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Experimental study of GFRP-concrete hybrid beams with low degree of shear connection

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HIGHLIGHTS

- Evaluation of the structural performance of different GFRP-concrete hybrid beam models.
- Comparative study with equivalent reinforced concrete beams and pultruded profiles.
- Research on the influence of partial interaction effects and concrete strength.
- Analytical assessment of experimental results for hybrid beams with low degree of shear connection.

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ABSTRACT

Recent developments in the design of advanced composite materials for construction have led researchers to create novel high-performance structural elements that combine fiber-reinforced polymer (FRP) shapes with traditional materials. The current study analyzes the experimental structural response of eight hybrid beams made of pultruded glass FRP (GFRP) profiles mechanically connected to reinforced concrete (RC) slabs, suitable for building floors as well as footbridge and marine pier superstructures. The influence of partial interaction is studied by considering a low degree of shear connection and an analytical assessment of the whole response is carried out using previous formulations, highlighting a good accuracy. The behavior of the hybrid beams is further evaluated against that of equivalent reinforced concrete beams and single GFRP profiles, thus proving the feasibility of the solution.

1. Introduction

Pultruded fiber-reinforced polymer (PFRP) profiles have been used in the past three decades in a significant number of applications where high corrosion or chemical resistance is required and where the weight of the structure plays an important role in the design [1–3]. Structural applications have included pedestrian and road bridges, building floors and frames, stair structures, cooling towers, offshore platforms, marine piers and light support structures.

The efficiency and versatility of this relatively new construction material are a result of its outstanding mechanical, physical and chemical properties. Besides the lightweight and high strength characteristics, composite manufacturers emphasize the fact that structures built with PFRP profiles are more durable, require virtually no maintenance and can be constructed in a simple and rapid manner, without the use of extensive scaffolding. Furthermore, opposed to custom-made composites, pultruded members are produced through a lower cost fabrication process and have dimensional stability.

Despite their great potential, PFRP profiles also present some disadvantages when compared to their steel counterparts: a relatively low stiffness (especially for glass FRP) that can lead to design constraints due to instability or large deformations, an inherent brittle behavior and a partially developed connection technology. In addition, the lack of codes as well as the current high initial costs of these advanced materials prevent a widespread use of pultruded profiles in civil engineering projects. To overcome some of these issues, researchers have proposed recently the introduction of new hybrid elements [4–6] that combine the advantages of PFRP

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profiles with those of traditional materials so as to obtain superior structural members.

Most of the hybrid beams designed up-to-date have been built by combining glass fiber-reinforced polymer (GFRP) profiles with concrete because of their low cost and high structural efficiency. Concrete is also preferred because it can provide confinement, increase flexural stability, strength and stiffness, all at the cost of an increased mass. This apparent inconvenient presents an upside in the sense that the structure will have better damping, as light structures are usually prone to unacceptable vibrations.

The GFRP profile and concrete layer can be connected using a bonded joint, mechanical connection or combined joint. Tests performed so far on hybrid beams with bonded joints have demonstrated that an adhesive layer will provide a high connection strength and will practically impede the occurrence of slip, providing a complete shear interaction [7–9]. Nevertheless, bonded joints require special tools, materials and installment conditions, are sensitive to environmental degradation and possess insufficient ductility characteristics. On the other hand, mechanical joints are easy to inspect and disassemble, have substantial post-elastic capacity but, due to the flexibility and the discrete nature of the connection, partial interaction effects need to be accounted for [10].

In the past two decades, numerous hybrid beam designs have been proposed and analyzed experimentally, fueling an increased interest in this area of advanced composite materials justified by the promising results. One of the first studies regarding hybrid beams was performed by Saiidi et al. [11] on graphite/epoxy concrete composite beams for bridge decks and floor slabs. The investigation focused on the flexural behavior of custom-made box and I-shaped profiles connected to concrete slabs with an epoxy layer, and studied the composite action and the effects of concrete strength on bond, flexural stiffness and capacity. Fragile failure modes were observed that consisted of shear debonding followed by longitudinal delaminations of the web. Analytical calculations based on the assumption of complete shear interaction and an estimated bond strength proved to be inexact. The study highlighted the need for pultruded shapes with better fiber orientation, lower costs and a more accurate analytical model.

