Review

Mechanical anchoring of FRP tendons – A literature review

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A R T I C L E   I N F O
Article history:
Available online 2 February 2012

Keywords:
Prestressing
Posttensioning
FRP
Anchorage
Wedge
FEM analysis
Laboratory tests

A B S T R A C T
High tensile strength, good resistance to degradation and creep, low weight and, to some extent, the ability to change the modulus of elasticity are some of the advantages of using prestressed, unidirectional FRP (Fibre Reinforced Polymer) tendon systems. Bonded and non-bonded versions of these systems have been investigated over the last three decades with results showing that prestressing systems can be very efficient when the FRP properties are properly exploited. However, there are often concerns as to how to exploit those properties to the full and how to achieve reliable anchorage with such systems. This is especially important in external post-tensioned tendon systems, where the anchorage points are exposed to the full load throughout the life span of the structure. Consequently, there are large requirements related to the long-term capacity and fatigue resistance of such systems. Several anchorage systems for use with Aramid, Glass and Carbon FRP tendons have been proposed over the last two decades. Each system is usually tailored to a particular type of tendon. This paper presents a brief overview of bonded anchorage applications while the primary literature review discusses three methods of mechanical anchorage: spike, wedge and clamping. Some proposals for future research are suggested. In general, the systems investigated showed inconsistent results with a small difference between achieving either a successful or an unsuccessful anchorage. These inconsistencies seem to be due to the brittleness of the tendons, low strength perpendicular to the fibre direction and insufficient stress transfer in the anchorage/tendon interface. As a result, anchorage failure modes tend to be excessive principal stresses, local crushing and interfacial slippage (abrasive wear), all of which are difficult to predict.

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0950-0618/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.conbuildmat.2011.11.049
which is isotropic and has plasticity. The literature describes setotropic properties, linear elasticity and brittleness, unlike steel, use in a variety of applications. FRP materials share identical orthotropic strength and stiffness properties which means it has potential for reliable. FRP materials may be produced with a range of different anchorages that can carry required capacities and be sufficiently stressing systems are well documented and tested, providing safe compared with existing steel post-tensioning systems. Steel pre-stressing has been developed that is economically and practically competitive with existing tendon systems for FRPs (Fibre Reinforced Polymers) plates [1–10], and NSMR (Near Surface Mounted Reinforcement) bars [11]. These methods all have their origins in bonded non-prestressed FRP systems where, often, a concrete fracture manifests as intermediate crack debonding (IC debonding) or end peeling as a result of the FRP’s high strength. Prestressing utilises the strength of the FRP material to a higher degree. A failure of the structure is then more likely to be due to a compressive failure in the concrete or a tensile failure in the tendon. Another type of failure that may also occur is slippage in the anchorage area. Proper anchorage seems to be the decisive factor in these systems, in ensuring reliable force transfer and interaction with the rest of the structure. To the authors’ knowledge, no FRP system has yet been developed that is economical and practically competitive compared with existing steel post-tensioning systems. Steel prestressing systems are well documented and tested, providing safe anchorages that can carry required capacities and be sufficiently reliable. FRP materials may be produced with a range of different strength and stiffness properties which means it has potential use in a variety of applications. FRP materials share identical orthotropic properties, linear elasticity and brittleness, unlike steel, which is isotropic and has plasticity. The literature describes several types of tendon and related anchorages that have been developed as alternatives to conventional steel systems. This literature review describes the most commonly used types of FRP tendon and charts the advances in the anchorage of FRP tendons over the years. In addition, this review explains some of the research that has been carried out on such systems.

2. Tendon properties

In composite prestressing systems, there are three materials that are mainly used to build tendons: AFRP (Aramid FRP), GFRP (Glass FRP) and CFRP (Carbon FRP). As shown in Fig. 1, the tensile properties of FRP materials can vary significantly depending on the fibre material, fibre fraction and resin type. As a consequence, the modulus of elasticity within each material group can be varied, something that is not possible with steel. However, the yield capability of steel would be advantageous, since it would provide ductility in the structure at the ultimate limit state.

2.1. AFRP systems

One of the first AFRP tendons manufactured was the Parafil® rope, which was developed in the 1960s to moor navigation platforms in the North Atlantic [14]. This type of tendon does not contain any matrix and consequently cannot be bonded to the structure. Burgoyne conducted extensive research on Parafil® rope with the core yarn made of Aramid (Kevlar 49) [15,16]. There are three versions of Parafil ropes, each with a different kind of core: Type A, Type F and Type G; the latter is normally used for structural applications due to its high modulus of elasticity. The research showed that the tendon itself had excellent fatigue performance, but was fragile when sheave bending fatigue tests were carried out, as the area being bent fractured due to stressing of the outer fibres. Research into the long-term behaviour of AFRP is still ongoing. Long-term stress rupture is one of the main reasons why engineers are reluctant to adopt AFRP tendons for prestressing and stay cable purposes. Long-term accelerated testing using both stepped isothermal and stepped isostress methods is therefore

**Fig. 1.** Stress/strain curve showing FRP and steel varieties [12,13].
used and has been shown to be able to predict the long-term changes in the properties of Aramid tendons; these testing methods simulate more than 100 years of use of the tendons [17]. Other types of AFRP tendons used are Araapree, reported on more extensively by Gerritse et al. [18–21], FiBRA [22] and Technora® [27,29].

