Experimental study on the bond behaviour of a transversely compressed mechanical anchorage system for Externally Bonded Reinforcement

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Abstract

This paper presents an experimental programme aiming at studying the bond behaviour of carbon-FRP (CFRP) for externally bonded reinforcement (EBR) systems mechanically anchored to concrete. Eleven large scale pull-out tests were carried out using concrete blocks of 200 mm × 500 mm × 800 mm. In each block a single CFRP laminate was mounted using the EBR technique and mechanically fixed to concrete through a commercial mechanical anchorage with different levels of transverse compression. The blocks were tested under a pull-out configuration until failure. The study of the CFRP EBR system comprises not only the mechanical anchorage but also the subsequent CFRP EBR laminate bonded to concrete. The debonding load is observed to be dependent on the laminate width, as expected, and a good relationship between the experimental results and analytical predictions is found. A model of the local bond shear stress-slip law in the bonded zone is adopted and calibrated to the experimental results taking into account the roughness of the concrete surface. Moreover, the effects of the laminate width and the compressive stress level on the anchorage effectiveness are evaluated. Results show that the mechanical anchorage generally provides adequate transverse compression of the CFRP laminate to concrete surface.

Keywords: bond behaviour, CFRP, EBR, transverse compression

1. Introduction

Fibre reinforced polymers (FRP) have emerged as technical and economically viable materials for strengthening applications of reinforced concrete (RC) elements in countless applications worldwide [1–3].
Different strengthening techniques have been developed with FRP, being the most commonly used (i) the externally bonded reinforcement (EBR) technique, and (ii) the near-surface mounted (NSM) technique. The EBR technique consists on gluing the FRP laminate on the tensile face of the RC element; whereas in the NSM technique the FRP strip or bar is inserted onto a groove previously cut in the concrete cover, and then is bonded to concrete with an appropriate groove filler. Epoxy adhesives are typically used as bonding agents in the EBR and the NSM technique. Several premature debonding failure modes have been reported in the literature for RC elements strengthened in flexure using FRP laminates [4]: concrete cover separation failure and plate interfacial debonding are typically developed at the laminate’s extremities; whereas the intermediate crack-induced debonding (IC debonding) and shear induced debonding (also referred as critical diagonal crack debonding) initiate away from the laminate ends [4]. The bond behaviour between FRP and concrete is generally a critical issue as it is shown by the significant number of studies found in the literature for both EBR [4–13] and NSM [6,12,14–17] techniques.

In some structural applications, the use of prestressed FRP reinforcement is convenient or even required. By prestressing the FRP material, the benefits of the EBR technique are combined with the advantages associated with external prestressing, mainly [8]: more efficient use of the FRP and concrete; deflection and crack width reduction, internal steel reinforcement strains relieved, higher fatigue resistance and increase of the ultimate capacity resistance among other advantages. In those applications with prestressed FRP reinforcements, special end anchorages are frequently used in order to transfer the high shear stresses, typically developed between the FRP reinforcement and the concrete, for the sake of avoiding undesirable premature FRP peeling-off failure [5,9]. Several anchorage devices can be already found in the literature, and can be classified into [4,18,19]: i) U-jacked anchors [20–23], ii) mechanically fastened metallic anchors [24–28], iii) FRP anchors [29–35] and iv) gradient anchorage [19,36,37]. Among them, mechanical anchorages have been demonstrated to be one of the most effective form of FRP anchorage device when applied to flexural strengthening, e.g. [4].

The effectiveness of mechanical anchorages to prevent premature failure in RC flexural elements strengthened with prestressed EBR CFRP laminates has been previously reported in the literature [38–42]. In most of the cases, debonding of (the adhesively bonded) CFRP laminate from the concrete, followed by the rupture of the laminate was attained [38]; however, a recent study with over fourteen
RC slabs strengthened with EBR prestressed CFRP laminates reported a premature failure by end debonding at the mechanical anchorage [40,41].

A relationship between the level of compressive stresses provided by the anchorage device and the tensile capacity of the system should be expected, as it enables friction in the cracked interface and, as a result, increases the load capacity of the anchorage [43]. It is well-known that the load capacity of an EBR anchorage without compressive stresses is limited by its effective bond length [44]. Nevertheless, when compressive stresses are applied, the concept of effective bond length is no longer suitable. In this case, the maximum anchorage capacity will be also dependent on its length. The imposed compressive stresses are responsible for the development of residual bond shear stresses. Consequently after the anchorage failure (by laminate slippage), the resisting load does not decrease to zero, but does to a fixed residual value that varies with the anchorage length and level of compressive stress [45].

The present paper aims at contributing to a better understanding of the bond behaviour of CFRP EBR systems mechanically anchored to concrete through an experimental study. Compressive stress provided by a commercial mechanical anchorage for the bond shear stress-slip response of an EBR CFRP-concrete joint is studied and the outcomes of the experimental results are presented and discussed. The study of the CFRP EBR system comprises not only the mechanical anchorage but also the subsequent EBR CFRP laminate, as typically found in an EBR intervention. The results from the large scale pull-out tests are compared with the prediction from the literature, analysed and discussed.

In addition, a model of the local bond shear stress-slip law in the bonded zone is adopted and calibrated to the experimental results. Finally, the effects of the level of compressive stresses through the torque applied and the laminate width on the anchorage effectiveness are evaluated.

2. Experimental programme

The experimental programme involved eleven prismatic concrete specimens of $200 \text{ mm} \times 500 \text{ mm} \times 800 \text{ mm}$. In these blocks, CFRP laminates were installed according to EBR technique and were mechanically anchored to the concrete substrate through an aluminium plate torqued to the concrete. Two main parameters were studied: (i) the laminate width (50, 80 and 100 mm), and (ii) the level of compressive stresses through the torque that was applied in the anchorage plate bolts (30, 100, 150 and 200 Nm). Regarding to the former parameter, the selected values are in agreement with the typical geometries of laminates used with this anchorage system. For the case of later parameter, the value of
200 N·m was defined based on limitations of usual chemical bolt-concrete systems (used to fix the anchorage plate), which yielded to a compressive stress level up to approximately 30 MPa. It should be highlighted that preliminary compression tests (in the transverse direction) on CFRP samples were performed up to 80 MPa, based on the mechanical properties of the CFRP laminates used. These tests revealed no signs of damage on the composite material. Values of torque of 150 N·m are currently used in applications at structural level, e.g. [40,41]. A negligible value of torque (30 N·m) was also considered in the present study, as well as an intermediate value between these two mention torques. All specimens are labelled with a generic denomination: LX_TY, where X indicates the laminate width in [mm] (50, 80 or 100), and Y stands for the torque level applied in the anchorage plate bolts in [N·m] (30, 100, 150 and 200).

