Development of a mechanical wedge-barrel anchor for CFRP rods: static and fatigue behaviours

Hossein Heydarinouri ¹; Masoud Motavalli ²; Alain Nussbaumer, M.ASCE ³; Elyas Ghafoori, M.ASCE ⁴

¹ Ph.D. candidate, Empa, Swiss Federal Laboratories for Materials Science and Technology and Swiss Federal Institute of Technology Lausanne (EPFL). Ueberlandstrasse 129, 8600 Duebendorf, Switzerland, Lausanne, Switzerland. E-mail: hossein.heydarinouri@empa.ch

² Professor, Head of the Structural Engineering Research Laboratory, Empa, Swiss Federal Laboratories for Materials Science and Technology, Ueberlandstrasse 129, 8600 Duebendorf, Switzerland. E-mail: masoud.motavalli@empa.ch

³ Professor, Resilient Steel Structures Laboratory, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland. ORCID: <http://orcid.org/0000-0002-8994-4926>. E-mail: alain.nussbaumer@epfl.ch

* ⁴ Group leader, Scientist, Empa, Swiss Federal Laboratories for Materials Science and Technology, Ueberlandstrasse 129, 8600 Duebendorf, Switzerland (Corresponding Author). ORCID: <http://orcid.org/0000-0002-4924-0668>. E-mail: elyas.ghafoori@empa.ch

Abstract

In this study, a mechanical anchorage for prestressed carbon fibre-reinforced polymer (CFRP) rods was proposed. The proposed anchorage consists of a steel barrel with a conical hole and three separate aluminium wedges that are in direct contact with the CFRP rod. The anchorage system relies only upon friction, without any adhesives required. The static and fatigue behaviours of the anchor were experimentally investigated according to the European guidelines for

testing post-tensioning kits (e.g., ETAG 013) and fulfilled their requirements. The average tensile strength of the anchorage system for the 8-mm CFRP rods was 2371.4 MPa, being greater than the guaranteed value of 2047 MPa. The fatigue tests revealed that the wedge seating distance (prior to pulling the rod) significantly affected the occurrence of slippage between the anchor components. Therefore, a new displacement-controlled presetting system was developed to ensure adequate wedge seating distance. It eliminated the need for hydraulic jacks and demonstrated the capability of applying presetting forces greater than 110 kN. Furthermore, the anchors were tested under loading frequencies of 5, 17, and 23 Hz. The proposed anchorage was observed to be insensitive to the loading frequency because no slippage or temperature rise occurred under these loading frequencies.

Keywords: CFRP tendon; Fatigue; Post-tensioning; Strengthening; Wedge–barrel anchor.

Introduction

Post-tensioned (PT) steel strands have traditionally been used in prestressed structures such as concrete girders, post-tensioned concrete slabs, cable-stayed bridges, and post-tensioned walls. Carbon fibre-reinforced polymer (CFRP) materials have been considered as effective substitutes for prestressed steel strands because steel is vulnerable to fatigue and corrosion while CFRP provides a higher strength-to-weight ratio and superior corrosion and fatigue resistance (Zhao 2013). However, because CFRP materials are weak in their transverse directions (Zhao 2013), the conventional anchorages used for steel components cannot be applied to these materials. Therefore, the development of proper anchorages for CFRP tendons, especially for prestressed applications, has been a research topic for the last couple of decades (Schmidt et al. 2012). Various bonded and unbonded (mechanical) PT anchorages have been developed for both CFRP plates and rods. In this study, a mechanical wedge–barrel anchor system for CFRP rods was introduced.

In the majority of the existing studies, only the static performance of the anchorages has been investigated, aiming to achieve the maximum tensile capacity of the CFRP tendons. However, only a limited number of studies have investigated the fatigue performance of PT anchorages for CFRP tendons due to the lack of standard test procedures and acceptance criteria. Some of the studies employed test procedures that were not based on standards. The following subsections present an in-depth literature review. First, a brief review of the PT systems for CFRP plates is presented. The existing PT systems for CFRP rods are reviewed in more detail, and previous studies of the fatigue performance of mechanical wedge-barrel anchors are presented. Finally, the main objectives of this study are summarised.

CFRP plate anchorages

Various resin-based anchors have been developed and experimentally investigated. Michels et al. 2013 proposed a gradient Anchorage system for CFRP strips, and Li and Xian 2018, 2019 developed wedge-shape anchors with optimized anchor parameters. At the Swiss Federal Laboratories for Materials Science and Technology, Empa, Switzerland, trapezoidal (Ghafoori and Motavalli 2015) and flat (Hosseini et al. 2018) mechanical prestressed unbonded reinforcement (PUR) anchorage systems were developed and later used to strengthen the girders of two bridges in Switzerland (Ghafoori et al. 2015) and Australia (Ghafoori et al. 2018; Hosseini et al. 2019), respectively. These anchorage systems clamped the prestressed CFRP plates and relied only upon friction. A friction-based wedge-type anchorage for prestressed CFRP plates was also developed and presented in Mohee and Al-Mayah 2017, 2018. In this type of anchorages, the wedges had a curved profile that provided proper contact pressure distribution on the CFRP plates, leading to a high static tensile strength. Various types of anchorages for CFRP plates have been reviewed (Mohee et al. 2016).

CFRP rod anchorages

As an alternative to CFRP plates, CFRP rods have been used in post-tensioned structures. Information regarding various types of bonded anchorages for FRP materials was collected and compared by Schmidt et al. 2012. Among the bonded anchorage systems for CFRP rods, the wedge-type anchor proposed in (Meier 1995, 2012) is of substantial importance, because it was the first time a gradient epoxy material was used in the wedge. In wedge-type anchors, when the tensile stress and contact pressure on the CFRP tendon are simultaneously high at the loading end, the CFRP premature rupture occurs due to the stress concentration. Meier 1995, 2012 developed an anchorage to avoid this stress concentration by fabricating the wedge using an epoxy, to which particles were added at different levels to achieve a stiffness gradient. In this anchorage, the elastic modulus of the mixture of the epoxy and particles continuously increased along the anchor, from the loading end to the free end, reducing the contact pressure on the CFRP tendon at the loading end and providing an anchorage efficiency of 92%. The anchorage efficiency was defined as the ratio between the actual PT tensile strength and the nominal tensile strength of the tendons. In another type of bonded wedge anchorage, the CFRP rod was split in the middle of its cross-section along a certain length, and a wedge was placed in the split (Arnautov et al. 2014; Li et al. 2020). The rod was anchored by applying epoxy between the CFRP rod and the steel barrel.

