EXPERIMENTAL STUDY ON THE BOND BEHAVIOUR OF A TRANSVERSELY COMPRESSED MECHANICAL ANCHORAGE SYSTEM FOR EXTERNALLY BONDED REINFORCEMENT

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Abstract
The use of Carbon Fibre-Reinforced Polymer (CFRP) laminates as Externally Bonded Reinforcement (EBR) has been widely used to strengthen concrete structures in flexure. In some strengthening applications, e.g. prestressing, end-anchorage systems are required at the end of the FRP element in order to transfer the high shear stresses, typically developed between the FRP reinforcement and the concrete substrate, so as to avoid a premature FRP peeling-off failure. A typical anchorage system is the mechanical anchorage, where the laminate is transversely compressed through an anchorage plate, which is fixed to concrete with prestressed bolt anchors. The influence of laminate width and compressive stresses created by the anchorage system still requires better understanding. This paper aims at studying the experimental bond response of concrete elements strengthened with mechanically anchored EBR CFRP systems. For this purpose, 6 concrete blocks of 200×500×800 mm^3 were strengthened with CFRP laminates of different widths using EBR technique; afterwards they were mechanically anchored to the concrete with different levels of transverse compression, and finally they were tested under a pull-out configuration until failure. The results of the investigation show the influence of the width of the laminate, the level of confinement on the bond strength and capacity of the system.

1. Introduction

The use of Fibre Reinforced Polymer (FRP) materials for strengthening and repairing existing concrete structures has appeared to be an adequate strategy due to several advantages of FRPs compared to conventional strengthening materials. In the case of Externally Bonded Reinforcement (EBR), the end anchorage of the laminate to the concrete substrate is of broad and current interest in order to avoid premature debonding failure, especially in those cases where the prestress technique is used [1-3]. This paper aims at investigating the adequacy of a mechanical anchorage system and the influence of the laminate width and the confinement level on the overall bond-slip response.

2. Experimental programme

In order to assess the adequacy of mechanically anchoring CFRP laminates to the concrete, an experimental programme with 6 prismatic concrete specimens was performed. The concrete specimens were 200×500×800 mm^3 and were strengthened with CFRP laminates of different widths (50, 80 and

100 mm) and a constant thickness of 1.2 mm. The CFRP laminates were mechanically anchored to the concrete substrate through a hard aluminium plate, provided by S&P Clever Reinforcement company, with six M16 8.8 bolt anchors torqued with two different load levels: (i) a minimum torque of 30 N·m, to be used as reference, and (ii) a value of 150 N·m, based on previous works (e.g. [2,3]). HIT-HY 200-A® chemical bond agent was used to fix the bolt anchors to concrete. According to the literature search carried out by the authors of the present work, for this specific or similar anchor plates, recommendations do not exist about the torque level to be used in order to avoid the slippage of the laminate.

The test setup is shown in Figure 1. The concrete specimens were first placed against a metallic plate and then fixed to the strong floor through a metallic profile located at the top rear part of the specimen. The CFRP laminate was connected to the hydraulic actuator through a metallic clamp specially designed for these tests, and, was pulled at a constant rate of 0.30 mm/min until the total debonding of the laminate in the EBR bonded length (250 mm), where the speed was increased up to 2 mm/min until the end of the test. The instrumentation included linear variable differential transformers (LVDT) to acquire the relative displacement of the laminate with respect to the concrete block at several locations: (i) at the loaded end of the laminate (LVDT-1), (ii) at the mid end (LVDT-2) and (iii) at the free end (LVDT-3). Strain gauges (S1 to S5) placed every 62.5 mm were also glued along the CFRP bonded length to obtain the strain profile in the laminate with the load.

