement industry to be able to establish standards for the use of FRP material in permanent ground anchors. A key area where research is required to ensure FRP products can form part of a ground anchor standard is the long term performance in extreme aggressive ground environments under no load and under sustained loading conditions.

6. CONCLUSION

Recent developments have seen not only the improvements to steel tendon 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, but it is only recently that these advanced composite materials have become available for research into use for foundation and ground improvement applications. FRP composites have the potential to minimise or eliminate corrosion limitations faced by designers and construction companies fabricating and installing steel -tendon ground anchors.

7. ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Monash University and the civil engineering laboratory and project sponsor Geotechnical Engineering.

8. REFERENCE

ACI (2004) *ACI 440.3R-04: Guide Test Methods for Reinforcing or Strengthening Concrete Structures*: American Concrete Institution.

ASTM (2000) *Standard test method for tensile properties of polymer matrix composite materials (D3039-00)*: ASTM.

Bakis, C. E., C. Bank Lawrence, V. L. Brown, E. Cosenza, J. F. Davalos, J. J. Lesko, A. Machida, S. H. Rizkalla, and T. C. Triantafillou (2002) "Fiber-Reinforced Polymer Composites for Construction---State-of-the-Art Review," *Journal of Composites for Construction*, Vol. 6, No. 2, pp 73-87.

Barley, Tony (1995) "Theory and Practice of the Single Bore Multiple Anchor System," *International Symposium on "Anchors in Theory and Practice*. Salzburg, Austria.

Barley, Tony (1997) "The Single Bore Multiple Anchor System," *ICE Conference on Ground Anchorages and Anchored Structures*. London.

Benmokrane, B., and Adil Chennouf (1997) "Tensile Characteristics and Bond Properties of AFRP and CFRP Tendons for Ground Anchor Applications," *Non-Metallic (FRP) Reinforcement for Concrete Structures - Proceedings of the third internation Symposium*, pp 727 - 734.

Benmokrane, B., P. Wang, T. M. Ton-That, H. Rahman, and J. F. Robert (2002a) "Durability of glass fiber-reinforced polymer reinforcing bars in concrete environment," *Journal of Composites for Construction*, Vol. 6, No. 3, pp 143-153.

Benmokrane, Brahim, Haixue Xu, and Itaru Nishizaki (1997) "Aramid and carbon fibre-reinforced plastic prestressed ground anchors and their field applications," *Canadian Journal of Civil Engineering*, Vol. 24, No. 6, p 968.

Benmokrane, Brahim, Burong Zhang, Kader Laoubi, Brahim Tighiouart, and Isabelle Lord (2002b) "Mechanical and bond properties of new generation of carbon fibre reinforced polymer reinforcing bars for concrete structures," *Canadian Journal of Civil Engineering*, Vol. 29, No. 2, pp 338-343.

Campbell, T. I., Nigel G. Shrive, K. Soudki, A. Al-Mayah, J. P. Keatley, and M. M. Reda (2000) "Design and evaluation of wedge-type anchor for fibre reinforced polymer tendons," *Canadian journal of civil engineering*, Vol. 27, No. 5, p 985.

CAN/CSA (2002) "CAN/CSA-S806-02: Design and Construction of Building Components with Fibre-Reinforced Polymers."

EN (2000) *EN1537:2000 Execution of special geotechnical work - Ground Anchors*: European Standards.

Habib, P. (1989) *Recommendations for the Design, Calculation, Construction and Monitoring of Ground Anchors*, Rotterdam: A.A. Balkema.

Hanna, Thomas H (1982) *Foundations in Tension - Ground Anchors*: McGraw-Hill Book Company.

ISIS-Canada (2006a) *ISIS Eduacational Module 8: Durability of FRP Composites for Construction*.

ISIS-Canada (2006b) *ISIS Educational Module 6: Application and Handling of FRP Reinforcements for Concrete*.

Littlejohn, G.S (1987) "Ground Anchorages: corrosion performance," *Proceedings - Institute of Civil Engineers*, Vol. Part 1, No. 82, pp 645-662.

Littlejohn, G.S., and D.A. Bruce (1977) *Rock Anchors - State of the Art*, Essex, England: Foundation Publications Ltd.