In addition, unbonded anchorages have been used in post-tensioned structures. In mechanical wedge anchors, when the wedges insert into the conical barrel hole, the contact pressure on the tendon increases, providing friction resistance against rod slippage. Similar to the gradient adhesive concept in bonded anchorages (Meier 1995, 2012), two common methods to prevent premature rupture due to the stress concentration at loading end of the anchor are: (i) providing a constant differential angle between the wedge and barrel cones and (ii) using curved conical shapes for both the wedge and barrel, thus providing a distribution of the differential angles along the anchor. The mechanism of contact pressure reduction at the loading end of the anchors using a constant differential angle was presented in (Kerstens et al. 1998). In this method, a

volume of the material is removed from the loading end of the wedge, leading to a reduction in the contact pressure on the wedge induced by the barrel. Consequently, it leads to a reduction in the contact pressure on rod at the loading end. The same mechanism is valid for the anchors with curved conical profiles.

Different researchers have developed mechanical wedge–barrel anchors with constant differential angles. In the anchorage system introduced in (Sayed-Ahmed and Shrive 1998; Sayed-Ahmed 2002), four steel split wedges had a differential angle of 0.1° . A soft sleeve, made of aluminium or copper, was used between the wedges and CFRP rod to avoid damaging the rod. The failure mode in the static tests was the CFRP rod rupture, with an average tensile capacity of 10% greater than the guaranteed value of the CFRP rods. A split-wedge–barrel anchor for 5.4 mm CFRP rods was introduced later by Terrasi et al. 2011 for prestressed concrete applications. The barrel and wedges were made of steel and polymer with glass fibres (PPS-GF40), respectively, with a constant differential angle of 0.23° . They performed static and creep tests on their anchor, which demonstrated an anchorage efficiency of only 73.4%. An easy-to-use two-piece wedge anchorage was introduced and investigated by Schmidt et al. 2010; Schmidt et al. 2011, in which the wedges were integrated with the sleeve and in direct contact with the CFRP rod. The integrated wedge was made of aluminium and had a differential angle of 0.4° . Static tests were performed on the 8 mm CFRP rods according to the European standards (*fib* 1993; Rostásy 1998; EOTA 2002), demonstrating that the tensile capacity of the anchorage exceeded the nominal strength of the CFRP rods.

Al-Mayah et al. 2006 proposed a wedge anchor with a curved conical shape for both the barrel and wedges to further reduce the stress concentration; the curves were circular. The differential angle at the loading end was small and increased towards the free end. It enabled a rapid increase in the contact pressure on the rod from the small value at the loading end. In this anchorage system, three split steel wedges were in contact with a steel barrel and a copper or

aluminium sleeve. The tensile strength of the anchorage system exceeded the guaranteed strength of the CFRP rods.

Fatigue tests on mechanical wedge-barrel anchors

In most of the previously discussed studies, only the static performance of the anchors was investigated. Few studies have addressed the critically important factor of fatigue performance and the corresponding acceptance criteria. The most relevant studies on the fatigue performance of mechanical wedge-barrel anchors are briefly presented in this sub-section with highlights of the limitations of each study.

The fatigue performance of a wedge-barrel anchor for an 8 mm CFRP rod with a constant differential angle was investigated by Al-Mayah et al. 2001. In their study, three cyclic loads with different stress ranges and ratios were applied, and the fatigue life and slippage of the CFRP rod during the fatigue tests were reported. However, no further information was provided regarding the selected cyclic load history and fatigue acceptance criteria. In other studies, fatigue tests were performed according to the procedure recommended by the Post-Tensioning Institute (PTI 1985), which is typically used for steel tendons (Sayed-Ahmed and Shrive 1998; Campbell et al. 2000; Taha and Shrive 2003; Elrefai et al. 2007). These studies concluded that the fatigue performance of the anchors could fulfil the requirements of PTI 1985. More recently, Kar et al. 2012 conducted tension-tension fatigue tests on the CFRP rods, with different stress ratios, focusing on the damage mechanisms during the fatigue loading. Li et al. 2019 performed tension-tension fatigue tests on hybrid carbon/glass rods, with different maximum stress levels at a fixed stress ratio. The focus of this study was the fatigue failure mode. However, none of these studies addressed the slippage behaviour of the anchorage components during the cyclic loadings in accordance to an acceptance criteria.

Primary objectives and outline of the study

In this study, a mechanical wedge–barrel anchor for CFRP rods is introduced, taking the advantages of the existing anchorages. To the best of the authors' knowledge, all previous studies performed their fatigue tests according to the PTI 1985. For the first time, in the present study, the European codes and standards are used to evaluate both the static and fatigue performance of the developed anchor. In addition, the effect of the wedge seating distance in the barrel (prior to the rod pulling) on the slippage behaviour of the anchor during the fatigue tests is investigated. Subsequently, a new displacement-controlled presetting system is proposed to ensure an adequate wedge seating distance. Finally, the effect of frequency on the slippage and temperature change in the anchorage components during the cyclic loadings is experimentally investigated.

Proposed anchorage system

The wedge–barrel anchor introduced in this study is a combination of anchors developed by Al-Mayah et al. 2006 and Schmidt et al. 2010; Schmidt et al. 2011. In the anchor developed by Al-Mayah et al. 2006, a curved (circular) profile was used for the contact surfaces between the wedges and barrel along the anchor length. The curved profile prevented stress concentration at the loading end while increasing the contact pressure rapidly towards the free end, resulting in a shorter anchor length required to achieve adequate frictional resistance. However, in this anchor, a soft sleeve (i.e., aluminium or copper) was used to prevent CFRP damage. Schmidt et al. 2010 eliminated the need for a soft sleeve by developing a wedge–barrel anchor that employed an integrated sleeve; the wedges and sleeve were both made of aluminium.

In the present study, a wedge–barrel anchor with a curved profile was used, as shown in Fig. 1. The profile curvature of the wedges and barrel was similar to that of Anchor A introduced in (Al-Mayah et al. 2006). The wedges were made of aluminium and were in direct contact with the CFRP rod, without the need for a sleeve. The use of aluminium wedges reduced the required presetting force because aluminium has a lower stiffness than steel, resulting in an

easier insertion into the barrel. This trend was demonstrated in a numerical study by Al-Mayah et al. 2013, which compared the insertion of different wedges composed of soft and hard steels. In addition, the aluminium plasticisation that occurs due to the high contact pressure inside the barrel can improve the gripping of the CFRP rod.