2.2. GFRP systems

Research on GFRP started in the 1970s, when several bridges were prestressed using GFRP cables in Germany and Austria. This prestressing was carried out to compensate for the low modulus of elasticity of the GFRP. One of the first structures constructed using GFRP technology was a two-span continuous highway bridge in Düsseldorf, Germany in 1986, which was post-tensioned using GFRP cables. Each pultruded GFRP rod used in the bridge had a diameter of 7.5 mm. In total, 19 of these rods were used in the tendon resulting in a post-tensioning force of 600 kN per tendon. The system used an epoxy-socket anchor, resulting in the tendons needing to be produced in pre-determined lengths. However, the type of anchorage that was used led to a large anchorage size and there were further concerns about the long-term reliability [23]. Further, Iyer et al. [24,25] described a one-span demonstration bridge that was prestressed using CFRP, GFRP and steel cables. The span width was notionally separated into thirds and each third was prestressed with each type of cable. This demonstrated that CFRP and GFRP cables worked in this application and that any short-term changes of their properties were predictable. Moreover, Neptco Inc. has produced a cable consisting of seven GFRP rods (one central rod surrounded by six others). The individual rods are twisted together and held in place by plastic straps or with a resin binder [26].

2.3. CFRP systems

CFRP has superior creep properties, low relaxation, high strength and can withstand high jacking stress, but at high cost [27]. One of the first products developed was the Leadline® CFRP tendon, which is produced with different surface patterns: smooth, with surface-indent or ribbed. These rods are usually pultruded and pitch-based (manufactured from resin precursor fibres after stabilization treatment, carbonisation and a final heat treatment) and most commonly anchored using a modified wedge anchorage system [14]. A similar CFRP is the Technora carbon fibre rod, a spirally-wound rod that is pultruded and impregnated with a vinyl ester resin [27,29]. Carbon stress rods are also made by pultrusion, then epoxy-impregnated and usually coated with sand to increase their anchorage when embedded in concrete [26]. CFCC (Carbon Fibre Composite Cable) tendons are another type of tendon and are in its final stage produced like conventional steel strands, where several smaller steel strands form one cable [28]. A CFCC tendon consists of bundles of cables with multiple pieces of prepreg (semi-hardened tows/strands with a resin precursor) that are treated with a suitable coating [27].

Grace conducted extensive research on CFRP tendons, performing internal prestressing of a double-tee (DT) bridge system that used CFRP tendons [30]. The DT was reinforced with CFRP bars and externally prestressed with CFRP tendons. Two deviation points and a crossbeam were placed at the midspan, where an externally post-tensioned and draped CFCC strand was applied. The magnitude of the draping angle and the deviator diameter were shown to affect the behaviour of the system [30,31]. Also, there are reports about larger, real life applications that have used external CFRP prestressing and poststressing of bridges [32,33]. A DT Beam was in [32] designed with pretensioned Leadline® tendons and post-tensioned CFCC strands to simulate the performance of DT-beams which had been used in the construction of a 3-span bridge. This design was first used in a prestressed and posttressed CFRRP bridge in the United States. It was reported that the ultimate failure mode was due to separation between the flange and the beam web which led to crushing of the flange and the rupture of the original prestressed CFRP tendons.

2.4. Anchorage and tendon properties

In order to exploit the properties of an FRP tendon fully, the stresses that develop in the interface between the anchorage and the tendon have to be properly managed. When measuring tendon behaviour, therefore, the anchorage must be sufficiently robust. As shown in Table 1, anisotropic FRP material, coupled with brittleness and weak transverse properties makes the issue of successful anchorage a difficult one, with the most common outcome being premature failure. Over the last few decades, there have been several bonded and mechanical anchorage designs, often tailored to a particular type of tendon. The following section briefly reviews bonded anchorages as an alternative to mechanical solutions, which are then described in greater depth. A review of the evolu-

### Table 1

Examples of GFRP, AFRP, CFRP properties compared to steel, after [27,34]. Shaded rows show where FRP properties are significantly weaker than steel prestressing steel.

<table>
<thead>
<tr>
<th>Tendon type</th>
<th>Units</th>
<th>AFRP</th>
<th>CFRP</th>
<th>GFRP</th>
<th>Prestressing steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre</td>
<td>(-)</td>
<td>Aramid</td>
<td>Carbon</td>
<td>Glass</td>
<td>–</td>
</tr>
<tr>
<td>Resin</td>
<td>(-)</td>
<td>Epoxy</td>
<td>Epoxy</td>
<td>Epoxy</td>
<td>–</td>
</tr>
<tr>
<td>Fibre volume ratio</td>
<td>(-)</td>
<td>0.65</td>
<td>0.65</td>
<td>0.55</td>
<td>–</td>
</tr>
<tr>
<td>Density</td>
<td>(g/cm³)</td>
<td>1.28</td>
<td>1.53</td>
<td>2.1</td>
<td>7.85</td>
</tr>
<tr>
<td>Longitudinal tensile strength (GPa)</td>
<td>1.25–1.4</td>
<td>2.25–2.55</td>
<td>1.08</td>
<td>1.86</td>
<td></td>
</tr>
<tr>
<td>Transverse tensile strength (MPa)</td>
<td>10</td>
<td>57</td>
<td>29</td>
<td>1860</td>
<td></td>
</tr>
<tr>
<td>Longitudinal E-modulus (GPa)</td>
<td>65–70</td>
<td>142–150</td>
<td>39</td>
<td>210</td>
<td></td>
</tr>
<tr>
<td>Transverse E-modulus (GPa)</td>
<td>5.5</td>
<td>5.7</td>
<td>8.6</td>
<td>210</td>
<td></td>
</tr>
<tr>
<td>In-plane shear strength (MPa)</td>
<td>4.9</td>
<td>71</td>
<td>85</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>In-plane shear modulus (GPa)</td>
<td>2.2</td>
<td>7.2</td>
<td>3.8</td>
<td>72.1</td>
<td></td>
</tr>
<tr>
<td>Major Poisson’s ratio</td>
<td>(-)</td>
<td>0.34–0.6</td>
<td>0.27</td>
<td>0.28</td>
<td>0.3</td>
</tr>
<tr>
<td>Minor Poisson’s ratio</td>
<td>(-)</td>
<td>0.02</td>
<td>0.02</td>
<td>0.06</td>
<td>0.3</td>
</tr>
<tr>
<td>Bond strength (MPa)</td>
<td>10–13</td>
<td>4–20</td>
<td>–</td>
<td>6.6–7.1</td>
<td></td>
</tr>
<tr>
<td>Maximum longitudinal strain (%)</td>
<td>2.0–3.7</td>
<td>1.3–1.5</td>
<td>2.8</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>Maximum transverse strain (%)</td>
<td>3.3</td>
<td>0.6</td>
<td>0.5</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>Longitudinal compressive strength (MPa)</td>
<td>158</td>
<td>228</td>
<td>128</td>
<td>1860</td>
<td></td>
</tr>
<tr>
<td>Transverse compressive strength (MPa)</td>
<td>158</td>
<td>228</td>
<td>128</td>
<td>1860</td>
<td></td>
</tr>
<tr>
<td>Longitudinal thermal expansion coefficient (1°C)</td>
<td>–2 × 10⁻⁶</td>
<td>–0.9 × 10⁻⁶</td>
<td>7 × 10⁻⁶</td>
<td>11.7 × 10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>Transverse thermal expansion coefficient (1°C)</td>
<td>60 × 10⁻⁶</td>
<td>–27 × 10⁻⁶</td>
<td>21 × 10⁻⁶</td>
<td>11.7 × 10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>Relaxation ratio at room temperature (% loss from jacking stress)</td>
<td>12 at 103 h</td>
<td>2–3</td>
<td>–</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>
tion of analytical models and finite element models to describe mathematically the function of an anchorage is also included.