2.1. Materials
The concrete strength was C30/37 with an exposure class of XC4(P) according to Eurocode 2 [46], with a maximum aggregate size of 12.5 mm. The concrete compressive strength and modulus of elasticity were assessed using compression tests following NP EN 12390-3:2011 [47] and LNEC E397 1993:1993 [48] recommendations, respectively. From the six cylindrical specimens tested (150 mm/300 mm), a mean compressive strength of 33.3 MPa with a coefficient of variation (CoV) of 1.31% and a mean modulus of elasticity of 24.7 GPa (CoV=5.26%) were obtained.

The CFRP used in this experimental work was a prefabricated pultruded laminate strip distributed by from S&P Company [31]. This laminate strip (type S&P laminate CFK) was made of unidirectional carbon fibres (fibre volume content is higher than 68%) assembled together by an epoxy vinylester matrix. Three different widths (50, 80, and 100 mm) with a constant thickness of 1.2 mm were tested.

Their tensile mechanical properties were obtained from six samples tested following the procedures included in ISO 527-5:2009 [49], and are summarised in Table 1. All specimens presented an explosive failure type, by rupture of the fibres located at the middle of the test sample.

The two-component epoxy S&P resin 220 was used to bond the CFRP laminate strips to the concrete surface. According to the manufacturer, after mixing the two components, the homogenized compound density is 1.70-1.80 g/cm³ and has the following mechanical properties: compressive strength >70 MPa; tensile E-modulus >7.1 GPa; shear strength >26 MPa; adhesive tensile strength to concrete or CFRP laminate >3 MPa (after 3 days of curing at 20 °C). In the scope of the present work the epoxy
adhesive was not characterized; however, a previous experimental programme reported a modulus of
elasticity of 7.2 GPa (CoV=3.7%) and a tensile strength of 22.0 MPa (CoV=4.5%), after 7 days of
curing at 22 °C [50].

2.2. Preparation of specimens

The present experimental programme aimed at investigating the bond behaviour of a mechanical
anchorage (MA) system for EBR strengthening technique. For that purpose the specimen configuration
was conceived in order to accommodate the anchorage and EBR components. This option assures
better representativeness of the real applications and allows better understanding of the bond behaviour
in the transition between the EBR and anchorage components. Thus, the following procedure was
implemented in all specimens (Figure 1):

(1) The surface roughness of the concrete was restored and enhanced with a sandblasting
technique. Six holes with a diameter of 18 mm and a total depth of 150 mm were drilled on
the concrete surface to allocate the metallic anchor bolts.

(2) After sandblasting and drilling, the holes and the concrete surface were carefully cleaned by
using pressurized air.

(3) The metallic anchor bolts were glued with HIT-HY 200-A® which is a chemical bond agent
to fix each aluminium anchorage plate.

(4) The bi-component epoxy resin was prepared according to the requirements provided by the
supplier. The CFRP laminate strip was properly cleaned with a solvent and the adhesive was
applied on the surface of the CFRP laminate, with a target minimum regular thickness of
1.5 mm along a total length of 272 mm (corresponding to the length of the plate) plus 250 mm
(which was considered an adequate upperbound value for the bonded length of the laminate
according to formulations suggested by technical literature, [51], in order to exceed the
effective bond length).

(5) A similar epoxy layer was applied on the cleaned concrete surface and the laminate was
carefully placed centred on the surface of the concrete block.

(6) The surface of the anchorage plate was slightly grinded with sandpaper and cleaned with a
solvent before applying the same batch of epoxy resin that was applied on the CFRP laminate
and the concrete.
Then, the metallic plate, which had 6 holes of 18 mm diameter to accommodate 6 bolt anchors of 16 mm, was placed on its predefined location.

Just after the mechanical anchorage was placed in its correct place, it was torqued to the concrete element with the aid of a dynamometric key that ensured the target level of compressive stress (torque level of 30, 100, 150 and 200 N·m).

After a curing time of 7-14 days, the specimens were ready to be tested. Aluminium tabs were glued at the end of the laminate for not damaging the CFRP when hold by the clamping system.

The anchorage plates are a commercially available solution from the same company that supplied the CFRP laminate strip and epoxy resin for the end-anchorage of a CFRP laminate prestressing system. A 2D drawing of the anchorage plate is presented in Figure 2. With the dimensions of 200 mm (height) by 272 mm (width) and a thickness of 12 mm, the metallic plate is made of hard aluminium and has 6 major holes (diameter of 18 mm) meant to accommodate M16 anchorage bolts. This aluminium plate also presents 12 additional threaded holes (4 M8 and 8 M12) that are used for the prestressing system. Two different types of anchor bolts were used in this experimental programme: M16 grade 8.8 for a predefined torque level of 30 N·m, 100 N·m and 150 N·m, and M16 10.9 for the torque level of 200 N·m.

It is commonly accepted that the bond stress of the interface concrete-FRP highly depend on the concrete roughness [10,44,52]. For that purpose, the concrete roughness characteristics after sandblasting procedure were measured in all blocks at three different locations (one at the middle of the bonded length, and two on the metallic anchorage zone) with a laser sensor, each sample with a total length of 150 mm. The properties of the measuring device are further detailed in [40].

Up to now, there is not a standard parameter to evaluate the concrete roughness in EBR applications, reason why in the current work the concrete roughness was evaluated following the Model Code 2010 [44]. Three parameters are generally used to evaluate the surface roughness on concrete-to-concrete interfaces [44]: the average roughness $R_a$, the root mean square $R_q$ and the peak to valley height $R_p$. The average roughness $R_a$ was defined as the average deviation of the surface profile from the mean line, and was calculated according to,

$$R_a = \frac{1}{l} \int_{0}^{l} |y(x) - \bar{y}| \, dx$$ (1)
where \( l \) is the length of the measurement, \( y(x) \) is the profile height at position \( x \) and \( \bar{y} \) is the mean line.

The root mean square \( R_q \) was defined as the square root of the arithmetic mean of the squares of each profile height \( (y_i - \bar{y})^2 \) for the number of scan readings \( n \) and was computed according to Eq. (2).

\[
R_q = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - \bar{y})^2}
\]  

(2)

The peak to valley height \( R \), was defined as maximum peak-to-valley-deviation in each assessment lengths. According to Model Code 2010 [44], the results obtained in Table 2 correspond to a smooth surface roughness. Only in 3% of the assessed lengths, a peak-to-valley-deviation higher than 3 mm (rough surface roughness) was observed. It is worth emphasising that in concrete-to-concrete interfaces the Model Code 2010 [44] categorisation (very smooth, smooth, rough and very rough) is useful for design proposes (shear resistance). However, in EBR applications a different categorisation should be considered, taking into consideration recent studies on this subject [10,11,40].