It is noted that an FE model of the wedge–barrel anchor was developed using ABAQUS software to achieve a proper contact pressure on the CFRP rod and was verified by the experimental results. The applied FE model is briefly described in the Appendix I. The FE model showed that the contact pressure on the CFRP rod for the split-wedge anchor was desirably the minimum at the loading end. Detailed descriptions of the FE model or a parametric study considering various wedge–barrel anchor configurations and geometries were beyond the scope of the present study and will be addressed in a future study.

Different anchor configurations

Two configurations of the wedge–barrel anchors, i.e., with integrated and split wedges, were developed for the preliminary static tests, as shown in Fig. 2(a) and (b), respectively. The integrated wedge shown in Fig. 2(a) had two 1-mm slits and a 3 mm gap. When the CFRP rod was pulled, it tended to bring the wedge into the barrel. When the wedges were inserted into the barrel, the circumferential pressure from the barrel caused wedge deformation. The existence of the slits and gaps facilitated this deformation during the insertion, i.e., the slits opened, and the gap tended to close. The anchor with the other configuration, shown in Fig. 2(b), had three split wedges with a gap distance of 1.5 mm.

Material properties of the anchorage components

The wedges were made of EN AW-6020 aluminium with an elastic modulus of 71.7 GPa, yield strength of 404 MPa, and ultimate tensile strength of 442 MPa, based on coupon tests according to DIN EN ISO 6892-1 (DIN 2017). The barrel was made of high strength V155 steel with a nominal elasticity modulus and tensile strength of 200 GPa and 1300 MPa, respectively.

The CFRP rods had a nominal diameter of 8 mm, a guaranteed tensile strength of 102.9 kN (equivalent to 2047 MPa), a fibre volume fraction of 65%, and a longitudinal elastic modulus of 160 GPa, according to ASTM D7205/D7205M-06 (ASTM D/DM 2016), provided by S&P Clever Reinforcement Company AG, Switzerland.

Preliminary static tests

The static performance of the integrated and split-wedge anchors was investigated in the preliminary design stage. Before pulling the CFRP rods, the wedges were preset using a 200 kN Amsler testing machine in a setup shown in Fig. 3(a). In this setup, the wedges were compressed by lifting the anchor to contact the fixed plate. A shaft was placed between the fixed plate and top surface of the wedges to transmit the compressive presetting force. The shaft had a hole in the center, with a diameter of 9 mm, so that the rod could pass through the hole. Therefore, the shaft completely rested on the top surface of the wedges. The static tensile tests on the wedge–barrel anchors were performed using the setup shown in Fig. 3(b).

Test results

The results of the preliminary static tests are presented in Fig. 4. The tests were performed on anchors with different presetting forces, P , ranging from 10 to 50 kN. As shown in Fig. 4(a), for the integrated wedge anchor and up to a presetting force of $P = 30$ kN, the failure mode of the PT system was CFRP rod slippage inside the integrated wedge. For the presetting forces of 40 and 50 kN, the failure mode changed to CFRP rod rupture; however, the ultimate tensile strength was approximately 80 kN, which is around 78% of the guaranteed tensile strength of the rod. Fig. 4(b) shows the CFRP rod and integrated wedge after failure. Interlaminar shear failure occurred in the gap area of the CFRP rod. In addition, cracks appeared near the slit because the slit opened during the insertion of the wedge into the barrel. The existence of a crack at the slit resulted from the constraint against the slit opening.

The results of the preliminary static tests on the split-wedge anchors are shown in Fig. 4(c) and indicated that, up to a presetting force of 20 kN, the failure mode was the rod slipping inside the wedges. No slippage of the CFRP rod occurred with a presetting force of 30 kN. This value was less than the 40 kN required to prevent the slipping in the integrated wedges. Because the split wedges were not connected to each other and, thus, did not resist the circumferential deformation of the adjacent wedges. Thus, they deformed more easily under the circumferential stresses compared to the integrated wedges. Therefore, a higher presetting force was required to activate the integrated-wedge anchor system. The tensile strength was in the same order of magnitude as the CFRP rod guaranteed tensile strength. Further, interlaminar shear failure did not occur in the split-wedge anchor system. This resulted from the fact that the free surfaces of the CFRP rod in the split-wedge anchor occurred in three small areas (see Fig. 2(b)). In the integrated-wedge anchor, however, the concentration of the free surface in the gap area triggered the premature interlaminar shear failure of the CFRP rod.

Notably, although the integrated wedge system demonstrated the lower tensile strength in the present study, an integrated wedge anchor system with a longer wedge and barrel, i.e., 95 and 105 mm, respectively, was statically tested by Schmidt et al. 2010 and provided a relatively higher tensile strength. This implies that further changes in the integrated wedge anchor geometry in the current study might result in a higher tensile capacity.

Modification on the split-wedge anchors

The split-wedge anchor was selected for further experimental and numerical investigations, based on the preliminary test results. The wedge and barrel geometries were modified to increase the tensile capacity of the PT system. Fillets were added to the edges of the wedge that were in contact with the CFRP rods to prevent stress concentration at the edges, i.e., the edges near the loading end and the longitudinal edges. In addition, the gap between the adjacent wedges was reduced from the initial 1.5 mm to 1 mm to increase the contact area. A fillet was

created in the barrel cone edges at the free end to enable an easier insertion of the wedges. The modifications are shown in the appendix II.

Experimental study on the modified split-wedge anchors

In this section, the European standard testing procedures for PT systems as well as the static and fatigue tests on the modified split-wedge–barrel anchors are described.

Standard static and fatigue testing procedures

This section discusses the relevant static and fatigue testing procedures and the acceptance criteria recommended in: (i) the European Technical Approval Guidelines ETAG 013 (EOTA 2002), (ii)), the International Federation for Structural Concrete (*fib*) recommendations for the acceptance of PT systems (*fib* 1993), which is typically used for steel PT systems, and (iii) the draft guideline for the acceptance testing of FRP PT tendons (Rostásy 1998).

Standard static tensile tests

The goal of static tensile testing is determining the tensile strength of the PT system, T_u , or the reduction in the tensile capacity (compared to the tendon strength) due to the anchorage effect. According to ETAG 013 (EOTA 2002) and the recommendations for the acceptance of PT systems (*fib* 1993), the acceptance criteria for static tests are as follows:

- (i) The failure mode must be a tendon fracture and not the failure of the anchorage components, i.e., excessive residual deformation in the anchorage components after testing.
- (ii) The maximum measured tensile load must be greater than 95% of the actual ultimate strength of the tendon, i.e., an efficiency factor of 0.95.
- (iii) The relative movements of the anchorage components must stabilise within the first 30 minutes at a tensile load level representing 80% of the characteristic tensile strength of the prestressing steel.

