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Flexural strengthening of RC beams using Hybrid Composite Plate (HCP): Experimental and analytical study

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ABSTRACT

Hybrid Composite Plate (HCP) is a reliable recently proposed retrofitting solution for concrete structures, which is composed of a strain hardening cementitious composite (SHCC) plate reinforced with Carbon Fibre Reinforced Polymer (CFRP). This system benefits from the synergetic advantages of these two composites, namely the high ductility of SHCC and the high tensile strength of CFRPs. In the material-structural of HCP, the ultra-ductile SHCC plate acts as a suitable medium for stress transfer between CFRP laminates (bonded into the pre-sawn grooves executed on the SHCC plate) and the concrete substrate by means of a connection system made by either chemical anchors, adhesive, or a combination thereof. In comparison with traditional applications of FRP systems, HCP is a retrofitting solution that (i) is less susceptible to the detrimental effect of the lack of strength and soundness of the concrete cover in the strengthening effectiveness; (ii) assures higher durability for the strengthened elements and higher protection to the FRP component in terms of high temperatures and vandalism; and (iii) delays, or even, prevents detachment of concrete substrate. This paper describes the experimental program carried out, and presents and discusses the relevant results obtained on the assessment of the performance of HCP strengthened reinforced concrete (RC) beams subjected to flexural loading. Moreover, an analytical approach to estimate the ultimate flexural capacity of these beams is presented, which was complemented with a numerical strategy for predicting their load-deflection behaviour. By attaching HCP to the beams' soffit, a significant increase in the flexural capacity at service, at yield initiation of the tension steel bars and at failure of the beams can be achieved, while satisfactory deflection ductility is assured and a high tensile capacity of the CFRP laminates is mobilized. Both analytical and numerical approaches have predicted with satisfactory agreement, the load-deflection response of the reference beam and the strengthened ones tested experimentally.

1. Introduction

Nowadays, reports on extensive studies of the applications of fibre Reinforced Polymers (FRPs) in both laboratory and practical scales can be found [1–3]. This widespread application of FRP for structural strengthening is mainly due to its practical feasibility and high strength to weight ratio. The long-term durability, thermal stability, and vulnerability against vandalism are, however, concerns that need to be properly addressed for a still more extensive use of the FRP [4–6]. Premature debonding of FRP systems at the interface with substrate, or detachment with concrete cover attached (rip-off), are other causes that limits the maximum tensile strain that FRP systems can sustain. In an effort to delay or overcome this problem, various configurations of mechanical anchors can be found in literature [7,8], but they may promote the risk of premature rupture of FRP material, since a stress concentration at the anchored zone of the FRP system is expectable.

Mechanically Fastened FRP (MF-FRP) system has recently emerged as an alternative to adhesively bonded FRP systems, mainly aimed at providing a rapid retrofitting technique for RC members [9–11]. According to this technique, pre-cured laminates with an enhanced bearing capacity are attached to the concrete substrate by means of mechanical fasteners, without applying any adhesive at FRP/RC interface. Although, as compared to adhesively bonded FRP systems, the MF-FRP technique is a promising

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retrofitting approach, offering feasibility for rapid installation, higher ductility, and potentially higher FRP/RC connection durability, still some concerns can be underlined. These concerns are related to the scale effects, the limited stress transfer between concrete and FRP (e.g., depends on the number and strength of the installed discrete fasteners and the quality of concrete cover), the potential of galvanic corrosion of the fasteners in contact with CFRP laminate, and the reliability of the FRP laminate yet exposed to the environmental conditions and vandalism. Moreover, for the full stress transfer between the FRP laminate and the RC element through a bearing mechanism (complete engagement of the strengthening layer) a relatively large slip of the FRP laminate is needed [12]. Consequently, if compared to the adhesively bonded retrofitting schemes, the MF-FRP system may provide a lower enhancement in the initial stiffness and the serviceability performance of the retrofitted element.

Techniques based on the applications of Strain Hardening Cementitious Composites (SHCCs) for the retrofitting of RC elements as an alternative to FRP systems have been recently studied. SHCC is a cementitious matrix reinforced with short discrete fibres, capable of developing higher tensile strengths by further stretching beyond the onset of the first crack, which offers tensile strain hardening capacity. Ductility of SHCC is quantified by the strain corresponding to its ultimate tensile strength and often designated as "tensile strain capacity". SHCCs are also known as High Performance Fibre Reinforced Cementitious Composites (HPRFCC) [13]. Retrofitting of damaged/undamaged RC beams (lacking shear or flexural reinforcements) by adhesively bonded prefabricated CARDIFRC strips to the beams tension face and lateral faces is an example of these studies [14,15]. CARDIFRC is a cementitious composite with an average compressive strength of 207 MPa and ultimate tensile strength in the range of 10–15 MPa. Despite a high steel fibre content (up to 8% of composite mix volume), the tensile strain capacity of CARDIFRC is restricted to a maximum of 0.6%. Comparison between the results of flexural tests performed on the small-scale retrofitted beams and the results of control beams confirmed the effectiveness of this technique in increasing the stiffness, ductility and energy absorption. However, it was also reported that the retrofitting effectiveness of this CARDIFRC plate is limited to an optimum thickness of that, lower than 20 mm.