2.4.1. Bonded anchorage

There are numerous types of bonded anchorage systems. Normally, an outer sleeve surrounds either a cementitious or resin bonding material to anchor the tendon. The main features of such systems are shown in Fig. 2. Several researchers have devised solutions to issues relating to bonded anchorage systems and how to deal with the monitoring of the performance of these anchorages and their mathematical evaluation. Mitchell et al. [35] worked on a mathematical study involving axisymmetric finite element analysis, using two types of end connections. These end connections consisted of a metal casing joined to the FRP tendon through a layer of potting material. Rostásy and Kepp [36] presented the results of static tensile loading tests and the influence of bond length of a steel-sleeved anchorage on the tendons ultimate load-bearing capacities. The strains in the sleeve and bond stress distribution were also described. Rostásy was one of the first researchers to propose test methods and acceptance requirements for post-tensioned FRP tendon systems that involved measurements on the anchorages that were used [37,38]. Budelmann et al. [39] discussed the fatigue behaviour of bond-anchored unidirectional GFRPs where the E-glass fibres were embedded in a quartz sand/PE-resin mortar and anchored in a cylindrical steel tube. Patrik et al. [40], EMPA (Eidg. MaterialPrüfungs- und VersuchsAnstalt für Industrie, Bauwesen und Gewerbe) developed a resin-potted anchorage with a stiffness gradient in its resin that handled 92% of the tendons tensile strength. The common mode of failure in this potted anchorage was excessive creep deformation in the resin [41,42]. Lees et al. [43] discussed the problem of induced stress concentrations in an anchorage of FRP tendons and how to solve this issue with expansive cement couplers. An experimental study was first carried out on couplers joining steel reinforcement bars and then extended to include the coupling of FRP materials onto steel prestressing bars. Nanni et al. [14] investigated some of the available commercial anchorage systems and studied their ultimate tensile capacity and tensile capacity during short-term sustained loading. They used grout to anchor a Technora tendon in a 500 mm long sleeve, while the CFCC tendon was anchored in a 165 mm long sleeve using an epoxy adhesive. Meier and Farshad [44] investigated the connection of high-performance CFRP cables to suspension and cable-stayed bridges using gradient materials (soft zone concept) and presented a new, reliable anchoring system, developed with computer-aided materials design and produced with advanced gradient bond materials based on ceramics and polymers.

Harada et al. [45–47] were among the first pioneers to use expansive cementitious materials to fill straight metal sleeve anchorages. The expansive cement was used to place a lateral pressure on the tendon in the sleeve, and thus prevent slippage of the tendon. It was shown that an internal pressure of between 25 and 40 MPa generated by the expansive cementitious material in the sleeve was enough to grip FRP tendons with different surface treatments. Benmokrane et al. [48,49] investigated ground anchorages and described the available AFRP and CFRP tendons, along with their properties and constituent materials (Arapree, Technora, FIBRA, CFCC and Leadline). They discovered that the grout pullout capacity was mainly affected by the properties of the cement grout, surface deformation of the rod, bond length and the modulus of elasticity of the anchorage tube.

Zhang et al. [50] analysed the mechanism of how bonded anchorages work with FRP tendons and presented a conceptual model to calculate the bond stress at the tendon–grout interface and the tensile capacity of the anchorages. This study was carried out to investigate why the bond distribution of bonded anchorages is non-uniform along the bonded length and why the point of peak bond stress shifts from the loaded end of the anchorage to a point inside the anchorage as the applied load increases. Zhang et al. [51] focused their investigation of tensile behaviour onto FRP ground anchorages. Sixteen monorod and four multi-rod grouted AFRP anchorages were tested with expansive cementitious materials to fill straight metal sleeve anchorages. The expansive cement was used to place a lateral pressure on the tendon in the sleeve, and thus prevent slippage of the tendon. It was shown that an internal pressure of between 25 and 40 MPa generated by the expansive cementitious material in the sleeve was enough to grip FRP tendons with different surface treatments. Benmokrane et al. [48,49] investigated ground anchorages and described the available AFRP and CFRP tendons, along with their properties and constituent materials (Arapree, Technora, FIBRA, CFCC and Leadline). They discovered that the grout pullout capacity was mainly affected by the properties of the cement grout, surface deformation of the rod, bond length and the modulus of elasticity of the anchorage tube.