In the acceptance criteria proposed in the draft guideline for FRP post-tensioning tendons (Rostásy 1998), the failure mode criterion is the same as item (i). However, it does not propose a criterion for the efficiency factor. In addition, it recommends a tensile load level of 70% instead of 80% of the tensile strength of the tendon for the slippage stabilisation of the anchorage components in item (iii).

In this study, the acceptance criteria for the static tests were as follows:

- For the failure mode, item (i) was adopted.
- An efficiency factor of 95% was required.
- For the relative movement stabilisation of the anchorage components, a tensile load level of 70% of the guaranteed tensile strength of the CFRP rod was applied.

Standard fatigue tests

The aim of fatigue tests is determining the fatigue strength of the anchors, which is defined as the stress range under which the PT system endures 2 million cycles. All the previously discussed standards and recommendations state that no fatigue failure should occur in either the anchorage or tensile elements during the fatigue tests. ETAG 013 (EOTA 2002) and *fib* (*fib* 1993) state that the minimum fatigue strength of PT systems for steel tendons is 80 MPa, with a maximum fatigue load of 65% of the characteristic tensile strength of the tendon. The draft guideline for FRP PT tendons (Rostásy 1998), however, does not provide a recommendation for the fatigue strength, only stating that the fatigue strength should be equal to the maximum in-service stress range. In this study, a stress range of 100 MPa, with a maximum load level of 65% of the CFRP nominal tensile strength applied for 2 million cycles without failure, was set as the acceptance fatigue criterion. In the following section, the procedures for and results of the static and fatigue tests on the split-wedge anchors are presented.

Static tests on the modified split-wedge anchors

Test procedure

The loading protocol for the static tests is shown in Fig. 5(a), in which the load increased stepwise at a loading rate of 0.08 kN/s (100 MPa/min) according to (fib 1993; EOTA 2002). At load levels of 0.2, 0.4, and 0.6 of the CFRP rod nominal tensile strength, T_{nom} , which was 102.9 kN, the displacement of the wedges and CFRP rod relative to the barrel, called relative draw-ins, were measured after five minutes, using a Mitutoyo digital dial gauge with a reading precision of 0.001 mm, as shown in Fig. 5(b). In addition, at a load of $0.7T_{nom}$, the stabilisation of the draw-ins after 30 minutes was evaluated.

A schematic of the dimensions of the dial gauge and ring and the parameters required for the measurement of the relative draw-ins are provided in Fig. 5(c). The relative draw-ins for the wedges, Δw , and CFRP rod, Δr , were calculated relative to a reference state. In the static tests, the reference states were the beginnings of the periods corresponding to each load level of 0.2, 0.4, 0.6, and 0.7 of T_{nom} . They were calculated based on the dial gauge measurements using the following equations:

$$\Delta w = D_{w,ref} - D_w ; \quad (1-a)$$

$$\Delta r = D_{r,ref} - D_r , \quad (1-b)$$

where $D_{w,ref}$, D_w , $D_{r,ref}$, and D_r are the dial gauge readings at the reference state and after the insertion of the wedges and CFRP rod, respectively. In Fig. 5(c), the wedge seating distance, S , which is the distance between the top surfaces of the wedges and barrel, determines the placement of the wedges in the barrel. This parameter significantly affects the fatigue performance of the anchors, which is discussed in more detail later in this paper and is obtained by

$$S = 13 + D_w . \quad (2)$$

Test results

The results of the static tests are presented in Table 1. Three presetting forces, P , i.e., 30, 50, and 70 kN, were applied to the wedges. As shown in Table 1, in all static tests, the tensile loading capacity was at least 10% greater than the nominal strength of the CFRP rods, even at the smallest presetting force of 30 kN. The relative draw-in measurements indicated that at a load of 70% of the nominal tensile strength, the draw-ins stabilised after 30 min. The load–displacement curves for the different anchors as well as the failed specimen S1 are illustrated in Fig. 6(a) and (b), respectively.

Specimen S4 was not sandblasted so that the effect of the friction between the inner surface of the wedges and the CFRP rod could be investigated. As shown in Fig. 6, although the loading capacity for this specimen was greater than the CFRP rod nominal strength, the CFRP rod slipped considerably inside the wedges. It was concluded that Samples S1 to S3 met the static test requirements.

Fatigue tests on the modified split-wedge anchors

Test procedure

The fatigue tests were performed under a load-controlled constant amplitude condition and a frequency of 12 Hz. The loading protocol for the fatigue tests is shown in Fig. 7. The upper load in the fatigue tests was $0.65T_{\text{nom}}$ (66.9 kN), which was equivalent to 1330.6 MPa for an 8 mm rod, with a stress range of 100 MPa. Each sample was subjected to a minimum of 2 million cycles.

Before the cyclic loading began, each specimen was statically loaded to 61.9 kN (i.e., the fatigue lower load) according to the test procedure presented in (fib 1993; EOTA 2002). This state was considered to be the reference state, and the dial gauge readings for the wedges, $D_{w,ref}$, and CFRP rod, $D_{r,ref}$, were measured. The subsequent relative draw-ins for the wedges and

CFRP rod were calculated relative to the reference state using Eq. (1). Then, each specimen was statically loaded to 66.9 kN (i.e., the upper fatigue load), and then the load was reduced to 61.9 kN; the relative draw-ins were measured at each of these load levels. The fatigue test then began and was stopped after every half-million cycles to determine the relative draw-ins of the CFRP rod and wedges for each anchor at the lower and upper loads.

In the acceptance test reports for steel strands, several single wedges and strands are selected, for which the relative draw-ins corresponding to the lower and upper loads are separately reported. In this study, measurements were performed for all the wedges and CFRP rods. The average of the relative draw-ins of all the wedges in the anchor was calculated and used to determine the relative draw-ins. In addition, after each half-million cycles, the averages of the relative draw-ins corresponding to the lower and upper loads were considered for both the wedges and CFRP rod. In this way, only the average values were reported for the wedges and CFRP rods for each anchor and after each half million cycles. This method of reporting the results helped to demonstrate the slippage of the anchor components during the fatigue tests more clearly.

The anchors were subjected to load-controlled fatigue loading, as given in Table 2. Because the top and bottom anchors were subjected to identical cyclic loading during the fatigue tests, the properties and test results for the top and bottom anchors are presented separately in Table 2.

Test results

For all specimens, no CFRP failure occurred during the fatigue tests. In addition, there was no increase in the machine displacement, showing that the stiffness of the post-tensioning system was constant during the fatigue tests. It would indicate that no significant damage occurred in the CFRP rods inside the anchors.