2.3. Test set-up and instrumentation

Figure 3 shows the test set-up used for the large scale pull-out tests. In order to study the transition from the debonding of the EBR CFRP laminate to the mechanical anchorage action, a total length of 522 mm of CFRP laminate was glued on the concrete surface: 272 mm corresponded to the length of the metallic anchorage plate, and 250 mm were assumed to be a bonded length.

The concrete specimens were firstly placed onto the floor against a metallic plate with a length of 60 mm, which was assumed to be a rough measure of a hypothetical neutral axis depth for the case of a flexural member of 200 mm height. Next, the specimens were fixed to the strong floor through a metallic profile located at the top rear part of the specimen, 50 mm apart from the bottom face of the block (see Figure 3). Once the concrete blocks had been correctly placed and fixed, the CFRP laminate were connected to the hydraulic actuator through a metallic clamp specially designed for these tests.

The test was displacement controlled at a constant rate of 0.30 mm/min until the total debonding of the laminate in the EBR bonded length (250 mm) was achieved; at that point, where the speed was increased up to 2 mm/min until the end of the test.

The relative displacement of the CFRP laminate with respect to the concrete block was acquired by means of linear variable differential transformers (LVDT) placed at different locations (Figure 3b): (i) at the location where the CFRP laminate starts to be bonded to the concrete (loaded end, LVDT-1), (ii)
at the side of the anchorage plate that the laminate is pulled (mid end, LVDT-2) and (iii) at the other side of the anchorage plate (free end, LVDT-3). The LVDT-1 has a range of ±5.0 mm and a linearity error of ±0.24%, whereas the LVDT-2 and LVDT-3 range of ±2.5 mm and a linearity error of ±0.24%. The load cell used has a maximum measuring capacity of 300 kN and a linear error of ±0.05%. The evolution of the strain profile in the laminate was registered by strain gauges (S1 to S5, TML PFL-30-11-3L) placed every 62.5 mm that were glued along the CFRP bonded length.

3. Experimental results analysis and analytical predictions

   As previously described, in the large scale pull-out tests one extremity of the laminate was pulled while the other was fixed against the concrete with a bonded region of 250 mm (EBR component) followed by the transversely compressed metallic anchorage with 272 mm of length (anchorage component).

   Firstly, the bonded region supports the increasing loads but when its maximum capacity is attained the new load increments are supported by the compressed metallic anchorage. The bond strength and debonding process varies between both regions as it is described in the following paragraphs.

3.1. Load-slip behaviour

   All concrete specimens experienced a similar pattern in terms of load-slip behaviour, which is represented in Figure 4. A first almost linear branch, governed by the EBR component, with a steep slope is observed in the loaded end until EBR debonding (Figure 4: 0-1). During this phase, the slip registered in the mid end is negligible, meaning that all the force is carried by the bonded length outside the mechanical anchorage. Next, the debonding starts to occur (Figure 4: 1). During the debonding process (Figure 4: 1-2), the load does not increase whilst the slip increases considerably due to the elastic energy accumulated in the bonded length. At the end of the debonding phase, the mid end immediately starts to register some slip; at that point, the mechanical anchorage activates. The pull-out test was controlled by the displacement of the laminate loaded end and, due to the configuration of the test, the transition from the EBR to the anchorage, although swift, occurred without damaging the CFRP laminate and without any loss in the total pull-out force. Once all the bonded length of the laminate is detached from the concrete surface, the CFRP laminate is firmly held between the clamping system and the mechanical anchorage plate, facing a continuous increase in its strain and sustained load. Due to the elastic behaviour of the CFRP laminate, a fairly linear load-slip response is registered.
in all cases. Finally, in the last stages of the test (Figure 4: 3-4), the laminate strain continues increasing but its linearity is lost due to some minor slip taking place in the mechanical anchorage and the aggregate interlock that exists at the interface CFRP/concrete (debonded zone). The test typically fails by CFRP rupture; consequently, LVDT-3 (free end) generally registers negligible results. The data from LVDT-3 can be, however, interpreted as an indication of the level of damage inside the metallic anchorage. The data registered in all three LVDTs is analysed in the following sub-chapters 3.2 and 3.3.

By subtracting the displacement obtained in LVDT 2 (mid end) from displacement obtained in LVDT 1 (loaded end), the effect of this minor slip derived from the mechanical anchorage can be removed from the loaded end slip. As a result, a linear load-slip curve is obtained after the debonding phase (see Figure 4). The average slope of each curve allows the computation of the elastic modulus of each CFRP laminate and the values are similar to those obtained in the material characterization (169 GPa, 173 GPa and 162 GPa for the laminates of 50 mm, 80 mm and 100 mm, respectively). Also, these curves showed that the influence of the aggregate interlock that exists at the deboned zone is relatively small (less than 4.7%). Finally, a line representing the axial stiffness of the CFRP laminate is also shown in Figure 4 for comparison purposes. The load-slip curve without considering the mid end slip compares relatively well with the axial stiffness of the CFRP.

In Figure 5, the load-slip behaviour of all specimens is represented at the loaded end, mid end and free end for comparison purposes. The dependence of laminate width is clearly observed in terms of stiffness and load carrying capacity of the overall system: the wider the laminate, the higher the stiffness and capacity. The influence of the level of torque can be also appreciated in the bond shear stress-slip curves after debonding of the EBR component: lower values of torque provide, in general, a less stiff response in terms of pullout-slip, meaning that more damage is generated inside the mechanical anchorage. On the contrary, higher levels of torque cause slightly stiffer responses. Therefore, specimens with the smallest level of torque (30 N-m) exhibit the highest ultimate slip and, as shown in Table 5 and Figure 5, as the torque level is increased, smaller values of the ultimate slip are observed at the loaded-end and at the mid-end. The values of slip at the free end are only illustrative of the potential movement of the laminate with respect to the metallic plate and the concrete; however, it is observed that lower values of torque (i.e. 30 N-m) provide more movement at the free end of the
laminate, proving that the level of damage inside the metallic anchorage is higher in these cases than
for high torque values.

3.2. EBR component

3.2.1. Debonding load and fracture energy

The debonding load ($P_{db}$, Table 3) is defined in this experimental programme as the load at which the
laminate (at the EBR component) is debonded from the concrete substrate and, consequently, the
mechanical anchorage starts to carry the entire load. Because the anchorage component had a length
higher than the effective bond length, it was possible to obtain a very stable value of the debonding
load (Figure 4: 1-2), which represents the asymptotic value of the transmissible force by an anchorage
of infinite length (without compressive stresses). In this experimental programme, the debonding
process is observed to occur sudden and abruptly in all cases. Moreover, the failure mode obtained is
cohesive in the concrete, a few millimetres beneath the concrete/epoxy interface, as it is well reported
in the literature [5].

