Abstract

Carbon fibre plates and flat bar have been used extensively for structural repairs for over a decade. Carbon fibre is inert in the majority of natural environmental condition and does not deteriorate in the alkaline environment of cementitious materials. As a tensile member it has numerous advantages to offer as a replacement of high grade steels which themselves are highly vulnerable to corrosion, and over a time period loss of section.

This research is indicative that carbon fibre anchor tendons can comply with the requirements of anchor codes and be installed as individual or as a multiple of bars each with a load capacity of between 400 and 500 kN. The use of such light weight components may allow fabrication at site level and avoid factory application of corrosion resistant barriers as demanded in the use of steel tendons

Introduction

The following introduction published in “Guide Test Methods for Fibre-Reinforced Polymers (FRPs) for reinforcing or strengthening Concrete Structures” – Ref ACI 2001 provides a fitting introduction to the challenges in the testing of FRP for use in cement grouted ground anchors and the potential benefits of FRP usage:

Conventional concrete structures (or the geotechnical equivalents in anchors and soil nails) are reinforced with nonprestressed steel, prestressed steel, or both. Recently, composite materials made of fibres embedded in a polymeric resin, also known as fibre-reinforced polymers (FRPs), have become alternatives to steel reinforcement. Because FRP materials are non-metallic and noncorrosive, the problems of steel corrosion are avoided with FRP reinforcement. Additionally, FRP materials exhibit several properties, such as high tensile strength, that make them suitable for use as structural reinforcement. FRP materials are supplied as bars for reinforced and prestressing applications (or for ground anchors) and in flat sheets or laminates for use as repair materials for concrete structures.

The mechanical behaviour of FRP differs from the behaviour of steel reinforcement, FRP materials are anisotropic due to the fibre orientation in the bars and laminates and re characterised by high tensile strength only in the direction of the reinforcing fibres. This anisotropic behaviour affects the shear strength and dowel action of FRP bars and the bond performance of FRP bars to concrete. FRPs are available with a wide range of mechanical properties (tensile strengths, bond strengths, and elastic moduli). Generally, FRP reinforcements are not covered by national material standards, as few such standards exist. Instead, manufacturers of FRP provide test data and recommend design values based on these test data. Unfortunately, also due to the lack of material standards, few standard test methods exist for FRP concrete reinforcements. Therefore, it is difficult to compare test results
between product manufacturers. In addition, research has considered the durability of FRP concrete reinforcements in environments containing moisture, high and low temperatures, and alkaline environments. Test methods that allow for the comparison of mechanical property retention in a wide range of standard environments are needed so that durable FRP reinforced concrete structures can be ensured.

This lack of guidance in the testing of CFRP materials relating to their use in structures also exists in their use in anchors. For this reason the authors have chosen to establish test methods that can be, where possible, related precisely to the performance of CFRP tendons at full scale in simulated ground anchors.

2.0 Potential CFRP Products Available for Ground Anchors

These are generally available from specialist suppliers in 6 to 40mm diameter circular bar form or in flat bar form in a wide variety of widths and thicknesses. The general range suitable for anchor tendon usage in a conventional size borehole is 3 to 8mm in thickness and 25 to 76mm in width. Members may have either ultra smooth faces or surfaces roughened faces. Clearly in order to enable bond with the cement grout in the fixed anchor length then the roughened or deformed surfaces are required over these bond lengths. Conversely smooth surfaces or sheathed surfaces are essential in the free tendon length in order to reduce or eliminate cement bond or the existence of unacceptable frictional forces.

Notable advantages available from CFRP products are: -

- High absolute stiffness
- High absolute strength
- Very light weight
- High stiffness to strength rations
- Coefficient of thermal expansion approaching zero

Typical CFRP composites have 65% fibre content, a density of 1.6 and an elastic tensile modulus of 150 GPa. Undoubtedly the high quality of this alternative material (conforming to the requirements of IS09002) for use in anchor tendons, in lieu of steel, has been strongly influenced by the universal adoption of this product in the Aerospace industry. Furthermore the tensile modulus is relatively close to the range presented by steel bar or prestressing strand and thus problems due to large extension during CFRP prestressing are not expected.

3.0 Development of a Gripping System for Trial Work

Extensive knowledge from the steel prestressing industry combined with that from other material gripping systems (even ropes) allowed the development of an appropriate flat bar gripper at the commencement for the investigation period (Figures I and 2).

This system allows the combination of:

- A materials transitional interface
- A rough steel interface
- A taper wedge system
- A tensile bolt pre stress system

The bolt system allows transitional application of stress along the loaded interface prior to and during execution of the test.
The use of this transitional load transfer mechanism has allowed the application of prestress up to 520 kN prior to bar failure (Figure 3). Over the 5% to 65% UTS loading range the tested bar exhibited an elastic tensile modulus of 163 GPa.

Figure 1  Gripping arrangement set up for early tests with preloaded tensile bars allowing grip increase on bar prior to and during loading

Figure 2  End view of Carbon Fibre flat bar being gripped and movement monitored during tensile tests.
4.0 CFRP Bond with Cement Grout

4.1 “Gunbarrel testing”

Tensile members encapsulated within a grouted steel tube, then subjected to pull out, have been carried out regularly over a 35 year period (Barley 1978, Littlejohn and Weerasinghe 1997, Barley 1997). Little modification of the gunbarrel test procedure or the grouting techniques was require to adapt the system to establish pull out capacity of CFRP flat bar.