Lubricant was not used between the wedges and barrels in anchors F5-T, F5-B, and F6-T to investigate the effect of the friction between the wedges and barrel on the anchor fatigue performance. The presetting force for these anchors was 50 kN. As shown in Fig. 8, the relative draw-ins for these anchors during the fatigue tests showed that the CFRP rods started slipping after several cycles. The slippage, shown in Fig. 8, represents the difference in the relative draw-in between the CFRP rod and wedges. The fatigue performance of these anchors did not meet the requirements of the aforementioned standards and recommendations due to the continuous slippage and excessive residual deformations of the anchorage components.

The use of the lubricant in anchors F6-B, F7-T, and F7-B, which all had a presetting force of 50 kN, resulted in no slippage during the cyclic loading, as shown in Fig. 9. Comparing the seating distances of the wedges, S , for the anchors with and without lubricant revealed that, for a given presetting force, the application of the lubricant between the wedges and barrels resulted in a greater insertion (a smaller S), due to the reduction in the friction between the wedges and barrel. This greater insertion of the wedges resulted in a higher contact pressure around the CFRP rods, and, consequently, no slippage occurred during the fatigue tests for anchors F6-B, F7-T, and F7-B (see Fig. 9).

The wedge seating distance under the tensile load of $T = 61.9$ kN, i.e., the minimum CFRP load in the fatigue tests, was measured for specimens F5 to F7 and the results are listed as $S_{61.9}$ in Table 2. The fatigue test results demonstrated that, when the value of $S_{61.9}$ was less than 19 mm, no slippage of the anchorage components occurred. It could be inferred that presetting the wedges (before pulling the CFRP rod) to a seating distance less than 19 mm would prevent the slippage. Therefore, the key parameter for preventing the CFRP rods from slipping inside the wedges during the fatigue tests (regardless of the lubrication condition) is the wedge insertion prior to the cyclic loadings and not necessarily the presetting force level.

Introduction of a new presetting system

A new presetting system was developed to ensure adequate wedge insertion, as shown in Fig. 10. In this presetting system, a ring was placed around the barrel using the threads at the free end (see Fig. 11). A hollow shaft was located around the wedges on the barrel surface. Adequate insertion of the wedges was determined to require 18.5 mm high hollow shafts. This value which was less than the 19 mm obtained based on the $S_{61.9}$ values and the corresponding fatigue test results in Table 2. Six M8 bolts were passed through the holes in the top plate and fastened using the threaded holes in the ring. By fastening the bolts, caused the top plate to push the wedges into the barrel until the top plate touched the hollow shaft, at which point the pre-setting was complete.

Although the proposed presetting system presets the wedges up to a certain displacement (i.e., it is a displacement-controlled system), it could also apply a substantial presetting force, depending on the bolt strength. For example, it was observed that using six M8, 8.8 bolts, it was possible to provide an approximately 110 kN presetting force by applying the standard bolt torque. The correlation between the applied torque to the bolts and the resultant presetting force is shown in the Appendix III. Moreover, the proposed system eliminated the need for hydraulic jacks to apply the presetting force. This is significant for cases wherein the use of hydraulic jacks is not possible, for example, due to geometric complexity. The anchors in specimen F8 were preset using the proposed system, and the fatigue test results for this anchor are presented in the following section.

Effect of the loading frequency

The relative displacement between the wedges, CFRP rod, and barrel could generate heat during fatigue tests, depending on the loading frequency (Baschnagel et al. 2018). The draft guideline for FRP PT tendons (Rostásy 1998) recommends that the loading frequency in the fatigue tests not be greater than 2 Hz.

The frequency effect on the slippage between the anchorage components was investigated by applying thermocouples to the barrel and one of the wedges in anchors F8-T and -B, as shown in Fig. 11(a) and (b), respectively. A thermocouple was also used to measure the room temperature. Any heating was considered to be an indication of slippage between the components.

The load-controlled constant amplitude fatigue tests followed the loading protocol shown in Fig. 7 and were performed at 5, 17, and 23 Hz for 0.5, 1, and 2 million cycles, respectively. The temperature changes in the anchorage components during the fatigue tests are represented in Fig. 12. The results show that, during the fatigue tests, the temperature changes in the different components were synchronised with the room temperature, without any progressive temperature rise. This indicates that no relative displacement occurred between the anchorage components.

After two million cycles at a loading frequency of 23 Hz, the thermocouples were dismantled, and the fatigue test was resumed under the same frequency up to 9 million cycles. The relative draw-ins are shown in Fig. 13. At frequencies as high as 23 Hz, no increase in the relative draw-ins was observed. Therefore, it could be concluded that the anchorage system was not sensitive to the loading frequencies. The fluctuation that can be seen in the magnified view of the relative draw-ins for anchor F8-T in Fig. 13(a) resulted from measurement error and was negligible. In addition, specimen F8 was preset with the developed presetting system, thus, the results of the fatigue tests on this anchor confirmed that the use of the proposed presetting system would provide reliable fatigue performance.

Residual strength tests

After the completion of the fatigue tests, Specimens F6 and F7 were statically loaded to failure to investigate if any significant damage developed in the system during the cyclic loadings. For both specimens, the tensile capacity was greater than the CFRP rod guaranteed

strength, as shown in Table 2 (T_{res}) and Fig. 14. This indicates that no significant damage accumulated in the anchors during the fatigue tests. Specimen F7 had the highest tensile capacity, with a tensile strength of 129 kN (equivalent to 2566 MPa). One possibility for such a high residual tensile capacity could be the alignment of carbon fibres with the loading direction during the fatigue test, which could lead to an increase in the tensile strength.

Considering these two static tests together with the static test results presented in Table 1, the average tensile capacity of the tested anchors was 119.2 kN (equivalent to 2371.4 MPa), which was approximately 16% greater than the nominal tensile strength of the CFRP rods.

Field application of the proposed anchorage

The proposed mechanical wedge–barrel anchor was used for fatigue-strengthening of the connections in an old riveted railway bridge in Switzerland (Heydarinouri et al. 2020b). The reliable fatigue performance of the strengthening system attached to the beam was confirmed in laboratory tests (Heydarinouri et al. 2020a). The CFRP rods used for the strengthening were prestressed to 994.7 MPa (approximately 50% of the guaranteed tensile strength of the rod). In this application, the wedges were required to be preset onsite, because the use of hydraulic jacks would have been difficult due to the geometric complexity of the structure. Therefore, the pre-setting system proposed in this study was used to preset the wedges onsite. On the bridge, the anchors were completely isolated from the air to prevent galvanic corrosion. The effectiveness of the proposed anchor in reducing the stresses in the bridge angles was demonstrated through short-term onsite measurements. In addition, the long-term performance of the anchor, i.e., the loss in the CFRP rod prestressing resulting from anchorage component slippage has been monitored using a wireless sensor network system since the anchors were installed in February 2020. No reduction in the prestressing level has yet been identified. More information about the application of prestressed CFRP rods for bridge strengthening can be found in (Heydarinouri et al. 2020b).