In the case where the CFRP laminate and adhesive properties were identical, equal values of ultimate
debonding strength would be assumed for all specimens, and hence a linear dependence of $P_{db}$ on the
laminate width would be expected. According to the literature [5,12,51] the used bonded length
(250 mm) surpasses the theoretical effective length, $L_e$, in this case of 200 mm [51], needed to achieve
the maximum debonding load. Although different CFRP modulus of elasticity were observed, the
relation between the mean value of $P_{db}$ and the laminate width can be assumed to be linear (a constant
value of 0.520 kN (CoV= 8.2%) per unit length of CFRP width was obtained for all specimens).

In general terms, the fracture energy associated to the bond shear stress-slip law $\tau(s)$ in the bonded
length, $G_f$, can be expressed as:

$$ G_f = \int_{0}^{\infty} \tau(s) ds $$

(3)

Assuming a stiffness in concrete much higher than the stiffness of the EBR reinforcement, the
equilibrium of energies can be assumed in the section where the maximum stress $\sigma_f$ is applied and the
following relationship can be deduced for a unit length [17]:

$$ \int \frac{1}{2} \sigma_f \varepsilon_f dA = w \int_{0}^{\infty} \tau(s) ds $$

(4)

Hence, a value of the fracture energy $G_f$ corresponding to $P_{db}$ can be calculated as:
\[ G_f = \frac{P_{deb}}{2E_f w A_f} \]  

where \( A_f \), \( E_f \) and \( w \) are the cross-section area, the modulus of elasticity and the width of the CFRP laminate, respectively. The values of \( G_f \) calculated according to Eq. (5), taking into account the experimental values of \( P_{deb} \), are also shown in Table 3. As expected, \( G_f \) keeps almost constant for all the specimens, ranging between 0.58 and 0.71 N/mm.

The experimental values of \( G_f \) can be compared with the ones predicted by different analytical approaches. For this particular case, CNR [51] predictions are assumed. CNR proposes a value for the design fracture energy (Eq. (6) – in [N/mm]) depending on the concrete compressive and tensile strength \( f_{cm} \) and \( f_{tm} \), respectively – in [N/mm²]), a confidence factor \( FC \), adopted equal to 1, a geometrical corrective factor \( k_b \) (dimensionless parameter) and an additional corrective factor taking into account the bonding system \( k_G \) (pre-cured or wet lay-up systems are considered), in [mm]."

\[ G_f = \frac{k_b k_G}{FC} \sqrt{f_{cm} f_{tm}} \]  

The theoretical results obtained with Eq. (6) assuming \( k_G \) equal to 0.063 mm (mean value for a pre-cured system, [51]) are presented in Table 3. It is observed a reasonable good fit between theoretical and experimental values, with a slight trend to theoretically overestimate \( G_f \). In fact, on average, \( G_f \) obtained experimentally is equal to 0.65 N/mm, whereas according to the CNR is equal to 0.69 N/mm.

The influence of the concrete roughness on the bond shear stress-slip behaviour has been previously reported in the literature [13], and some studies have provided a roughness coefficient to take into account its influence on \( G_f \) [10,53]. Iovinella et al. [10], for instance, adjusted the CNR formulation (Eq. (6)) thought a roughness factor \( k_R \) that considers the average of individual measures peak-to-valley heights and the inclination angle of the profile. A more recent study [53] has proposed an improvement on Eq. (6) to consider the effect of the roughness of the concrete surface on the calculation of the fracture energy, by only considering the average roughness, \( R_a \) (dimensionless parameter):

\[ G_f = \frac{k_b k_G k_R}{FC} \sqrt{f_{cm} f_{tm}} \]  

\[ k_R = 1.1 R_a + 0.8 \]

In Table 3, the value of \( G_f \) taking into account the roughness coefficient is shown together with the experimental value and the one obtained by Eq. (7). It can be easily observed that for this experimental programme, the approach proposed by [53] provides a better fit to the experimental values.
The ultimate strength [51], defined as the maximum allowed strength before debonding assuming that the provided bonded length is equal or larger to the optimal bonded length, is assumed to be:

\[ f_{f,dd} = \frac{1}{\gamma_{f,dd}} \sqrt{\frac{2E_f G_f}{t_f}} \]  \hspace{1cm} (9)

where \( \gamma_{f,dd} \) is a partial safety factor. In Table 3, the ultimate strength has been calculated considering a safety factor \( \gamma_{f,dd} \) of 1.0 in order to obtain the theoretical value of \( P_{deb} \) and considering the theoretical value of \( G_f \) obtained by Eq. (7). The \( \eta \) value shows the ratio between the experimental (\( P_{deb,exp} \)) and the predicted (\( P_{deb,th} \)) value for \( P_{deb} \). In general terms, the experimental value of \( P_{deb} \) is in accordance (with a confidence interval of ±5%) with the predicted by CNR taking into account the roughness coefficient \( k_R \). Figure 6 shows the values of the debonding and the ultimate load for all the specimens, together with theoretical predictions. The theoretical prediction of the debonding load was obtained from equations (5) and (9). A good relation between the experimental debonding load, \( P_{deb,exp} \) (grey bars) and the predicted debonding load, \( P_{deb,th} \) (black bars) can be observed.

### 3.2.2. Strain profile in the CFRP laminate

The strain profile along the CFRP laminate in its bonded length, which in this study was assumed to be 250 mm, can provide information about the active transfer length at different levels of load. The strain profile obtained from the L50-T30 and L80-T30 is presented in Figure 7a and Figure 7b, respectively. Both graphs show that the activated length increases with the applied load, and complete debonding takes place when there is no more undeformed bonded length. It can be seen that the strain at the loaded end (S1, \( x = 0 \) mm) increases with the load from the beginning of the test at an almost constant rate, as expected. At the beginning of the debonding process, the load is transferred to the next strain gauge, and, in most cases, it is transferred to the next strain gauge in a relatively sudden pattern with almost no increase in load (Figure 7a). In other cases, the debonding process is somehow less abrupt, and the load is transmitted through the bonded length with a slight increase of its value (Figure 7b). Once debonding has taken place, the strain in the laminate increases in a similar strain rate in all positions.