Hybrid Composite Plate (HCP) is another retrofitting solution that utilizes SHCC, with a relatively high tensile strain capacity, in combination with FRP to overcome, even if partially, the aforementioned shortcomings of conventional FRP strengthening systems [16]. This hybrid system is composed of an SHCC plate reinforced either by externally bonded CFRP sheets, HCP$^{(s)}$, or near surface mounted CFRP laminates, HCP$^{(L)}$. Thus, as depicted schematically in Fig. 1, HCP integrates the synergetic advantages of these two composites, namely strength and ductility, in retrofitting of reinforced concrete (RC) structures. Thanks to the high ductility of SHCC, this prefabricated plate (with a thickness ranging from 15 to 25 mm) can be attached to the substrate by means of anchors, adhesives or a combination thereof to transfer forces between HCP and RC substrate.

If anchors are the only connection system, the force transfer between the HCP and the RC element occurs mainly at the fastened locations and through the bearing capacity of the SHCC plate. This is a mechanism similar to MF-FRP system, where any increase in the deformation of the retrofitted element is accompanied by a sliding between the strengthening layer and the concrete substrate. The mechanism of contribution of an anchored strengthening scheme is well identified and discussed by other researchers; for example, where numerical approaches based on bearing-slip model were proposed and incorporated to predict flexural responses of MF-FRP strengthened RC elements [17–19]. However, once anchors are

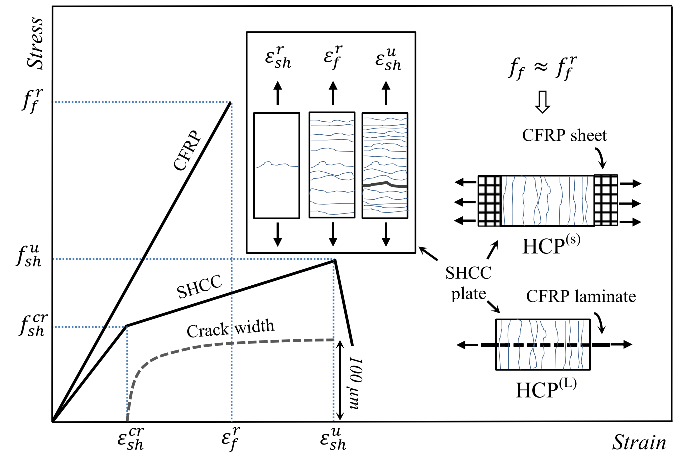

Fig. 1. Schematic presentation of tensile behaviour of CFRP and SHCC, crack propagation and crack width in SHCC at different loading stages, and crack propagation close to the rupture of CFRP at HCP (see list of notations for description of the adopted symbols).

used in combination with HCP/RC interface bonding adhesive, they are primarily aimed at providing a vertical pressure to HCP in order to delay/prevent a possible detachment, but they also have another beneficial effect. In fact, the anchors contribute, through the SHCC bearing capacity, in transferring the shear stresses released at the detached regions of the HCP and those resulting from a further increase in deformation demand of the retrofitted element. As compared to the anchored HCP, the MF-FRP or the adhesively bonded FRP systems, a connection based on combination of anchors and adhesive is suitable to exploit a larger tensile capacity of high strength retrofitting HCP, where is needed. Such connection is also expected to improve the serviceability performance of the retrofitted element more notably than a discrete connection made of only anchors.

Moreover, HCPs were developed to suppress, even if partially, the above-mentioned shortcomings of bonded FRP systems in structural strengthening. For example, in the case of HCP$^{(L)}$, SHCC provides a minimum cover of 8 mm to the laminates, which provides insulation for both FRP and bonding material used in the structure of an HCP, so the system can endure higher levels of temperature in comparison to traditional applications of FRP systems. Up to the rupture strain of CFRP materials, which is often below 2%, impermeable fine diffused cracks are formed in the SHCC, with a maximum crack width limited to 0.1 mm, which potentially assures a long-time performance for the constituents of the HCP system, and enhances the durability of the elements to be strengthened (see Fig. 1). Results of experimental tests on HCP retrofitted RC elements indicated a promising performance of this system, since a substantial increase was attained in terms of flexural and shear capacity of RC beams, and energy dissipation and lateral load carrying capacities of RC beam-column joints under seismic loading [16,20–22].

This paper describes an experimental program and presents and discusses the relevant obtained results on the assessment of the effectiveness of HCP$^{(L)}$ for the flexural strengthening of under-reinforced RC beams. Moreover, an analytical formulation to predict the ultimate moment capacity of such strengthened beams is presented. Finally, by employing a section-layer analysis technique, the moment-curvature of each of the retrofitted beams was obtained, and then was introduced into a numerical model to estimate the load-deflection response of these RC beams. To evaluate the accuracy of the adopted numerical approach, the estimated results were then compared to the results of the experimental tests.