Summary and conclusions

In this study, a mechanical wedge–barrel anchor consisting of a steel barrel and three split aluminium wedges was introduced. The proposed anchor took the advantages of existing mechanical wedge–barrel anchors: (i) a curved conical profile for both the wedge and barrel to achieve a proper contact pressure distribution on the CFRP rod and (ii) aluminium wedges to eliminate the need for sleeves and reduce the required presetting force. For the first time, the European standard test procedures for mechanical PT anchorages were used to examine the static and fatigue performance of the anchorage. The conclusions regarding the performance of the anchor are summarised as follows:

- The uniaxial static tensile tests showed that the failure mode was always the rupture of the CFRP, with an average tensile strength of 2371.4 MPa, which is approximately 16% greater than the guaranteed value of 2047 MPa.
- In the fatigue tests, the CFRP rods did not rupture up to the minimum of 2 million cycles. However, for some of the anchors, progressive slippage occurred between the wedges and CFRP rods, which revealed the importance of the wedge seating distance before pulling the CFRP rod.
- A new displacement-controlled presetting system was developed to ensure an adequate wedge seating distance. The wedges could be preset to a specific distance using this system, regardless of the lubrication condition between the wedges and barrel.
- The developed anchorage was not sensitive to the loading frequency. No noticeable slippage or temperature rise occurred in the anchorage components under loading frequencies between 5 and 23 Hz.
- The residual tensile capacity of the system at the end of the fatigue tests was greater than the guaranteed tensile strength of the CFRP rods, with a maximum residual strength of 2566

MPa. This indicated that no significant fatigue damage accumulated in the anchors during the cyclic loading.

Data Availability Statement

All data and models from the experimental results and FE models that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgement

The authors acknowledge the Innosuisse Swiss Innovation Agency (Grant ID: 19240.1 PFIW-IW) for funding this research project. The authors would also like to acknowledge the financial and technical support from the project partners, namely: S&P Clever Reinforcement Company AG, Switzerland; the Swiss Federal Railways (SBB) AG, Bern; and dsp Ingenieure + Planer AG Engineering Office, Uster, Switzerland.

Appendix I. FE model development

An FE model was developed for the wedge–barrel anchor using the ABAQUS FEM software to optimise the contact pressure on the CFRP rod. The FE model shown in Fig. 15(a) is briefly described here. Only one-third of the anchor was modelled (i.e., one wedge) due to its symmetry, as shown in Fig. 15(a). In the FE analysis, the components were modelled as 3D eight-node quadratic solid elements. The wedge and barrel were modelled as an isotropic materials, and the CFRP rod was modelled as an orthotropic material. The plastic behaviour of the aluminium wedge was considered, while the other parts (i.e., the barrel and rod) exhibited linear elastic behaviours. In the normal direction, hard contact was used to prevent the parts from penetrating each other. Tangential contact was considered using a penalty function formulation.

The contact pressure on the CFRP rod on the path shown in Fig. 15(a) is shown in Fig. 15(b) for CFRP tensile loads of 61.7 and 120 kN. Fig. 15(b) shows that the contact pressure gradually increased from its minimum value at the loading end, which is the desired distribution to avoid

stress concentration. Furthermore, due to the greater CFRP tensile load of $T = 120$ kN, the wedges inserted further into the barrel, and consequently, the maximum contact pressure on the rod was nearly twice that when $T = 61.7$ kN.

Appendix II. Modifications on the split-wedge anchor

Fig. 16(a) shows the fillets on the wedges, with the radii of 0.2 and 1 mm, to prevent the damage of the fibres. In addition, a 1-mm gap (instead of 1.5 mm gap in the initial design) was used between the wedges. For the barrel, as shown in Fig. 16(b), a fillet with a radius of 1 mm was applied at the free end to facilitate the insertion of the wedges.

Appendix II. Resulting presetting force by the new presetting system

The correlation between the applied torque to each of the six M8, 8.8 bolts and the resulting presetting force applied to the wedges was obtained by measuring the presetting force using a KMR 200 kN load cell (HBM, AG, Darmstadt, Hesse, Germany), as shown in Fig. 17(a). The load cell was located on top of the wedges.

The measured presetting force versus the applied torque to each bolt is plotted in Fig. 17(b). As shown in the figure, there is a nearly linear relationship between the applied torque to each bolt and the resulting presetting force. In addition, application of a standard torque of 27 N.m. to each bolt resulted in a presetting force of approximately 110 kN.

Notation

The following symbols are used in this paper:

f = loading frequency;

D_r = dial gage reading for the CFRP rod;

$D_{r,ref}$ = dial gage reading for the CFRP rod in the reference state;

D_w = dial gage reading for the wedges;

530 $D_{w,ref}$ = dial gage reading for the wedges in the reference state;

531 N = number of cycles;

532 S = wedge seating distance;

533 $S_{61.9}$ = wedge seating distance at the lower fatigue load;

534 P = presetting force;

535 T = tensile load of the CFRP rod;

536 T_{nom} = nominal tensile strength of the CFRP rod

537 T_{res} = residual tensile strength of the CFRP rod;

538 T_u = ultimate tensile strength of the CFRP rod;

539 Δr = relative draw-in of the CFRP rod; and

540 Δw = relative draw-in of the wedges.

541 **References**

542 Al-Mayah, A., K. Soudki, and A. Plumtree. 2001. "Mechanical behavior of CFRP rod anchors
543 under tensile loading." *Journal of Composites for Construction*. 5(2): 128-135.
544 doi:10.1061/(ASCE)1090-0268(2001)5:2(128).

545 Al-Mayah, A., K. Soudki, and A. Plumtree. 2006. "Development and assessment of a new
546 CFRP rod-anchor system for prestressed concrete." *Applied Composite Materials*. 13(5): 321-
547 334. <https://doi.org/10.1007/s10443-006-9019-6>.

548 Al-Mayah, A., K. Soudki, and A. Plumtree. 2013. "Simplified anchor system for CFRP rods."
549 *Journal of Composites for Construction*. 17(5): 584-590.
550 [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000367](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000367).

551 Arnautov, A., G. Terrasi, V. Kulakov, and G. Portnov. 2014. "Fastening of a High-Strength
 552 Composite rod with a Splitted and Wedged end in a Potted Anchor 1. Experimental
 553 Investigation." *Mechanics of composite materials*. 49(6): 595-604.
 554 <https://doi.org/10.1007/s11029-013-9376-9>.