### 3.2.1. Bond stress-slip curves
The local bond stress-slip curve along the bonded length can be easily derived from the strain values. The mean bond shear stress between two consecutive strain gauges \((\tau_{i+1/2})\) was calculated by equilibrium between the tensile pull-out force carried by the CFRP laminate and the shear force supported at the interface between concrete and laminate:

\[
\tau_{i + 1/2} = \frac{E_f t_f (\varepsilon_{i+1} - \varepsilon_i)}{x_{i+1} - x_i}
\]

(10)

where \(t_f\) is the thickness of the CFRP laminate, \(\varepsilon_i\) and \(\varepsilon_{i+1}\) are the strain values at "\(i\)" and "\(i+1\)" locations, respectively, and \(x_i\) and \(x_{i+1}\) are the locations of the strain gauges. Similarly, the slip of the CFRP laminate at the mean location "\(i+1/2\)" \((s_{i+1/2})\) was calculated by integrating the experimental values of strain:

\[
s_{i + 1/2} = s_{i - 1/2} + \frac{\varepsilon_i + \varepsilon_{i+1}}{2} (x_{i+1} - x_i)
\]

(11)

A typical distribution of bond shear stress versus slip is depicted in Figure 8. The same figure also presents the experimental bond shear stress-slip curves, and the average experimental bond shear-slip curve. A first fairly linear ascending branch is observed in all cases up to 50% of the peak value of the bond stress \(\tau_{\text{max}}\). The ascending branch is observed to be similar amongst the different pairs of strain gauges. After the peak bond stress is attained, the typical softening descending curve is registered, albeit the scatter of results is higher in this case. An upperbound value of 0.30 mm is considered for the maximum slip for not interfering with the results derived from the mechanical anchorage.

There are several approaches in the literature to model the local bond shear stress-slip law of FRP-concrete interface [54–56]. In this work, the law described in [57], adapted from [58], is adopted and calibrated to the experimental results:

\[
\tau(s_p) = \frac{S_p}{S} \left(\frac{n}{n - 1} + \left(\frac{s_p}{\overline{s}}\right)^n\right)
\]

(12)

where \(\tau\) and \(s_p\) are the interface shear stress and slip, \(\overline{\tau}\) and \(\overline{s}\) represent the maximum shear stress and its corresponding slip, and \(n (> 2)\) is the parameter governing the descending branch (higher values of \(n\) diminish the fracture energy of the system, whereas values lower than 2 provide negative and/or finite quantity values of the fracture energy, [57]). The resultant parameters \(\overline{\tau}, \overline{s}\) and \(n\) have been calibrated to the bond stress-slip law by a least-squares methodology and are summarised in Table 4 for the tested specimens. In general terms, the resultant parameters are relatively similar to the ones obtained in [13]. The maximum bond stress tends to reduce with the laminate width, being its value between 3.23 and
4.97 MPa. The influence of the width of FRP plate on the debonding process was recently investigated in [59]. In their study, the authors conclude that the maximum stress is higher near the FRP plate edge than in its centre due to the non-homogeneity of material at the mesoscale level and due to the difference between the elastic modulus between FRP and concrete. Based on the width effect reported by [59], variations in the maximum shear stress $\bar{\tau}$ can be expected for each laminate width because the experimental values were measured in the centre of the CFRP laminate. The corresponding slip and the $n$ parameter, however, do not present a clear trend depending on the laminate width. In Figure 9, the mean experimental bond shear stress-slip curve is depicted for each case, together with its adjusted analytical expression.

3.3. Anchorage component

3.3.1. Ultimate load and failure mode

The results, in terms of ultimate load and failure mode are shown in Table 5. Contrary to what it was obtained in [40,41], the rupture of the laminate was attained in most of the cases, proving the good performance of the mechanical anchorage in the actual test setup.

The ultimate load $P_u$ was defined as the load at which the whole specimen faced failure. As expected, in those cases where the rupture of the CFRP laminate was attained, a clear dependence between $P_u$ and the laminate width was observed. In these cases, $P_u$ was adequately predicted by the tensile strength obtained from characterization of the CFRP laminates, and a maximum difference between the predicted (from tensile tests) and experimental (from pull-out tests) $P_u$ of 6.9% was obtained. In the particular case of L80-T150 specimen, the value of ultimate load was not possible to acquire, due to slippage of the laminate from the camping system, and in the case of L100-T150, the ultimate load was not registered due to an acquisition problem during the last stages of the test. The only specimen that faced slippage of the CFRP laminate from the mechanical anchorage system was L100-T30, at a load of 280.80 kN, which was approximately 94% of the capacity of the laminate. The ultimate load is presented in Figure 6 which allow a visible comparison between the experimental results (light blue bars) and the expected ultimate load (dark blue bars) considering the maximum CFRP strength.

The ultimate strain shown in Table 5 is the maximum strain registered by the strain gauges all along the bonded length at the ultimate load. In the cases where the rupture of the laminate is attained, its
value is very close to the ultimate strain obtained by the characterization of the CFRP laminate (see 
Table 1), being the ratio theoretical/experimental ultimate strain between 0.92 and 1.18. 

Based on the observed failure modes and values of normal stress attained in the CFRP laminate at the 
ultimate load, it can be concluded that the studied anchorage system did not cause premature failure of 
the CFRP laminate, mainly due to gripping effects.

3.3.2. Influence of the torque level

Although rupture of the CFRP laminate was the dominant failure mode, there is an intrinsic relation 
between the compressive stress level and anchorage performance, which could be observed in the 
present experimental programme. The ultimate slip registered at the loaded end (LVDT-1, Figure 3) 
was always higher than the expected elastic deformation of the CFRP laminate in the bonded length 
(250 mm) – between LVDT’s 1 and 2 – indicated that slip at mid-end always occurred. Furthermore, 
the ultimate slip increased with the decrease of the torque level, showing that increasing the 
compressive stress provided by torquing the anchorage allowed less slip inside the mechanical 
anchorage. The same relation can be observed in the mid end (LVDT-2, Figure 3). For each laminate 
width, the specimens with the smallest torque level (30 N·m, red line in Figure 5b) presented the 
highest ultimate slip. In fact, the relation between the torque level and the slip in the metallic anchorage 
can be easily observed in the mid end because, contrary to the slip registered at the loaded end, the 
elastic deformation of the CFRP laminate can be neglected. As referred before, the slip registered in the 
free end (LVDT-3, Figure 5c) shows negligible results. Contrary to L100_T30, where the failure mode 
was slippage, the remaining specimens failed by CFRP rupture, thus making very difficult the 
correlation between the slip registered in the free end at the maximum load and the torque level. 
However, Figure 5c shows that during the pull-out test some specimens exhibit higher movement on 
the free-end. The registered movement on LVDT-3 is related to the (increasing) degradation of the 
bond conditions provided by the anchorage system that occur during the increase of pull-out force. 
Here, a similar remark related to the level of torque can be attained: for the lowest torque level and, 
consequently, the smallest compressive stress level on the anchorage component, the highest the 
damage on the inside of the metallic anchorage is observed.