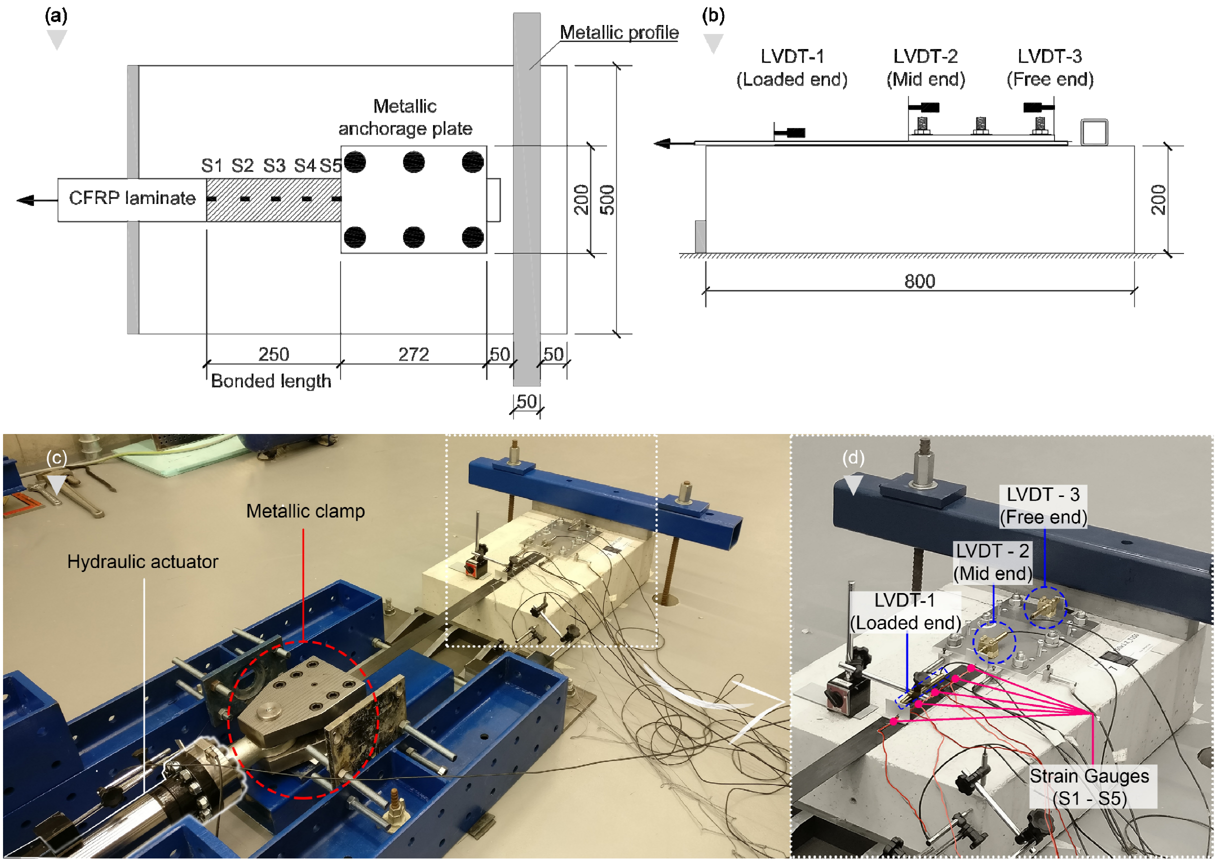

Figure 1. (a) Top view and (b) side view of the test setup and instrumentation; (c) photograph of the test setup and (d) detail of the instrumentation. Units in [mm].

Six cylindrical concrete specimens (150 mm/300 mm) were used to evaluate the compressive strength and the modulus of elasticity through the NP EN 12390-3:2011 [4] and LNEC E397 1993:1993 [5] recommendations, respectively. The mean concrete compressive strength was 33.3 MPa, with a coefficient of variation (CoV) of 1.31%, whereas its modulus of elasticity was equal to 24.7 GPa (CoV=5.26%). The tensile mechanical properties of the CFRP laminate (type S&P Laminate CFK) were obtained using six samples by following the procedures included in ISO 527-5:2009 [6] (results are summarised in Table 1). A two-component epoxy resin (type S&P Resin 220) was used to bond the CFRP laminate to the concrete substrate. Although the epoxy resin was not characterized in the present work, another experimental program 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 ºC [7].

3. Experimental results

The results, in terms of debonding load, ultimate load and mode of failure are shown in Table 1. Contrary to what it was obtained in [2], in most of the cases, the rupture of the laminate was attained. This was the case of the L50 specimens, in which a certain degree of homogeneity was observed in the ultimate load results. In some of the cases, the rupture of the laminate was immediately followed by the slip of the laminate from the clamping system. Specimen L80-T150 suffered a premature failure due to slippage of the laminate from the clamping system. The clamp was re-designed in order to avoid such a failure in the following specimens and this failure was no further observed. Although the rupture of the laminate was observed in specimen L100-T150, the ultimate load was not registered due to an acquisition problem during the last stages of the test. Finally, specimen L100-T30 was the only one that faced the slippage of the laminate from the mechanical anchorage system.

Table 1. Specimens and experimental results.

Specimen	CFRP laminate properties			P_{deb} (kN)	P_{ult} (kN)	Failure mode
	Width (mm)	E-modulus (GPa)	Tensile strength (MPa)			
L50-T30	50	176.4 (CoV=2.0%)	2222.4 (CoV=4.7%)	26.9	134.1	R-CFRP
L50-T150				27.3	137.6	R-CFRP
L80-T30	80	170.5 (CoV=0.3%)	2428.0 (CoV=4.6%)	46.5	250.3	R-CFRP
L80-T150				43.0	171.2	Slippage[1]
L100-T30	100	169.4 (CoV=1.4%)	2480.2 (CoV=4.0%)	48.1	280.8	Slippage[2]
L100-T150				42.6	297.6[3]	R-CFRP

[1] Premature slippage from the clamping system; [2] Slippage from the mechanical anchorage; [3] The ultimate load was not registered due to a technical problem, thus the value presented is the theoretically expected value.