555 ASTM D/DM. 2016. "Standard Test Method for Tensile Properties of Fiber Reinforced
 556 Polymer Matrix Composite Bars." *ASTM International*. West Conshohocken, PA.

557 Baschnagel, F., R. Härdi, Z. Triantafyllidis, U. Meier, and G. P. Terrasi. 2018. "Fatigue and
 558 durability of laminated carbon fibre reinforced polymer straps for bridge suspenders."
 559 *Polymers*. 10(2): 169.

560 Campbell, T., N. G. Shrive, K. Soudki, A. Al-Mayah, J. Keatley, and M. Reda. 2000. "Design
 561 and evaluation of a wedge-type anchor for fibre reinforced polymer tendons." *Canadian*
 562 *Journal of Civil Engineering*. 27(5): 985-992. <https://doi.org/10.1139/100-048>.

563 DIN, E. 2017. 6892-1: 2017-02-Metallische Werkstoffe-Zugversuch-Teil 1: Prüfverfahren bei
 564 Raumtemperatur (ISO 6892-1: 2016); Deutsche Fassung EN ISO 6892-1: 2016, Beuth Verlag
 565 GmbH, Berlin. .

566 Elrefai, A., J. S. West, and K. Soudki. 2007. "Performance of CFRP tendon–anchor assembly
 567 under fatigue loading." *Composite Structures*. 80(3): 352-360.
 568 <https://doi.org/10.1016/j.compstruct.2006.05.023>.

569 EOTA. 2002. ETAG 013 Guideline for European Technical Approval of Post-Tensioning Kits
 570 for Prestressing of Structures, EOTA Brussels, Belgium.

571 *fib*, I. F. f. S. C. 1993. *Recommendations for the acceptance of post-tensioning systems*.
 572 Lausanne, Switzerland: *fib*.

573 Ghafoori, E., A. Hosseini, R. Al-Mahaidi, X.-L. Zhao, and M. Motavalli. 2018. "Prestressed
 574 CFRP-strengthening and long-term wireless monitoring of an old roadway metallic bridge."
 575 *Engineering Structures*. 176: 585-605. <https://doi.org/10.1016/j.engstruct.2018.09.042>.

576 Ghafoori, E., and M. Motavalli. 2015. "Innovative CFRP-Prestressing System for Strengthening
577 Metallic Structures." *Journal of Composites for Construction*. 19(6): 04015006.
578 [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000559](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000559).

579 Ghafoori, E., M. Motavalli, A. Nussbaumer, A. Herwig, G. Prinz, and M. Fontana. 2015.
580 "Design criterion for fatigue strengthening of riveted beams in a 120-year-old railway metallic
581 bridge using pre-stressed CFRP plates." *Composites Part B: Engineering*. 68: 1-13.
582 <https://doi.org/10.1016/j.compositesb.2014.08.026>.

583 Heydarinouri, H., M. Motavalli, A. Nussbaumer, and E. Ghafoori. 2020a. "Development of
584 mechanical strengthening systems for bridge connections using prestressed CFRP rods."
585 *Submitted to Journal of Structural Engineering, Under revision*.

586 Heydarinouri, H., A. Nussbaumer, M. Motavalli, and E. Ghafoori. 2020b. "Multiaxial Design
587 Criterion for Fatigue Strengthening of Steel Connections in a 92-Year Old Railway Bridge
588 Using Prestressed CFRP Rods." *Submitted to Journal of Bridge Engineering, Under revision*.

589 Hosseini, A., E. Ghafoori, R. Al-Mahaidi, X.-L. Zhao, and M. Motavalli. 2019. "Strengthening
590 of a 19th-century roadway metallic bridge using nonprestressed bonded and prestressed
591 unbonded CFRP plates." *Construction and Building Materials*. 209: 240-259.
592 <https://doi.org/10.1016/j.conbuildmat.2019.03.095>.

593 Hosseini, A., E. Ghafoori, M. Motavalli, A. Nussbaumer, X. L. Zhao, and R. Al-Mahaidi. 2018.
594 "Flat Prestressed Unbonded Retrofit System for Strengthening of Existing Metallic I-Girders."
595 *Composites Part B*. 155: 156-172. <https://doi.org/10.1016/j.compositesb.2018.08.026>.

596 Kar, N., Y. Hu, E. Barjasteh, and S. Nutt. 2012. "Tension-tension fatigue of hybrid composite
597 rods." *Composites Part B: Engineering*. 43(5): 2115-2124.
598 <https://doi.org/10.1016/j.compositesb.2012.03.006>.

Kerstens, J., W. Bennenk, and J. Camp. 1998. "Prestressing with carbon composite rods: a numerical method for developing reusable prestressing systems." *ACI Structural Journal*. 95: 43-50. [10.14359/525](https://doi.org/10.14359/525).

Li, C., R. Guo, G. Xian, and H. Li. 2020. "Innovative compound-type anchorage system for a large-diameter pultruded carbon/glass hybrid rod for bridge cable." *Materials and Structures*. 53(4): 1-15. <https://doi.org/10.1617/s11527-020-01510-y>.

Li, C., and G. Xian. 2018. "Novel wedge-shaped bond anchorage system for pultruded CFRP plates." *Materials and Structures*. 51(6): 162. <https://doi.org/10.1617/s11527-018-1293-x>.

Li, C., and G. Xian. 2019. "Design optimization and experimental validation of a novel wedge-shaped bond anchorage system for prestressed CFRP plates." *Polymer Testing*. 75: 167-174. <https://doi.org/10.1016/j.polymertesting.2019.02.001>.

Li, C., G. Xian, and H. Li. 2019. "Tension-tension fatigue performance of a large-diameter pultruded carbon/glass hybrid rod." *International Journal of Fatigue*. 120: 141-149. <https://doi.org/10.1016/j.ijfatigue.2018.11.007>.

Meier, U. 1995. "Extending the life of cables by the use of carbon fibers". *Proc., International Association for Bridge and Structural Engineering Symp.*

Meier, U. 2012. "Carbon fiber reinforced polymer cables: Why? Why not? What if?" *Arabian Journal for Science and Engineering*. 37(2): 399-411. <https://doi.org/10.1007/s13369-012-0185-6>.

Michels, J., J. Sena-Cruz, C. Czaderski, and M. Motavalli. 2013. "Structural strengthening with prestressed CFRP strips with gradient anchorage." *Journal of Composites for Construction*. 17(5): 651-661. [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000372](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000372).