Finally, a measure of the level of visible damage inside the mechanical anchorage at the ultimate load 
was analysed by separating the metallic plate from the concrete specimen at the end of the pull-out test.
As can be seen in **Figure 10**, there is a visible damage that can be observed over the laminate and in
the metallic plate. The visible damage over the laminate is composed mainly by missing fragments of
epoxy, which stayed glued to the metallic plate. This kind of damage wasn’t observed on specimens
L50_T150 and L50_T200. In these two specimens, a peculiar dark stain could be observed on the
metallic anchor but no visible damage was observed over the laminate (**in the adhesive**). The dark stain
can be also observed in other plates, however in these two cases no fragments of epoxy were detected.
This area of visible damage has a rectangular shape with the same width of its respective laminate and
variable length. Then, the length of the visible damage was recorded and, based on the measurements,
the percentage of damage was accessed. The percentage of visible damage (VD) is the ratio between
the damaged length and the total length of the plate (**Table 5**). In general terms, the level of visible
damage inside the metallic plate increased with the decrease of torque, which proved the effectiveness
of a transversely compressed anchorage. In the case of L80_T150, the observed degree of visible
damage was lower than expected due to the premature failure obtained in this test. On the other hand,
the level of visible damage increased with the laminate width. **Assuming a constant distribution of**
compressive stress (**in transverse direction**) along the laminate width, it is foreseen that for the same
level of torque (and hence the same transverse force), a wider laminate receives less compressive stress
and consequently the system suffers higher degree of damage. Finally, in most of the cases, it could be
observed that the increase in visible damage along the laminate width was not evenly distributed, being
more pronounced in the centre of the CFRP (**see Figure 10**). This observation indices that there are,
inside the anchorage, higher axial stresses in the centre of the laminate. In fact, the prestress of the
anchor bolts slightly bended the anchorage plate (deformation not measured, just observed by naked
eye) and, consequently, produced higher compressive stress in the extremities of the laminate. This
bent deformation was not prevented in order to be representative of the real applications of this
commercial anchorage system.

**Figure 11** plots the influence of the compressive stress level over the average tangential stress inside
the anchorage for the load of failure. It should be pointed out that the area and shape of tangential stress
distribution inside the anchorage region could not be precisely identified. Therefore the average
tangential stress is based on the area of visible damage. Here, the area of visible damage is considered
to be the area for which the tangential stresses are developed at the joint between laminate and
concrete. The compressive stress level was computed based on the prestress applied in the six M16
anchor bolts and the area of the CFRP laminate in contact with the metallic plate. The prestress level was measured with a dynamometric key and, simultaneously, in two of the six bolts of each anchorage system, using strain gauges. Because the strain in the monitored anchor bolts was constantly measured it was possible to observe that the compressive stress level was the same in the test day.

Because the average tangential stress and compressive stress level exhibit a good relation, it can be foreseen that the anchorage ultimate load capacity can be increased with the torque level applied in the M16 anchor bolts. In Figure 11 specimens L50_T150 and L50_T200 were not represented because the visible damage (mobilized anchorage zone) was close to zero, being the level of tangential stresses in this zone very high.

As referred before, the maximum load attained at failure corresponds to the maximum tensile capacity of the FRP. In consequence, applying a compressive stress in the anchorage region seems to be a practical solution for increasing the anchorage resistance. However, the ultimate load capacity of the anchorage could be reduced due to environmental exposure, thermal or loading cycling, as is the case of the observations in [40,41]. Correia et al. [40,41] have performed durability tests on RC slabs strengthened with prestressed CFRP laminate strips under different environmental and loading conditions. In this work the prestressed CFRP laminates were anchored at the ends with the system studied in the scope of the present manuscript. Different environmental conditions were considered: (i) wet-dry cycles, (ii) moisture, (iii) freeze-thaw and (iv) thermal cycles. With the exception of the control specimens, where the failure occurred by CFRP laminate rupture, in the remaining specimens the failure occurred by slippage of the CFRP laminate at the end anchorages. Many reasons have been pointed out for such results, mainly plasticization of the epoxy adhesive and thermal cycling fatigue in the involved materials that yielded to the degradation of the bond at the interfaces. Additionally, it is well-known that when the epoxy adhesives are submitted to temperatures higher than to the corresponding glass transition temperature (for this type of epoxy adhesive is in the range of 55 to 60 °C), their mechanical properties are significantly decreased. This critical aspect may be decrease the performance of mechanical anchorage system and has been observed by Firmo et al. [60]. For that reason, further studies should be carried out.
4. Conclusions

This paper has presented the results of an experimental programme aimed at studying the effectiveness of a mechanical anchorage of EBR CFRP laminates bonded to concrete structures. For this purpose, the results of 11 large-scale pullout tests comprising prismatic concrete blocks externally bonded with CFRP laminates (of three different widths) and mechanically anchored (with four torque levels), have been presented and discussed. From the experimental results, the following observations and conclusions can be drawn:

- In general terms, the mechanical anchorage used in this experimental programme provides adequate compressive stress of the CFRP laminate to the concrete substrate, regardless of the torque level (30, 100, 150 or 200 N-m). However, for a laminate width of 100 mm, the lowest torque level (30 N-m) yielded to slippage of the CFRP laminate;

- A typical cohesive failure in the concrete was observed in the bonded length (EBR component). The debonding load increased with the laminate width. However, some deviations are observed due to the different modulus of elasticity of the laminates;

- The load-slip behaviour at the loaded end showed all the typical stages during the debonding process: (i) a first almost linear and steep branch, (ii) debonding of the laminate and (iii) a phase where the laminate was firmly held by the mechanical anchorage plate, until rupture of the laminate, or, in case of L100-T30 specimen, slippage of the laminate from the plate;

- The debonding process along the EBR bonded length was registered by the strain gauges placed along the laminate, showing similar behaviour to the one reported by the literature, mainly [13,17,51,53];

- A local bond shear stress-slip curve was experimentally obtained from the data registered by the strain gauges for each specimen, and was adjusted to the model presented in [31], obtaining an average bond shear strength, corresponding slip and the parameter governing the descending branch of 4.2 MPa, 0.082 mm and 3.7;

- The majority of the tested specimens failed when the maximum capacity of the CFRP was reached. By removing the anchorage plate from the specimen, an assessment of the visible damage was carried out and a relation Mohr-Coulomb between the compressive stress level and average shear stress at the maximum load was observed with a cohesion and friction angle of 5.26 MPa and 13.7°, respectively;
• Over the completed test campaign, it was possible to predict an increase on the anchorage capacity with the compressive stress level, expressed by the reduction of the slip at the mid end.