Fig. 2. Example of contoured and straight sleeve anchorages.

Fig. 3. Example of a spike anchorage system.
2.4.3. Spike anchorage

Anchorage of FRP tendons. Several ideas have been proposed, but pose great challenges when using FRP tendons; this is because the tendon is made of an isotropic and yieldable material such as steel, but is difficult to protect, the tendons had to be pre-cut, and the anchorage parts had to be attached before mounting, thus involving tight tolerances.

Issues related to bonded anchorage evidently lay in the long curing time of the bonding material, creep of the cementitious bond material and anchorage lengths that make the technique more suitable for ground anchorage than for structural applications, where instant anchorage is required and there is little mounting space. However, the bonded anchorage protects the FRP tendon and is considered useful in internally poststressed applications where the tendon is stressed and grouted. Still, the control of the stresses in bonded anchorages is difficult and demanding, when the soft zone concept is used to prevent high stresses at the loaded end of the anchorage.

2.4.2. Mechanical anchorages

A mechanical anchorage relies mainly on friction in the interface between the tendon and the inner anchorage surface, so a compressive force perpendicular to the tendon has to be applied. Compression is normally obtained through a cone-shaped interface between a barrel and a wedge, or by clamping the tendon. These techniques work well for traditional prestressing materials, where the tendon is made of an isotropic and yieldable material such as steel, but pose great challenges when using FRP tendons; this is because of the anisotropic properties of FRP that makes the material weak in a direction perpendicular to the fibres. Several ideas have been developed to address the issues related to mechanical anchorage of FRP tendons.

2.4.3. Spike anchorage

The spike anchorage, shown in Fig. 3, consists of an internal spike that presses the fibres of the tendon/rope against the barrel wall, thus holding the single fibres and ensuring full anchorage of the tendon/rope. This system has been used previously with steel strands, but is also considered suitable as an anchorage for Parafil® ropes. Burgoyne [15] described the properties of Parafil® ropes with Aramid core yarns together with a presentation of ongoing research on these materials and related project applications. The method of anchoring Parafil® ropes was explained and the results of tests carried out at Imperial College of Science and Technology, London were detailed. The purpose of the research was to verify long-term properties, thermal properties and fatigue resistance when Parafil® ropes were subjected to tensile bending and sheave bending. It was reported that the system could be successfully used in structural engineering applications. At an ACI Convention in 1988, Burgoyne also explained the use of external FRP prestressing and described anchorage techniques (mainly for Parafil® ropes), fibre relaxation, durability, fatigue, thermal response and bonding [54]. More tests were described in [16], where Parafil® ropes with a nominal tensile capacity of 600 kN were tested. The specimens were tested under tensile bending with a cyclic lateral load being carried. Five tests were conducted, where the cable was preloaded with 300 kN in three tests, 200 kN in one test and 400 kN in one test. The failure mode was mainly at the cable deflector and the measured life cycles ranged between 69,000 cycles and 100,000 cycles. Sheave bending tests were also performed; all ropes failed where the rope was alternately straight or curved during each cycle. This was due to inter-fibre fretting, which was expected to be highest in these areas.

2.4.4. Wedge anchorage

The split wedge anchorage system is shown in Fig. 4. It consists of a barrel that is contoured inside, wedges with an external angled surface that matches the inside of the contoured barrel (the angle can be changed to control the stresses), and a sleeve to distribute compressive stresses from the wedges to the tendon and thus prevent premature failure. Mechanical friction anchorages use large compression forces in order to grip the tendon. This introduces high principal stresses at the loaded end of the anchorage, where longitudinal tensile forces in the tendon are at their maximum and transverse compression forces from the wedges may also be large. To overcome these problems, the compressive stresses (essential for the correct operation of the wedge) can be transferred to the back of the anchorage, where the tensile stresses are lower. Currently, there are two concepts that have been developed to achieve this – the differential angle design and curved angle design. Sayed-Ahmed and Shrive [34] were amongst the first to use the differential angle concept and developed a new wedge anchorage system that could be used for both bonded and unbonded Leadline CFRP tendons. The anchorage system consisted of a steel barrel and four wedges, greased between the barrel/wedge interface. It was constructed with a differential angle of 0.1° between the barrel and wedge. The external wedge, angled at 2.09°, was smooth on the outside and sandblasted on the inner surface. The sleeve could be made of either aluminium or copper. The thin inner sleeve distributes the radial stresses from the wedge more uniformly around the tendon. Early barrel prototypes were made of mild steel because it was hypothesised that a long gripping length (length of 127 mm and outer diameter of 100 mm) would be required to transfer the load and prevent a concentration of high stress in that area. However, numerical analyses showed that it was possible to reduce the dimensions, resulting in a new smaller design, as shown in Fig. 5.

The new anchorage was made of high performance stainless steel (a 0.2% proof stress of 862 MPa and a tensile strength of 1000 MPa). The edges of the inner surface of the four-piece wedge were rounded because tightening of the wedges introduced yielding of the soft metal sleeves that deformed into the wedge gaps.
Possible sharp corners of the wedges could dig into the soft-metal sleeve, creating stress concentrations that can cause premature failure. In the static tests carried out, one of the aims was to obtain a 95% anchorage performance of the ultimate tensile capacity of the tendons, corresponding to a load of 99 kN. Modifications after the initial tests resulted in a range of load capacity from 105 kN to 124 kN. In total, 24 tests were performed: 10 using the prototype anchorage and 14 using the smaller, refined wedge anchorage. Fatigue testing was also carried out: three tests were performed on the prototype anchorages and two on the refined anchorage. Tests were performed with a fixed number of total cycles, which were split up into smaller test series involving different stress ranges and number of cycles (a summation of the numbers of cycles in these tests gave the total number of cycles). The stress range appeared to have a significant effect on the CFRP fatigue strength, where a narrow stress range was thought to result in a load increase. It was claimed that the system worked at the efficiency required by the PTI (Phoenix, Arizona, Post-Tensioning Institute) [55,56] for steel strands and anchorages.

