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Flexural behaviour of RC slabs strengthened with prestressed CFRP strips using different anchorage systems

Luís Correia [a], Tiago Teixeira [a, †], Julien Michels [b], João A.P.P. Almeida [a], José Sena-Cruz [a, *]

[a] ISISE, Dept. of Civil Engineering, Univ. of Minho, Azurém, 4800-058 Guimarães, Portugal
[b] Structural Engineering Research Laboratory, Swiss Federal Laboratories for Materials Science and Technology (Empa), Überlandstrasse 129, 8600 Dübendorf, Switzerland

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ABSTRACT

The Externally Bonded Reinforcement (EBR) technique using Carbon Fiber-Reinforced Polymers (CFRP) has been commonly used to strengthen concrete structures in flexure. The use of prestressed CFRP material offers several advantages well-reported in the literature. Regardless of such as benefits, several studies on different topics are missing. The present work intends to contribute to the knowledge of two commercially available systems that differ on the type of anchorage: (i) the Mechanical Anchorage (MA), and (ii) the Gradient Anchorage (GA). For that purpose, an experimental program was carried out with twelve slabs monotonically tested under displacement control up to failure by using a four-point bending test configuration. The effect of type of anchorage system (MA and GA), prestrain level (0 and 0.4%), width (50 mm and 80 mm) and thickness (1.2 mm and 1.4 mm) of the CFRP laminate, and the surface preparation (grinded and sandblasted) on the flexural response were the main studied parameters. Better performance was observed for the slabs: (i) with prestressed laminates, (ii) for the MA system, and (iii) with sandblasted surface preparation.

1. Introduction

Nowadays, Fibre Reinforced Polymer (FRP) materials and related strengthening techniques are well-known and used by the construction industry [1–7]. In the context of retrofitting Reinforced Concrete (RC) structures, Carbon FRP materials (CFRP) are used due to their superior performance, mainly higher stiffness, strength and fatigue life, almost no creep rupture and less susceptibility against aggressive environments [4–7]. From different attempts, one main strengthening technique has been selected [4–7]: the Externally Bonded Reinforcement (EBR). In this technique the FRP reinforcements are glued to the external surfaces of the elements to be strengthened. Typically epoxy adhesive are used as bond agent.

In some specific cases, the use of prestressed FRP materials for strengthening RC structures is convenient or even required. This technique presents several positive aspects since it combines the benefits of passive EBR FRP systems with the advantages associated with external prestressing, mainly [8]: (i) use of non-corrosive materials; (ii) deflection reduction; (iii) crack widths reduction and the onset of cracking is delayed; (iv) internal steel reinforcement strains are relieved; (v) higher fatigue failure resistance; (vi) more efficient use of the concrete and FRP; (vii) opposes stresses due to both dead and live loads; (viii) reduction risk of premature debonding failure between the FRP and concrete; (x) ultimate capacity can be further increased; (xi) it can be worked as a substitute of internal prestress that has been lost; (xii) shear capacity is increased by the longitudinal stresses induced by prestressed FRP laminates.

Laminates [9–13,16–18,25–29], sheets [14,15,20–23,25] and bars [20,29] are the most common prestressed FRP shapes, the former being the most prominent. Several systems have been proposed to induce a prestress in the FRP and can be divided in three categories [8]: (i) cambered prestressing systems; (ii) prestressing against an independent element; and, (iii) prestressing against the element to be strengthened. In spite of each one having advantages and disadvantages [8], the systems that apply the prestressing against the element to be strengthened have known so far the biggest success. Special end-anchorage systems are required at the ends of the prestressed FRP element to transfer the high shear stress developed from the reinforcement into the concrete

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[*] Corresponding author. Tel.: +351 253 510 200; fax: +351 253 510 217.
E-mail address: jsena@civil.uminho.pt (J. Sena-Cruz).

[†] Passed away on May 4th, 2015.

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substrate, in order to avoid a premature FRP peeling-off failure. From all the proposed systems, two of them have been used, mainly [31]: the mechanical anchorage (MA) fixed to the ends of the FRP reinforcement and the gradient anchorage (GA). Detailed information about these systems is given in Section 2.3 of the present publication. Up to now, the majority of the studies focus on the development/improvement of the prestressing systems as well as the structural behaviour in terms of serviceability and ultimate resistance of the strengthened elements.

Surface preparation also plays a key role in the overall response of the strengthening systems. Some of the most common surface preparation methods are: grinding, brushing, scarifying, steel shotblasting, sandblasting, and bush-hammering. Each one of these methods presents advantages and disadvantages associated at several factors as the desired roughness, cost and processing time. Iovinella et al. [32] developed an interesting work on the influence of surface roughness on the bond of FRP materials to concrete. The study presents not only the investigations developed up to date, but also a detailed study performed on the influence of distinct surface treatments mainly, brushing, grinding, brush-hammering and sand blasting on bond strength and fracture energy of EBR strengthening systems. From this investigation Iovinella et al. [32] concluded that the bush-hammering and sand blasting were the most effective and in general the surface preparation significantly improves the roughness homogeneity along the surface, increasing the stability of results.