Based on the obtained results it is important to, in future works, investigate the influence of transverse compressive stress in the bond of externally bonded reinforcement with mechanical anchorages when exterior actions are applied, namely, temperature, humidity, and load cycling since the existing literature has shown a decrease of efficiency (capacity of avoiding the CFRP slippage from the anchorage system) when this system is utilized in the strengthening of RC slabs.

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Figure captions

Figure 1. Strengthening procedure.

Figure 2. 2D drawing of the anchorage plate (unit in [mm]).

Figure 3. Test set-up: (a) photo of the set-up, (b) side view and (c) top view of the test set-up and instrumentation (units in [mm]).

Figure 4. Typical load-slip at the loaded end and mid end.

Figure 5. Load-slip curves (a) at the loaded end, (b) at mid end, and (c) at free end.

Figure 6. Debonding and ultimate load.

Figure 7. Strain profile in the CFRP laminate for (a) L50-T30, (b) L80-T30. Note: exceptionally, in L50-T30 six strain gauges spaced by 50 mm were used.

Figure 8. Typical adjustment curve of local bond shear stress–slip law.

Figure 9. Experimental mean and adjusted local bond shear stress–slip law for (a) L50, (b) L80 and (c) L100 specimens.

Figure 10. Damage level observed in each anchorage plate.

Figure 11. Effect of transverse confinement in the average tangential stress.
Table captions

Table 1. Mechanical properties of the CFRP laminates (mean values).

Table 2. Concrete surface roughness.

Table 3. Experimental debonding loads and comparison with analytical predictions.

Table 4. Experimental parameters for adjustment of the bond stress-slip law in Eq. (10).

Table 5. Experimental values at ultimate and mode of failure.
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Figure 2. 2D drawing of the anchorage plate (units in [mm]).
Figure 3. Test set-up: (a) photo of the set-up, (b) side view and (c) top view of the test set-up and instrumentation (units in [mm]).
Figure 4. Typical load-slip at the loaded end and mid end (L50_T30).
Figure 5. Load-slip curves (a) at loaded end, (b) at mid end, and (c) at free end.
Figure 6. Debonding load and ultimate load.

Note: (a) The ultimate load was not registered due to technical problems (data acquisition system). This value is the expected value, considering the observed failure mode (CFRP rupture). (b) Premature CFRP slippage from the clamping system.
Figure 7. Strain profile in the CFRP laminate for (a) L50-T30, (b) L80-T30. Note:

exceptionally, in L50-T30 six strain gauges spaced by 50 mm were used.
Figure 8. Typical adjustment curve of local bond shear stress – slip law (L80-T30).
Figure 9. Experimental mean and adjusted local bond shear stress–slip law for (a) L50, (b) L80 and (c) L100 specimens.
<table>
<thead>
<tr>
<th>Laminate Geometry: 50 mm × 1.2 mm (L50)</th>
<th>Laminate Geometry: 80 mm × 1.2 mm (L80)</th>
<th>Laminate Geometry: 100 mm × 1.2 mm (L100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque level: 30 N·m</td>
<td>Torque level: 30 N·m</td>
<td>Torque level: 30 N·m</td>
</tr>
<tr>
<td>(Mid end)</td>
<td>(Free end)</td>
<td>(Mid end)</td>
</tr>
<tr>
<td>Torque level: 100 N·m</td>
<td>Torque level: 100 N·m</td>
<td>Torque level: 100 N·m</td>
</tr>
<tr>
<td>(Mid end)</td>
<td>(Free end)</td>
<td>(Mid end)</td>
</tr>
<tr>
<td>Torque level: 150 N·m</td>
<td>Torque level: 150 N·m</td>
<td>Torque level: 150 N·m</td>
</tr>
<tr>
<td>(Mid end)</td>
<td>(Free end)</td>
<td>(Mid end)</td>
</tr>
<tr>
<td>Torque level: 200 N·m</td>
<td>Torque level: 200 N·m</td>
<td>Torque level: 200 N·m</td>
</tr>
<tr>
<td>(Mid end)</td>
<td>(Free end)</td>
<td>(Mid end)</td>
</tr>
</tbody>
</table>

Note: Estimated based on the observation of the damage zones of specimens L80_T100 and L80_T200.

Figure 10. Damage level observed in each anchorage plate.
Figure 11. Effect of transverse compressive stress in the tangential stress.
Table 1. Mechanical properties of the CFRP laminates (mean values).

<table>
<thead>
<tr>
<th>Laminate</th>
<th>Laminate width [mm]</th>
<th>Modulus of elasticity [GPa]</th>
<th>Tensile strength [MPa]</th>
<th>Ultimate strain [mm/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L50</td>
<td>50</td>
<td>176.4 (2.0%)</td>
<td>2222.4 (4.7%)</td>
<td>12.5 (2.2%)</td>
</tr>
<tr>
<td>L80</td>
<td>80</td>
<td>170.5 (0.3%)</td>
<td>2428.0 (4.6%)</td>
<td>14.6 (6.7%)</td>
</tr>
<tr>
<td>L100</td>
<td>100</td>
<td>169.4 (1.4%)</td>
<td>2480.2 (4.0%)</td>
<td>14.6 (5.8%)</td>
</tr>
</tbody>
</table>

**Note:** the values between parentheses are the corresponding CoV.
### Table 2. Concrete surface roughness.

<table>
<thead>
<tr>
<th></th>
<th>$R_a$ [mm]</th>
<th>$R_q$ [mm]</th>
<th>$R_v$ [mm]</th>
<th>$R_p$ [mm]</th>
<th>$R_t$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>0.116</td>
<td>0.147</td>
<td>-1.573</td>
<td>0.534</td>
<td>1.098</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.244</td>
<td>0.296</td>
<td>-0.374</td>
<td>2.678</td>
<td>3.525</td>
</tr>
<tr>
<td>Average</td>
<td>0.167</td>
<td>0.217</td>
<td>-0.888</td>
<td>0.955</td>
<td>1.843</td>
</tr>
<tr>
<td>CoV</td>
<td>19.03%</td>
<td>17.94%</td>
<td>-26.24%</td>
<td>41.17%</td>
<td>25.35%</td>
</tr>
</tbody>
</table>