Experimental and numerical evaluations of a stainless steel wedge anchorage for CFRP tendons were conducted by Al-Mayah et al. [57], who tested an anchorage consisting of a stainless steel barrel (inside angle 1.99°), four stainless steel wedges (with a differential angle of 0.1°) and an aluminium sleeve. An 800 mm long, 8 mm diameter CFRP Leadline tendon was tested with presetting (seating of the wedge before tensioning of the tendon) levels of 50 kN (representing 48% of the design tensile capacity), 65 kN (63% of the capacity) and 80 kN (77% of the capacity) and 100 kN (96% of the capacity). The test specimens were loaded both statically and with controlled deformation, and capacities of approx. 100–115 kN were measured. The displacement showed three distinct phases: The displacement in relation to the barrel of the rod and sleeve and the rod’s displacement in relation to the sleeve, see Fig. 6. The first phase starts when the load reaches the slope point, F1. Only the rod moves under this load, with a load displacement rate given by slope 1. When the load reaches load level F2,
the sleeve starts to slip, which results in a decrease in displacement rate shown by slope 2. The load then increases to the ultimate load of the tendon. Slope 3 shows the load/deformation rate of the sleeve, which after slip is initiated, is almost solely responsible for further slip in the entire system. It was also shown that the load levels reached before the slippage of the rod (F1) and the sleeve (F2) could be sustained with reused anchorages. A similar conclusion was reached when a presetting load of 100 kN was applied, which is double the load of that used in the tests that produced the data shown in Fig. 6. Furthermore, Sayed-Ahmed [58] presented research into single and multi-strand steel anchorage systems for CFRP tendons/stays, where the effect on the radial stress of a differential angle between the anchorage wedge and the CFRP tendon was investigated. It was proposed that several differential anchorage wedges in a steel seating plate were used, where nine wedge systems were placed and jacked. The system was shown to fulfill the PTI requirements.

Additional research by Al-Mayah et al. [59] showed the development of a new CFRP rod anchorage system using the curved angle concept. The anchorage components were the same as in former experiments, that is, an outer cylinder (barrel), four wedges, and a soft metal sleeve. However, the contacting surfaces of the wedges and barrel had a circular profile along the length of the anchorage, as shown in Fig. 7. Tensile testing using different presetting loads, geometric configurations, and rod sizes was carried out. Both aluminium and copper sleeves were used on the 6.4 mm and 9.4 mm diameter rods, with a length of 1000 mm. The curved wedges were 80 mm long and the barrel 70 mm long. Tests with and without presetting were performed. The tensile load was applied at a rate of 0.50–0.65 mm/min. A number of specimens were also tested at a load rate of 5.0 mm/min. The loading rate had no effect on anchorage performance. The tangential angle to the curved interface between the wedges and the barrel was small so as to reduce the principal stresses at the loaded end. It was important for the angle to increase smoothly along the length of the anchorage so that the highest wedge compression value at the unloaded end of the rod could be handled. It was reported that, in general, the anchorage performed satisfactorily with presetting (80 kN) as well as without presetting, which however caused the largest slippage. Further, the different FRP rod sizes did not affect performance.

2.4.5. Clamping anchorage

Another type of mechanical anchorage frequently used by researchers is the clamping anchorage. This is used where size, ease of use and aesthetic aspects are of less importance. These anchorages generally consist of two rectangular steel plates, a sleeve (most commonly made of aluminium or copper) and clamping bolts, as shown in Fig. 8. Each steel plate is manufactured with a circular longitudinal notch on one side and holes for the bolts. The aluminium sleeve is thin, with slits along the part clamped in the anchorage. A short section of the sleeve is left without slits to hold the parts together; this part is called the sleeve head and is positioned on the outside of the plates when they are clamped. It is vital that the right torque is applied to the bolts to obtain the proper amount of friction. If the torque is too small, the rod could slip, but too much torque could result in premature failure of the rod due to stress concentrations. These stress concentrations are normally caused by the high principal stresses at the loaded end of the anchorage but can be controlled by applying torque on the bolts in steps. Thus, less torque is applied to the bolt pair at the loaded end of the anchorage and then linearly increased until maximum torque is applied at the unloaded end of the anchorage.

3. Slip at the anchorage/tendon interface

The surface composition of the FRP tendon is critical when using a mechanical anchorage. When using such an anchorage, the composition of the matrix surface layer and the smoothness of the surface are two critical parameters [49,60–62]. Al-Mayah et al. [63,64] addressed this issue and explained the effect of
surface texture, in this case created by sandblasting, between the contact interfaces in the CFRP couplers. This study examined the sliding behaviour of a CFRP rod in contact with copper and aluminium sleeves, simulating the components of a wedge anchorage system. The CFRP rod that was tested was a single spiral indented CFRP rod with a nominal diameter of 9.4 mm, which was then anchored with a clamping anchorage system. A general load displacement relationship was observed across three regions of the graph and there was a load fluctuation amplitude with a height (h), as shown in Fig. 9. In region 1 (slope 1), from zero to a certain maximum load (F1), the load can be explained as the shear stress, where the maximum force is divided by the nominal surface area of the rod. In region 2 (slope 2), a gradually decreasing load over the remainder of the sliding distance follows the maximum peak load. Region 3 (slope 3) is reached in some cases, where complete sticking occurs and the load increases sharply. In conclusion, the interfacial shear stress capacity between a metal sleeve and a CFRP rod increased with increased contact pressure, and the local surface area was increased when the surface was sandblasted, again resulting in an increase in shear stress capacity.