Littlejohn, s, and D Mothersille (2008a) "Maintenance and monitoring of anchorages: case studies," *Geotechnical Engineering*, Vol. 161, No. 2, pp 107-114.

Littlejohn, s, and D Mothersille (2008b) "Maintenance and monitoring of anchorages: guidelines," *Geotechnical Engineering*, Vol. 161, No. 2, pp 93-106.

Mallick, D.K (1993) *Fibre-reinforced composites: materials, manufacturing, and design*, New York: Marcel Deckker, Inc.

Mothersille, D (2006) "ANCOLD Conference Presentation - Recent Development in Permanent Ground Anchor Technology," Geoserve Global Ltd & Geotech Pty Ltd, p 54.

PTI (2004) *Recommendations for Prestressed Rock and Soil Anchors*: Post-Tensioning Institute.

Reda, M. M., and N. G. Shrive (2003) "New Concrete Anchors for Carbon Fibre-reinforced Polymer Post-Tensioning tendons - Part 1: State-of-the-Art Review/Design," *ACI Structural Journal*.

RTA (1999) "RTA QA Specification B114 (Rev3)."

Santoh, Norihiko (1993) "CFCC: Carbon Fiber Composite Cable," *Developmetns in Civil Engineering*, Vol. 42, pp 223-248.

Sentry, M, A Bouazza, R Al-Mahaidi, L Carrigan, and D Loidl (2007a) "Developments in Ground Anchor Technology: Carbon Fibre Reinforced Polymer (CFRP)," *Common Ground - 10th Australia New Zealand Conference on Geomechanics*. Brisbane.

Sentry, M, A Bouazza, R Al-Mahaidi, D Loidl, C Bluff, and L Carrigan (2007b) "Advancements in Ground Anchors: Carbon Fibre Reinforced Polymer (CFRP) Strands," *ICE International Conference on Ground Anchorages and Anchored Structures in Service 2007*. London.

Standards (2002) "AS4678-2002 Earth-retaining structures," Australian Standard.

Tardif, D, K.W. Neale, M Demers, A.R Zaki, and G Tadros (2007) "Potential use of CFRP and GFRP in precast prestressed reinforced bridge deck system with extended service life," *Third international conference Durability and field applications of fibre reinforced polymer (FRP) composites for construction*. Quebec City, Quebec, Canada.

Van der Wal, J.S., and M Boulfiza (2007) "A step forward in characterizing the performance of GFRP rods in concrete," In: B Benmokrane, and E El-Salakawy, Eds., *Third International Conference Durability and field applications of fibre reinforced polymer (FRP) composites for construction*. Canada.

Weerasinghe, Dr. R.B, and Mr. D Adams (1997) "A Technical Review of Rock Anchorage Practice 1976-1996," *Ground Anchorages and Anchored Structures*. London: Thomas Telford, pp 481-491.

Weerasinghe, Dr. R.B, and R.W.W Anson (1997) "Investigation of long term performance and future behaviour of existing ground anchorages," *International Conference on Ground Anchorages and Anchored Structures*. London: Thomas Telford publications.

Xanthakos, Petros P. (1991) *Ground Anchors and Anchored Structures*, New York, USA: John Wiley & Sons, Inc.

Zhang, Burong, and Brahim Benmokrane (2002) "Pullout Bond Properties of Fiber-Reinforced Polymer Tendons to Grout," *Journal of Materials in Civil Engineering*, Vol. 14, No. 5, pp 399-408.

Zhang, Burong, and Brahim Benmokrane (2004) "Design and evaluation of a new bond-type anchorage system for fibre reinforced polymer tendons," *Canadian Journal of Civil Engineering*, Vol. 31, pp 14-26.

Zhang, Burong, and Brahim Benmokrane (2005) "Large model test of prestressed carbon fibre reinforced polymer ground anchors," *Canadian Journal of Civil Engineering*, Vol. 32, No. 6, p 1064.

Zhang, Burong, Brahim Benmokrane, and Adil Chennouf (2000) "Prediction of Tensile Capacity of Bond Anchorages for FRP Tendons," *Journal of Composites for Construction*, Vol. 4, No. 2, p 39.