**Note:** $R_a$ - arithmetic average of absolute values; $R_q$ - root mean squared; $R_v$ - maximum valley depth; $R_p$ - maximum peak height; $R_t$ - maximum height of the profile.
Table 3. Experimental debonding loads and comparison with analytical predictions.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$P_{d,e,x,p}$ [kN]</th>
<th>$P_{d,e,x,p}$ [kN]</th>
<th>$G_{f,e,xp}$ [N/mm$^2$] (Eq. 5)</th>
<th>$G_{c,h}$ [N/mm$^2$] (CNR, Eq. 6)</th>
<th>$G_{c,h}$ [N/mm$^2$] (Eq. 7)</th>
<th>$P_{d,e,x,p}$ [kN] (Eq. 9)</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>L50-T30</td>
<td>26.85</td>
<td>26.25 (6.0%)</td>
<td>0.65</td>
<td>0.69</td>
<td>0.64</td>
<td>26.02</td>
<td>1.01</td>
</tr>
<tr>
<td>L50-T100</td>
<td>23.54</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>L50-T150</td>
<td>27.30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L50-T200</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>L80-T30</td>
<td>46.48</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L80-T100</td>
<td>42.70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L80-T150</td>
<td>43.00</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>L80-T200</td>
<td>40.50</td>
<td></td>
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<tr>
<td>L100-T30</td>
<td>48.10</td>
<td></td>
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</tr>
<tr>
<td>L100-T100</td>
<td>55.50</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>L100-T150</td>
<td>42.60</td>
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</table>

Note: the values between parentheses are the corresponding CoV.
Table 4. Experimental parameters for adjustment of the bond stress-slip law in Eq. (12).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$\tilde{\tau}$ [MPa]</th>
<th>$\tilde{s}$ [mm]</th>
<th>$n$</th>
<th>$\tilde{\tau}$ [MPa]</th>
<th>$\tilde{s}$ [mm]</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>L50-T30</td>
<td>4.62</td>
<td>0.077</td>
<td>2.8</td>
<td>4.79 (2.74%)</td>
<td>0.081 (12.91%)</td>
<td>3.33 (18.46%)</td>
</tr>
<tr>
<td>L50-T100</td>
<td>4.72</td>
<td>0.070</td>
<td>3.4</td>
<td></td>
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<td>L50-T150</td>
<td>4.86</td>
<td>0.098</td>
<td>4.3</td>
<td></td>
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<td>L50-T200</td>
<td>4.97</td>
<td>0.078</td>
<td>2.8</td>
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<tr>
<td>L80-T30</td>
<td>4.67</td>
<td>0.108</td>
<td>6.4</td>
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</tr>
<tr>
<td>L80-T100</td>
<td>4.48</td>
<td>0.087</td>
<td>3.7</td>
<td>4.15 (10.49%)</td>
<td>0.089 (12.69%)</td>
<td>4.30 (28.53%)</td>
</tr>
<tr>
<td>L80-T150</td>
<td>3.85</td>
<td>0.080</td>
<td>3.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L80-T200</td>
<td>3.61</td>
<td>0.081</td>
<td>3.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L100-T30</td>
<td>3.23</td>
<td>0.070</td>
<td>2.9</td>
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<td></td>
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</tr>
<tr>
<td>L100-T100</td>
<td>3.98</td>
<td>0.091</td>
<td>3.3</td>
<td>3.53 (9.18%)</td>
<td>0.077 (12.51%)</td>
<td>3.43 (14.53%)</td>
</tr>
<tr>
<td>L100-T150</td>
<td>3.38</td>
<td>0.071</td>
<td>4.1</td>
<td></td>
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</tr>
</tbody>
</table>

Note: the values between parentheses are the corresponding CoV.
Table 5. Experimental values at ultimate and mode of failure.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( P_u ) [kN]</th>
<th>( P_{u,av} ) [kN]</th>
<th>( \varepsilon_u ) [10^{-3}]</th>
<th>( \varepsilon_{u,av} ) [10^{-3}]</th>
<th>( s_{u,1} ) [mm]</th>
<th>VD [%]</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>L50-T30</td>
<td>134.06</td>
<td>137.09</td>
<td>12.95</td>
<td>13.33</td>
<td>5.09</td>
<td>72.22</td>
<td>R-CFRP</td>
</tr>
<tr>
<td>L50-T100</td>
<td>137.51</td>
<td></td>
<td>13.39</td>
<td>5.06</td>
<td>55.19</td>
<td>R-CFRP</td>
<td></td>
</tr>
<tr>
<td>L50-T150</td>
<td>137.58</td>
<td></td>
<td>13.53</td>
<td>4.91</td>
<td>0.00</td>
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<tr>
<td>L50-T200</td>
<td>139.21</td>
<td></td>
<td>13.44</td>
<td>4.57</td>
<td>0.00</td>
<td>R-CFRP</td>
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</tr>
<tr>
<td>L80-T30</td>
<td>250.27</td>
<td>252.49 (c)</td>
<td>14.06 (d)</td>
<td>14.68 (d)</td>
<td>6.00</td>
<td>92.22</td>
<td>R-CFRP</td>
</tr>
<tr>
<td>L80-T100</td>
<td>258.78</td>
<td></td>
<td>15.10</td>
<td>5.36</td>
<td>79.63</td>
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<tr>
<td>L80-T150</td>
<td>171.22</td>
<td></td>
<td>9.66</td>
<td>2.93</td>
<td>22.96 (d)</td>
<td>R-CFRP</td>
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<tr>
<td>L80-T200</td>
<td>248.43</td>
<td></td>
<td>14.89</td>
<td>5.18</td>
<td>58.51</td>
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<tr>
<td>L100-T30</td>
<td>280.80</td>
<td>295.79 (c)</td>
<td>13.36</td>
<td>13.75 s (c)</td>
<td>5.74</td>
<td>100.00</td>
<td>Slippage b</td>
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<tr>
<td>L100-T100</td>
<td>293.95</td>
<td></td>
<td>15.15</td>
<td>5.03</td>
<td>-</td>
<td>R-CFRP</td>
<td></td>
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<tr>
<td>L100-T150</td>
<td>297.62 (c)</td>
<td></td>
<td>12.37</td>
<td>4.19</td>
<td>62.59</td>
<td>R-CFRP</td>
<td></td>
</tr>
</tbody>
</table>

Note: \( P_u \) – Ultimate load; \( P_{u,av} \) – Average ultimate load; \( \varepsilon_u \) – Ultimate strain; \( \varepsilon_{u,av} \) – Average ultimate strain \( s_{u,1} \) – Ultimate slip at the loaded end; VD – Percentage of visible damage; cPremature slippage from the clamping system; dSlippage from the anchorage system; The ultimate load was not registered due to a technical problem. This value corresponds to the theoretically expected result; eThe specimens L80-T150 and L100-T30 were not included in the assessment of the corresponding parameters.