Schön [55,66] investigated the wear of CFRP and the coefficient of friction for aluminium in contact with the CFRP, conducting experiments on a double lap joint with an overlapping length of 40 mm, as shown in Fig. 10. The HTA-6376 carbon fibre epoxy matrix, with nominal ply thicknesses of 0.13 mm, had a quasi-isotropic stacking sequence corresponding to [±45°/0°/90°], meaning a symmetrical layout where the outer friction surface has a fibre direction of 45°. Testing was carried out using displacement-controlled machinery with the application of a 1.5 mm displacement to the specimen for 15 s. The loading was stopped for 15 s to allow the contact surfaces to cool and then reversed. The friction coefficient was calculated using:

\[ \mu = \frac{F}{2P} \]  

(1)

In the tests, the normal force \( P \) was set to 5 kN, which corresponds to a realistic load on bolted joints. Typically, the friction coefficient initially increases rapidly to a high value and then decreases slightly to a constant level.

Friction force and displacement were measured during the sliding sections of the displacement cycle. A high friction force resulted in stick-slip behaviour, which was also seen after the coefficient of friction had increased, as shown in Fig. 11. The friction force was seen to increase from a negative value as a result of the previous loading in the reverse direction, when the direction of the grip displacement was reversed and almost linear until the sliding restarted. In general, specimens with composite/composite contact and aluminium/composite contact behaved in a similar way.

The coefficient of friction initially increased and then decreased slowly. The initial coefficient of friction measured for the composite/aluminium specimens was lower than that measured for the composite/composite specimens. The effective coefficient of friction was predicted according to the following equation:

\[ \mu = \frac{1}{P} (\mu_{fa}P_{fa} + \mu_{fb}P_{fb}) \]  

(2)

where \( \mu \) is the effective coefficient of friction, \( P \) is the total normal force, \( \mu_{fa} \) and \( \mu_{fb} \) are the coefficients of friction of epoxy and fibre in contact with the aluminium, \( P_{fa} \) is the load carried by the epoxy and \( P_{fb} \) is the load carried by the fibre. During the reciprocating sliding, this matrix was worn away and the fibres in the 45° ply layer became visible. The initial coefficient was calculated to be approximately 0.23, whereas the peak coefficient after wear was found to be approximately 0.68. The coefficient of friction was described as being independent of the normal load.

Al-Mayah et al. [64,67] reported the same phenomenon in pull-out experiments, which investigated the interfacial behaviour of CFRP – metal couples under different contact pressures, with different composite surface profiles and different ultimate CFRP tensile capacities. The composite rods were, in these experiments, in contact with either annealed or as-received aluminium or copper sleeves. The capacity to transfer shear stress increased significantly when a smooth machined CFRP rod was used. It was observed that patches of fibres and epoxy were formed when the sliding started and increased as the sliding continued. The contact shear stress was seen to increase with increased contact pressure when the aluminium sleeve, particularly when made with annealed aluminium, was used. In addition, soft annealed sleeves combined with higher tensile strength CFRP rods resulted in higher contact shear stress, whereas a lower shear stress was recorded when using the higher strength rod with the harder, as-received aluminium, sleeve. As a result of these observations, it is recommended that soft sleeves should be used in the design of a wedge anchorage, regardless of the strength or profile of the rod.

4. Evolution of analytical and finite element (FE) models

Early literature on the subject of wedge anchorages for FRP tendons attempted to use basic analytical and FE models to evaluate their behaviour. Over the years, these models have become more advanced. The static 2D rigid body analytical models which had been applied to thin walled cylinder theory are now used with thick walled cylinder theory. FE models have evolved from being two dimensional and axisymmetric to being three dimensional. Static 2D rigid body models are exemplified in the calculations performed within the work of [41,42,68–70]. The models are typically built upon a static equilibrium between the forces, such as in Fig. 12, where the forces acting on the different parts are illustrated, as described in [70]. The barrel vector, \( \mathbf{R}_{\text{tw}} \), is often of interest if a minimum barrel thickness is to be calculated and the resulting equation is described in [3], where \( \mu_{\text{tw}} \) is the coefficient of friction between the wedge and the barrel.
The space between the wedges is not considered, since the theory of the application, combining calculations for the assembled rod, either plane stress or plane strain conditions are required to solve the problem. However, the axisymmetric FE model has the ability to include orthotropic material properties and longitudinal stresses, it cannot take account of the effect of the spaces between the wedges. This was demonstrated by Mitchell et al. [35], where the variation of radial stresses throughout the thickness of the wedge was shown after a complete axisymmetric analysis. The analysis showed high shear stresses at the loaded end of the anchorage during seating and again when the anchorage was fully loaded. A uniform compression from the wedges was also shown, whereas the axial stress in the tendon linearly decreased from the full load at the loaded end of the anchorage to zero load at the unloaded end of the anchorage.

Axisymmetric models have given researchers a sound understanding of how the longitudinal distribution of normal stresses on the rod vary with differences in the angle between the wedge and the barrel, with curved interfaces and with different presetting distances. Campbell et al. [69] showed that there could be a significant redistribution of the radial stresses on the rod by simply changing the difference in the angle between the wedge and the barrel from 0° to 0.2°, with the latter value resulting in a favourable change of peak pressure towards the unloaded end of the anchorage.

