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Review

Mechanical anchorage of FRP tendons – A literature review

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ABSTRACT

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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Nomenclature

D_1	length of region 1 and turning point to region 2
d_B	inner diameter of barrel
F_1	maximum load of region 1
F	applied tensile force
F_{TW}	resulting force vector from the tensioned tendon
F_{WB}	resulting force vector between barrel and wedge
f_u	ultimate tensile capacity
h	height
P	prestressing or clamping force
P_{ea}	load carried by the epoxy
P_{fa}	load carried by the fibres
R_{TW}	friction force between tendon and wedge
R_{WB}	friction force between wedge and barrel
t	thickness
t_B	thickness of the barrel
l_B	barrel length
d	deformation
m	effective coefficient of friction
m_{ea}	coefficient of friction for epoxy in contact with aluminium
m_{fa}	coefficient of friction for fibre in contact with aluminium
m_T	coefficient of friction
m_{WB}	coefficient of friction between wedge and barrel
σ	stress
σ_T	circumferential stress
σ_{WB}	internal pressure

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1. Introduction

In recent decades, there have been several proposals for the design of external post-tensioned 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 economically 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.

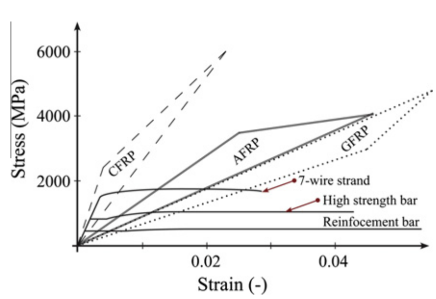

Fig. 1. Stress/strain curve showing FRP and steel varieties [12,13].

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