Mohee, F. M., and A. Al-Mayah. 2017. "Development of an innovative prestressing CFRP plate anchor: numerical modelling and parametric study." *Composite Structures*. 177: 1-12. <https://doi.org/10.1016/j.compstruct.2016.12.039>.

Mohee, F. M., and A. Al-Mayah. 2018. "Effect of barrel, wedge material and thickness on composite plate anchor performance through analytical, finite element, experimental and 3D prototype investigations." *Engineering Structures*. 175: 138-154. <https://doi.org/10.1016/j.engstruct.2018.08.003>.

Mohee, F. M., A. Al-Mayah, and A. Plumtree. 2016. "Anchors for CFRP plates: State-of-the-art review and future potential." *Composites Part B: Engineering*. 90: 432-442. <https://doi.org/10.1016/j.compositesb.2016.01.011>.

PTI. 1985. "Post-tensioning manual". *Post-Tensioning Institute*.

Rostásy, F. S. 1998. "Draft guidelines for the acceptance testing of FRP posttensioning tendons." *Journal of Composites for Construction*. 2(1): 2-6. [https://doi.org/10.1061/\(ASCE\)1090-0268\(1998\)2:1\(2\)](https://doi.org/10.1061/(ASCE)1090-0268(1998)2:1(2)).

Sayed-Ahmed, E. Y. 2002. "Single-and multi-strand steel anchorage systems for CFRP tendons/stays". *Proceedings, Annual Conference-Canadian Society for Civil Engineering*.

Sayed-Ahmed, E. Y., and N. G. Shrive. 1998. "A new steel anchorage system for post-tensioning applications using carbon fibre reinforced plastic tendons." *Canadian Journal of Civil Engineering*. 25(1): 113-127. <https://doi.org/10.1139/l97-054>.

Schmidt, J. W., A. Bennitz, B. Täljsten, P. Goltermann, and H. Pedersen. 2012. "Mechanical anchorage of FRP tendons—A literature review." *Construction and Building Materials*. 32: 110-121. <https://doi.org/10.1016/j.conbuildmat.2011.11.049>.

Schmidt, J. W., A. Bennitz, B. Täljsten, and H. Pedersen. 2010. "Development of mechanical anchor for CFRP tendons using integrated sleeve." *Journal of Composites for Construction*. 14(4): 397-405. [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000096](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000096).

Schmidt, J. W., S. T. Smith, B. Täljsten, A. Bennitz, P. Goltermann, and H. Pedersen. 2011. "Numerical simulation and experimental validation of an integrated sleeve-wedge anchorage

648 for CFRP rods.” *Journal of Composites for Construction*. 15(3): 284-292.
649 [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000171](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000171).

650 Taha, M. M. R., and N. G. Shrive. 2003. “New concrete anchors for carbon fiber-reinforced
651 polymer post-tensioning tendons—Part 2: Development/experimental investigation.”
652 *Structural Journal*. 100(1): 96-104. 10.14359/12443.

653 Terrasi, G. P., C. Affolter, and M. Barbezat. 2011. “Numerical optimization of a compact and
654 reusable pretensioning anchorage system for CFRP tendons.” *Journal of Composites for*
655 *Construction*. 15(2): 126-135. [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000080](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000080).

656 Zhao, X. L. 2013. “FRP-Strengthened Metallic Structures”. Boca Raton, FL. *Taylor and*
657 *Francis*.

658

Table 1

Table 1. Results of the split-wedge anchor static tensile tests

Specimen	<i>P</i> (kN)	Sandblasting	<i>T_u</i> (kN)	Observation
S1	50	Yes	113.5	A*
S2	70	Yes	118.6	A
S3	30	Yes	118.3	A
S4	30	No	117.8	Excessive slippage

* A: Accepted.

Table 2

Table. 2. Fatigue test results

Specimen	Anchor	P (kN)	Lubricant	N (millions)	Observation during the fatigue test	$S_{61.9}$ (mm)	T_{res} (kN)
F5	F5-T	50	No	2	NA *: Slippage	20.4	-
	F5-B		No		NA: Slippage	20.4	
F6	F6-T	50	No	2.5	NA: Slippage	19.6	118.2
	F6-B		Yes		A **	18.3	
F7	F7-T	50	Yes	2	A	19.0	129
	F7-B		Yes		A	18.9	
F8	F8-T	***	Yes	9	A	18.5	-
	F8-B		Yes		A	18.5	

*NA: Not accepted; ** A: Accepted; *** Using developed system.

Figure 1

Figure 2

(a)

(b)

Figure 3

(a)

(b)

Figure 4

(a)

(b)

(c)

Figure 5

(a)

(b)

(c)

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

(a)

(b)

Figure 12

Figure 13

(a)

(b)

Figure 14

Figure 15

Figure 16

Figure 17

Figure caption list:

Fig. 1. Geometric details of the developed wedge–barrel anchor.

Fig. 2. Anchor configurations with: (a) Integrated and (b) Split wedges.

Fig. 3. Test set-up used for: (a) Application of the presetting force; (b) Static and fatigue tests.

Fig. 4. Preliminary static test results: (a) Load–displacement curves for the integrated wedge anchor; (b) Failure of the integrated wedge anchor; (c) Load–displacement curves for the split-wedge anchor.

Fig. 5. Static test procedure and measurements: (a) Loading protocol; (b) Relative draw-in measurement using the digital dial gauge, (c) Relative draw-in measurement detail.

Fig. 6. Static test results for the modified split-wedge anchors: (a) Load–displacement curve; (b) Fractured CFRP rod for specimen S1.

Fig. 7. Loading protocol in the fatigue tests.

Fig. 8. Relative draw-ins for the anchors without lubricant: (a) F5-T; (b) F5-B; (c) F6-T.

Fig. 9. Relative draw-ins for the lubricated anchors: (a) F6-B, (b) F7-T, (c) F7-B.

Fig. 10. Proposed presetting system.

Fig. 11. Thermocouples on: (a) F8-T; (b) F8-B.

Fig. 12. Temperature changes in the anchor components under the loading frequencies of: (a) 5 Hz; (b) 17 Hz; (c) 23 Hz.

Fig. 13. Relative draw-ins under different loading frequencies for anchors: (a) F8-T; (b) F8-B.

Fig. 14. Residual tensile strengths of Specimens F6 and F7.

Fig. 15. FE model of the split-wedge–barrel anchor: (a) von Mises stress distribution under the tensile load of $T = 120$ kN; (b) Contact pressure on the CFRP rod.

Fig. 16. Modifications on the split-wedge anchors (a) Wedges; (b) Barrel.

Fig. 17. (a) Measuring the presetting force using a 200 kN load-cell; (b) Measured presetting force versus the applied torque to each bolt.