In Al-Mayah et al. [76,72] an improvement is made to the theory with the inclusion of 3D modelling. The two papers describing 3D models focus on two attempts to improve the design of the wedge anchorage. Al-Mayah et al. [76] altered the outer diameter of the barrel such that the thick end was made thinner. Again, this was to transfer a larger portion of the radial stresses towards the unloaded end of the anchorage. Load–displacement curves from the model showed good agreement with experimental data. A more detailed model was presented in [72]. This model aimed to reproduce the behaviour of the anchorage with the longitudinally curved inner surfaces as shown in Fig. 13. The meshed model is shown in Fig. 14. The spaces between the wedges were assumed to be symmetrical to minimise computational costs; this should not affect the accuracy of the model. The model described in [72] used the material properties given in Table 2, and all parts were modelled as being isotropic except for the rod, which was modelled with an orthotropic composition. The coefficient of friction was 0.02 for the barrel–wedge interface, 0.24 for the sleeve–rod interface and 0.4 for the wedge–sleeve interface. The resulting longitudinal distribution of radial stresses onto the rod for an outer longitudinal curvature of the wedge was included in the models and the coefficients of friction were all given as constants. In reality, friction is a function of several variables, such as normal force and sliding distance and, with extreme stresses acting on the components; it is obvious that yielding must occur. The model is consequently not a perfect representation of the anchorage, but a representation that can produce the same load–displacement curve as derived from experiments. For even better calibration, other measurements should also be compared to the results from the FE calculations. These other measurements might be the circumferential, longitudinal stresses on the rod and the shear stresses in the sleeve. A comparison with other experiments was given however and so the model cannot be evaluated. Note that these calculations were based upon forces calculated using the static 2D rigid body model, which is a highly simplified representation of the real stresses involved. Al-Mayah et al. [57,72] described a further development of the application, combining calculations for the assembled rod, internal sleeve, wedge and barrel, and thus obtained a better understanding of the radial stress distribution within the anchorage. The results, compared with results from an axisymmetric finite element model, are shown in Fig. 13. The anchorage modelled was designed using the curved angle concept and so the highest stresses were reached at the back of the anchorage. According to Al-Mayah et al., differences between the analytical and numerical models were due to the orthotropy of the rod, something that is excluded in the analytical model. However, the thick walled cylinder theory also has some limitations. As mentioned by Al-Mayah et al., all materials are modelled as being isotropic, and are also assumed to be linearly elastic with the same mechanical properties under tension as well as under compression. The space between the wedges is not considered, since the theory assumes axial symmetry. All longitudinal forces are ignored and either plane stress or plane strain conditions are required to solve the system of equations. The fundamentals of the theory can be found in references such as [73,74].

\[
R_{WB} = \frac{P}{\mu_{WB} \cdot \cos(\theta) \cdot \sin(\theta) + \tau_0}
\]

Using values of \(\mu_{WB} = 0.1\) and \(\theta = 2.1^\circ\) results in a value of \(R_{WB} = 7P\). This value is used by Campbell et al. [69] and Reda Taha and Shrive [41] together with the thin walled cylinders theory, equation [4], to calculate the minimum thickness of a barrel made of UHPC (Ultra High Performance Concrete). \(\sigma_{WB}\) is the internal pressure, \(\sigma_t\) is the circumferential stress, \(d_b\) is the inner diameter, \(t_b\) is the thickness of the cylinder and \(l_b\) is the length of the barrel.

\[
\sigma_t = \frac{\sigma_{WB} \cdot d_b}{2 \cdot t_b} \Rightarrow t_b = \frac{\sigma_{WB} \cdot d_b}{2 \cdot \sigma_t}
\]

where \(\sigma_{WB} = \frac{2 \cdot R_{WB}}{\pi \cdot d_b \cdot l_b}\) (4)

Using the previous example, with an ultimate tensile capacity of the concrete equal to 9 MPa, a maximum prestressing force, \(P\), of 104 kN and a barrel length of 180 mm, a barrel thickness of 140 mm would be required.

Shaheen and Shrive [70] compared results from tests where the barrel failed at a prestressing load of 40 kN. Using a value of 40 kN in equation [4], the stress in the concrete when it fails should be 8 MPa. When compared to the expected 25 MPa, the thin walled cylinder theory obviously does not adequately describe the stresses within the barrel. This is a common conclusion in literature on the subject of shells and cylinders. For example, Roark and Young [71] stated that the theory is only applicable when the cylinder’s thickness is less than one-tenth of its radius. Shaheen and Shrive [70] advanced this theory when they used the thick walled cylinder theory as well as the thin walled cylinder theory to find the required ultimate tensile strength of a UHPC barrel. No comparison with other experiments was given however and so the model cannot be evaluated. Note that these calculations were based upon forces calculated using the static 2D rigid body model, which is a highly simplified representation of the real stresses involved. Al-Mayah et al. [57,72] described a further development of the application, combining calculations for the assembled rod, internal sleeve, wedge and barrel, and thus obtained a better understanding of the radial stress distribution within the anchorage. The results, compared with results from an axisymmetric finite element model, are shown in Fig. 13. The anchorage modelled was designed using the curved angle concept and so the highest stresses were reached at the back of the anchorage. According to Al-Mayah et al., differences between the analytical and numerical models were due to the orthotropy of the rod, something that is excluded in the analytical model. However, the thick walled cylinder theory also has some limitations. As mentioned by Al-Mayah et al., all materials are modelled as being isotropic, and are also assumed to be linearly elastic with the same mechanical properties under tension as well as under compression. The space between the wedges is not considered, since the theory assumes axial symmetry. All longitudinal forces are ignored and either plane stress or plane strain conditions are required to solve the system of equations. The fundamentals of the theory can be found in references such as [73,74].