The present work aims at contributing to the existing knowledge on the flexural behaviour of RC slabs strengthened with prestressed CFRP strips. For that purpose, the performance of mechanical and the gradient end-anchorage systems were compared by means of an experimental program. Additionally, the effect of the prestrain level, the width and thickness of the CFRP laminate, as well as the surface preparation (grinded and sandblasted) on the flexural response were investigated.

2. Experimental investigation

2.1. Experimental program, specimens and test configuration

The experimental program was composed of twelve slabs, divided into two series according to the surface preparation method (see Table 1): in series S1, composed of eight reinforced concrete (RC) slabs, the concrete surface region where the FRP reinforcement was installed was treated by means of grinding with a stone wheel, whereas in series S2 the surface preparation of the three RC slabs was performed by sand blasting. In both cases the main aim was to remove the weak concrete laitance layer and expose the aggregates of the substrate. Three slabs were used as control specimens (S1_REF1, S2_REF2 and S2_REF). In each series one slab was strengthened with a simple CFRP laminate strip according to the EBR technique without any prestressing (S1_L50 × 1.4_EBR and S2_L50 × 1.2_EBR). The remaining seven slabs were strengthened with one externally bonded prestressed CFRP laminate strip with either a mechanical anchorage (MA) or a gradient anchorage (GA). As it is shown in Table 1, all specimens are labelled with a generic denomination: X_LY_Z, where X is the specimen series (S1 or S2), Y is the cross-section geometry of the laminate strip in millimetres (50 × 1.4, 50 × 1.2 or 80 × 1.4) and Z is the type of anchorage (MA or GA) or the EBR slab identification.

The specimens' geometry and test configuration are shown in Fig. 1. The slabs have a total length of 2600 mm, the rectangular cross section is 600 mm wide and 120 mm thick. The upper and lower longitudinal inner reinforcement is composed of three steel bars with a diameter of 6 mm (3Ø6) and 5 bars with diameter 8 mm (5Ø8), respectively. To avoid shear failure of the slabs, steel stirrups Ø6 were installed at a spacing of 300 mm. Three types of CFRP laminates strips (50 × 1.2 mm^2, 50 × 1.4 mm^2 and 80 × 1.2 mm^2) with 2400 mm of length were used as external reinforcement.

In order to assess the service and ultimate behaviour of all specimens, monotonic tests up to failure were performed using a four point bending configuration. The instrumentation included 5 linear variable differential transducers (LVDT1 to LVDT5) to record the deflection along the longitudinal axis of the slab; 3 strain gauges (SG1 to SG3) with the aim of measuring the strain in the laminate and concrete; and 1 load cell used to measure the applied load (F). Fig. 1 shows the position of each LVDT: three in the pure bending zone with the range of ±75 mm and a linearity error of ±0.10% and two between the supports and the applied load points with a range of ±25 mm and the same linearity error. The load cell used has a maximum measuring capacity of 200 kN and a linear error of ±0.05%. Two different strain gauge types were used: (i) two TML BFLA-5-3 strain sensors (SG1 and SG2) glued on the laminate surface at the mid-span and at the force application point; and, (ii) one TML PFL-30-11-3L strain sensor (SG3) for the measuring the concrete strain in the mid-span. All tests were carried out with a servo-controlled equipment under displacement control at a rate of 1.2 mm/min. The crack width evolution was measured during the test through a handheld USB microscope. This equipment consists on the VEHO VMS-004 D microscope, with a native resolution of 640 × 480 pixels and magnification capacity up to 400×. In the present experimental program, the crack width acquisition was done with a magnification factor of 20× up to predefined applied load.

It should be highlighted that, usually, in real applications cracks already exist at the moment of the FRP application. Consequently, the present experimental program does not totally reproduce the major part of the existing structures that require upgrading. However, critical aspects such post-cracking behaviour, yielding of the longitudinal reinforcements, ultimate load and failure modes can be well-captured by the present experimental program be representative of the expected real behaviour. Hence, the slabs' structural behaviour can be considered representative of the expected real behaviour. Additionally, with this work it is also possible to evaluate the effect of the FRP prestressing on crack initiation.

2.2. Material characterization

The material characterization included the evaluation of the mechanical properties of the materials involved in this experimental program, namely concrete, steel, CFRP laminate strip and epoxy adhesive.

Four batches (B1 to B4) were used to cast the RC slabs (see Table 1). Concrete characterization included evaluation of the modulus of elasticity and compressive strength through LNEC E397-1993:1993 [33] and NP EN 12390-3:2011 [34] recommendations, respectively. For each concrete batch six cylindrical specimens with 300 mm of height and 150 mm of diameter were used. Table 2 shows the obtained results at the testing day. The average compressive strength of series S1 was about 53 MPa, whereas for the series S2 was about 40 MPa.

The tensile properties of the steel reinforcement were assessed throughout the NP EN ISO 6892-1:2012 [35] standard. A minimum of three specimens were used for each bar type. Table 2 includes the Young's modulus (E_s) as well as the yield (f_y) and ultimate (f_u) strengths obtained from the tensile tests. The average value of the modulus of elasticity was about 212 GPa and 235 GPa for the lower longitudinal steel reinforcement in series S1 and S2, respectively. The steel of the longitudinal bars and stirrups has a denomination of A400 NR SD according to the NP EN 1992-1-1:2010 [36].