Initial tests demonstrated that the rough faced exposed surface on the CFRP flat bar (Figure 4) was inadequate to provide the satisfactory resistance to pull out over the two tested bond lengths (0.8 and 1.6m). Loads of 150, 138, 210 and 300 kN were achieved exhibiting average failure bond stresses ranging from 1.97 to 2.13N/mm². Although these bond stress values are not inconsistent with the pull out capacity of non deformed strand anchors over similar lengths, they were considered inadequate to comply with the severe demand requirements of the CFRP multiple unit anchor system under development. The low capacity demanded a review of the method of surface roughening utilised by the manufacturer in his application to standard products.

After considerable research the 6mm flat bar thickness was increased to 8mm and a greater surface roughness was achieved (Figure 5).

In order to eliminate any effect of mechanical gripper efficiency in the second set of trials, two identical 2m long gun barrels were grouted a distance of approximately 1m apart. The meter gap contained a 60 ton capacity hollow ram jack which allowed complete equal and uniform loading of the opposing gun barrels. (Figure 6)
Surface roughness of CFRP bars (6mm) used in initial tests were inadequate to provide high enough bond capacity with cement grout to comply with the severe test requirements.

Increase surface roughness has been achieved in development of a slightly thicker CFRP Bar (8mm).

Load cycles were built up whilst monitoring ram extension and base movement of each gun barrel and movement of the contained grout and bar at the base. This extensive monitoring allowed the accurate assessment of the relative movements of the components and result analysis allowed prediction of the final failure mechanism even prior to the exhumation of the tested bars.
Figure 6  Double Ended Gunbarrel Test with hydraulic jack contained between the two gunbarrels to ensure equal and uniform loading.

Figure 7  Longitudinal bar splitting at the junction with the grout
4.2 Observation at Cement/Bar Failure and Non Failure Interfaces

The dissection of the steel gunbarrels allowed access to the grouted body and the subsequent exposure of each grout to bar interface. Visual inspection then allowed the determination of the failure mechanism over the full length of the exposed interfaces in both gun barrels.

Progressive debonding takes place in all load transfer involving longitudinally bonded elastic members such as steel or FRP bonded in cement grout. The occurrence of such a mechanism is apparent and dominant in these trials.

Figure 7 illustrates the longitudinal splitting of the CFRP bar at the entrance to the gunbarrel, whilst Figure 8 illustrates the pull out mode (progressive debonding) from zero to 900mm depth. This involves the shearing of the white cement grout nominally outside the roughened bar surface.

Between 900 and 1100 mm into the gunbarrel (Figure 9) some transition in the failure mechanism begins to occur. The whole failure interface becomes grey which suggest that the failure interface is integral with both the black resin protrusions and the white grout both in shear. In Test A, beyond 1100mm the CFRP bar remains fully bonded within the cement grout (Figure 9) and the test demonstrates an overall average bond stress of 3.4 N/mm² without failure.

However, with due consideration of the exhibited progressive debonding and the likely hood that the sliding friction was low over the top metre it may be realistic to consider that an adhesive bond as high as 10 N/mm² was exhibited over a bonded 0.5 m length.

However, in Test B failure took place at approximately 80% of the capacity of the 520 kN bar and an average bond stress at failure of 2.6 kN/mm² was exhibited. Despite failure this is considerably better than that exhibited in the preliminary trials on the smoother facing.

The test results generally support the benefits of utilizing a multiple of short bond length anchor tendons associated with the patented system as compared with the severe problems encountered with debonding in long individual members.

Figure 8   Exposed CFRP bar near the top of Test A illustrates the shear of cement grout
Figure 9  Progressive debonding along Test A to a fully bonded non slip area

Figure 10  No debonding of bar from grout exists at 1200mm depth in Test A
7.0 Development of Permanent Gripping System for use in CFRP Ground Anchors

Development of permanent fixed end grippers has followed a number of possible systems involving CFRP to resin bond, a combination of CFRP to resin bond incorporating wedge grippers, and the jointing of CFRP with steel members.

This development is well advanced after considerable liaison and co-operation with specialists in the Industry. Owing to the confidentiality demanded by the parties more precise details cannot yet be published.

8.0 Conclusion

The development of CFRP permanent anchor tendons and associated gripper and bonding systems to provide the industry with a non-corrodible, non-degradable tensile member within a cementitious environment is well advanced. Existing Codes of Practice for Ground Anchorages generally consider steel tendons and demand pre-application of corrosion protection under factory conditions. This inevitably demands expensive double handling of heavy steel tendons.

CFRP bar can be delivered to site in coils and simply assembled into multiple bar anchor tendons, even varied to suit the encountered ground conditions.

CFRP multiple anchor type tendons with a working capacity 1000 kN of typical anchor length of 35m and a weight of only 75 kg is a realistic option for the future.
9.0 References

American Concrete Society (2001) “Guide Test Method for Fibre-Reinforced Polymers (FRP) for reinforcing or strengthening Concrete Structures”.
Barley A.D. (1997) “Ground Anchor Tendon Protected against Corrosion and damage by a Double Plastic Layer”.