The debonding load (P_{deb}, Table 1) was defined in this experimental program as the load at which the laminate was completely debonded from the concrete substrate and, consequently, the mechanical anchorage started to carry all the load. In this experimental programme, the debonding process was observed to occur sudden and abruptly in all cases, as it is shown in Figure 2b, where the strain evolution along the bond length is shown at determined loads. In the case where the 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_{deb} on the laminate width would be expected. In this experimental programme, P_{deb} increases with the laminate width (with exception of specimen L100-T150); however, the relationship between P_{deb} and the laminate width is not linear. This could be explained due to the different modulus of elasticity of the different laminate types.

The ultimate load (P_u, Table 1) was the load at which the whole specimen faces failure. P_u was obviously dependent on the failure mode. In those cases where the rupture of the laminate was attained, a clear dependence on the laminate width was observed. Furthermore, the experimental ultimate load was well predicted by the tensile tests on the laminates; a maximum difference between the theoretical (from the tensile tests) and the experimental (from the pullout tests) load carrying capacity of 6.9% was registered.

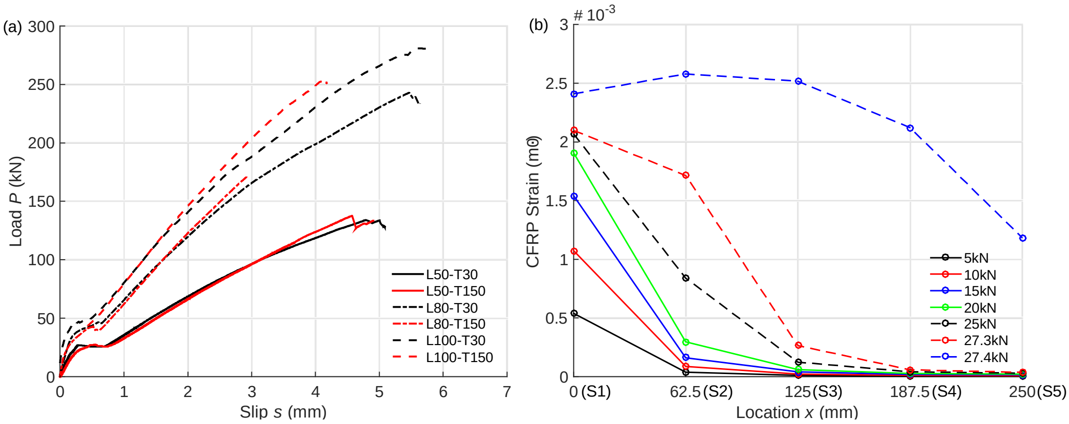

Figure 2. (a) Load-slip in the loaded end, (b) Typical strain evolution on the CFRP laminate.

The load-slip behaviour in the loaded end LVDT is shown in Figure 2a, for all specimens. A first almost linear branch is observed, corresponding to the elastic behaviour of the laminate until the initiation of debonding. Next, the debonding of the laminate from the concrete substrate starts to occur; during debonding, the load does not increase significantly, whilst the slip increases considerably due to the elastic energy accumulated in the bonded length. Once all the bonded length of the laminate is detached from the concrete surface, the laminate is firmly held between the clamping system and the mechanical anchorage plate, facing a constant 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, the laminate strain continues increasing but its linearity is lost probably due to some minor slip taking place in the mechanical anchorage and the aggregate interlock that exists at the interface CFRP/concrete (debonded zone). In Figure 2a, these different stages can be clearly identified.

Finally, the debonding process along the bonded length, registered by the strain gauges placed on top of the CFRP laminate (Figure 1a), is shown in Figure 2b. It can be seen that the strain gauge located at the loaded end (S1) increases with the load from the beginning of the test at an almost constant rate. For the particular specimen in Figure 2b, the load is transferred to S2 strain gauge at around 27.3 kN, where the S2 increases dramatically and transfers the load to S3. This procedure is repeated until the end of the bonded length, where the strain does not increase at the same rate because of the effect of the mechanical anchorage. From that state, although it is not represented in the figure, the strain increases in a similar strain rate in all positions (S1-S4) except for S5, which registers lower values.

4. Conclusions

This paper presents the preliminary results of an experimental programme aiming to study the effectiveness of a mechanical anchorage of EBR CFRP system to concrete structures. For this purpose, the results of 6 prismatic blocks EB with CFRP laminates of three different widths and two torque levels were presented. The main conclusions from the experimental results are:

- In general terms, the mechanical anchorage used in this experimental programme provides adequate transverse confinement of the laminate to the concrete substrate, regardless of the torque level (30 or 150 N·m). However, for a laminate width of 100 mm, the lowest torque level yielded to slippage of the CFRP laminate whilst the highest torque was proven to be enough to ensure the adequate mechanical anchorage of the plate;
- The debonding load increased with the laminate width, as expected. However, some deviations are observed due to the different modulus of elasticity of the laminates;
- The overall load-slip behaviour at the loaded end was registered. All the expected stages during the debonding process could be observed, including the effect of the mechanical anchorage;

- The debonding process along the bonded length was registered by the strain gauges placed along the laminate, showing similar behaviour to the one reported by the literature.

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