Fig. 14. FE model used in [72].
The main failure modes are closed mechanical anchorage system works seems to be very common and an unsuccessful anchorage is small. The way in which the anchorage, that is, the difference between a successful anchorage and an unsuccessful anchorage requires the instant curing of bonding agents and needs longer anchorage lengths. Several mechanical anchorages have been developed to anchor FRP tendons such as wedge anchorages or clamping anchorages. However, the stability of the anchorages is unreliable, and experimental results suggest that only small differences in the mounting procedure greatly affect the performance of the anchorage, that is, the difference between a successful anchorage and an unsuccessful anchorage is small. The way in which the closed mechanical anchorage system works seems to be very complex to model and verify through tests. The main failure modes are

(i) premature failure at the loaded end of the anchorage due to high principal stresses, (ii) local crushing and (iii) sliding of the contact interface between the FRP rod and sleeve where the tendon resin layer has worn off. The literature studied suggests that anchorages using soft aluminium are beneficial in transferring shear stresses to the wedges without causing any premature failure. Controlling, understanding and thus reducing the number of possible failure modes are some of the main areas to study and solving these problems might solve the FRP anchorage issue. Analytical models are limited, ranging from static, 2D rigid body models using both the thin walled cylinder theory and the thick walled cylinder theory, to FE models, which have evolved from 2D evaluations and axisymmetric models to 3D models. However, there is huge complexity in modelling all the anchorage parts with their properties, shapes, tendon forces, sliding distances, extreme stresses and yielding effects and, as these are specific for each type of anchorage, the task is demanding. It is evident that the development of a reliable, easy-to-produce and mount anchorage still remains to be achieved, though several anchorage designs have been proposed. For FRP prestressing applications, such anchorages have to be developed to meet the same requirements as those for steel prestressing systems and thus compete at the same level. Critical issues relating to FRP anchorages and the use of proper test methods to verify their performance have to be addressed more consistently in the future. Furthermore, the testing of FRP tendons has shown that, often, there is brittle behaviour that causes a sudden failure at high levels of force. It can therefore be difficult to distinguish between a tendon and an anchorage failure. This means that a fracture which seems to have been caused by a tendon failure at high levels of force. It can therefore be difficult to distinguish between a tendon and an anchorage failure. This means that a fracture which seems to have been caused by a tendon failure can easily have been caused by the anchorage failing instead. The difficulty is whether to focus on the level of stress on the tendon or on the whole system (anchorage + tendon). The literature study has revealed some areas of FRP anchorage that could be focussed on in the future:

5. Discussion and future research

Currently, there are no efficient and competitive prestressing systems for FRP tendons despite research over the last two decades. A great challenge lies within the anchorage of the FRP tendon itself and there have been several attempts to develop FRP anchorage systems. Different types of anchorages grip in different ways. A mechanical anchorage is preferred because it is easy to mount and control the stress through it, whereas a bonded anchorage requires the instant curing of bonding agents and needs longer anchorage lengths. Several mechanical anchorages have been developed to anchor FRP tendons such as wedge anchorages or clamping anchorages. However, the stability of the anchorages is unreliable, and experimental results suggest that only small differences in the mounting procedure greatly affect the performance of the anchorage, that is, the difference between a successful anchorage and an unsuccessful anchorage is small. The way in which the closed mechanical anchorage system works seems to be very complex to model and verify through tests. The main failure modes are

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5.1. Reliability and durability

- Anchorage requirements to provide for a safe failure, which are comparable with existing requirements for steel systems.
- Definition of stable and reliable friction surface between the FRP tendon and the anchorage.
- Monitoring of stresses in the anchorage in tests and field applications.
- More testing of the life span of FRP anchorages as, so far, there have been only limited investigations into the life span (short and long-term effects).
- Development of working deviators and anchorage–concrete connections with respect to the maximum curvature and transverse capacities of the tendons.
- Standards and guidelines relevant to FRP anchorage.

5.2. Testing

- Addressing failure modes and their acceptability.
- Long-term resistance and fatigue resistance.

Table 2

<table>
<thead>
<tr>
<th>Property</th>
<th>Rod</th>
<th>Sleeve</th>
<th>Wedge</th>
<th>Barrel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material (–)</td>
<td>CFRP</td>
<td>Copper</td>
<td>Steel</td>
<td>Steel</td>
</tr>
<tr>
<td>E-modulus, $E_1$ (GPa) (Longitudinal direction)</td>
<td>124</td>
<td>117</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>E-modulus, $E_2$ (GPa) (Transverse direction)</td>
<td>7.4</td>
<td>117.0</td>
<td>200.0</td>
<td>200.0</td>
</tr>
<tr>
<td>Shear modulus, $G_{12}$, $G_{13}$ (Transverse direction)</td>
<td>7.0</td>
<td>44.7</td>
<td>77.0</td>
<td>77.0</td>
</tr>
<tr>
<td>Major Poisson's ratio $\nu_{12}$, $\nu_{13}$, $\nu_{23}$</td>
<td>0.26</td>
<td>0.31</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>Minor Poisson's ratio $\nu_{21}$, $\nu_{31}$</td>
<td>0.02</td>
<td>0.31</td>
<td>0.30</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Fig. 15. (a) Radial stresses onto the rod for different presetting distances; and (b) comparison of FE and experimental results, after [72].

the barrel, the relative motion between the components within the anchorage and shear stress distribution in the interfaces between adherent and adhesives.
5.3. Material properties and geometry

- What effect does the material and geometry of the wedge and barrel have on the performance of the anchorage?
- How are the anchorage and the system as a whole best modelled and verified?
- Could materials other than metals be used as anchorage parts (cement or fibre based)?
- Can the ease of mounting match that of conventional steel prestressing?

References