Sekijima et al. [12,13] investigated the behavior of GFRP-concrete beams made with H-shaped FRP profiles. The shear transfer mechanism consisted of conventional studs which had been used for steel–concrete composite beams, arranged in a cross stitch pattern to prevent cracking between holes. There was no buckling of the hybrid specimens observed; however, the failure was sudden and occurred in the web of the profiles. The experimental behavior was linearly elastic up to failure and slip between the two materials was noted.

Studies carried out by Biddah [14] and by Fam and Skutezky [15] analyzed the response of several hybrid beams with profiles encased or filled with concrete and observed that compared to the other specimens the beams displayed less deformation and slip. It was noted also that the concrete prevented local buckling of the web or flanges to occur.

Different authors have recently proposed various solutions to improve the characteristics of the hybrid systems by tailoring the properties and microstructure of the composite profiles [16], by using high performance or fiber-reinforced concrete layers [17–20], or by adapting a failure sequence for the whole system [21,22]. A custom hybrid profile made from CFRP and GFRP layers was designed and tested by Mutsuyoshi et al. [23] in both a simple and composite configuration. The profile alone failed in flexure due to delaminations at the interfacial layers and web crushing, while the composite beam performed better in every aspect. Research done by El-Hacha and Chen [24] on FRP-UHPC hybrid beams and by Gonilha et al. [25] on GFRP-SFRSCC elements for prototype bridge decks revealed that the increased strength of the concrete slab led to a linear-elastic flexural response of the system and did not provide a failure warning, as the performance was still limited by the mechanical characteristics of the composite profiles or connection.

Subsequently, current research indicates that there is still a great need to investigate experimentally the structural behavior of pultruded FRP-concrete hybrid beams and to find solutions with lower costs. Furthermore, to this point, many studies have limited their analyses by considering a state of complete shear interaction although slip phenomena had been previously observed during testing.

2. Experimental program

2.1. Scope

The investigation discussed herein focuses on the analysis of the experimental structural performance of hybrid beams made of pultruded glass fiber-reinforced polymer (GFRP) profiles mechanically connected to reinforced concrete (RC) slabs, suitable for building floors as well as footbridge and marine pier superstructures. The proposed hybrid system is designed to exploit the main advantages of its composing materials whilst overcoming some of the issues that characterize their individual behavior. Thus, the GFRP members are expected to carry mainly the tensile and shear forces in the composite beam, with the concrete layer acting as a compressive and stabilizing top element. Commercially available profiles were used in order to reduce costs and normal strength concrete was chosen so as to improve the ductility of the beams. Due to the hybrid nature of the constructive system, special attention was also paid to the influence of the mechanical joint between the two constitutive parts, by considering a low degree of shear connection.

Following the results and observations of an initial experimental campaign carried out on small-scale hybrid beams with various cross-section configurations [26], a hybrid system similar to standard steel–concrete composite beams was chosen as design basis for a second and more comprehensive experimental campaign performed on real-scale specimens. A number of eight hybrid beams were fabricated and their flexural behavior was assessed against that of equivalent reinforced concrete beams and single GFRP structural profiles. The variables of the research were the type of hybrid cross-section and the concrete strength class. The experimental campaign was divided in two phases depending on the specific test setup configuration and observations were made regarding the short term behavior of the novel elements under positive bending moments. An analytical assessment of the results in terms of capacities, deflections and internal strains and stresses was also performed, highlighting a good agreement.

2.2. Materials

Design began with choosing an off-the-shelf glass fiber-reinforced polymer pultruded profile shape from GDP SA, France. The IPE 120 profile, classified as structural, is made from a thermosetting PR500 grade unsaturated polyester matrix (with basic formulation) reinforced with E-glass fibers. As shown in Fig. 1, the highly inhomogeneous profile is composed of unidirectional fibers which act as longitudinal reinforcement and non-woven continuous strand mats (CSM) disposed on the contour of the shape and at the center plane of the web which perform the role of shear, transverse reinforcement. The anisotropic nature of the composite material is clearly emphasized in the same figure by an electronic microscope photograph taken at the web-flange junction.

The measured apparent density of a profile is 1.93 kg/dm^3 and the percentage of reinforcement ratting in weight lies between 50 and 65%. Flexural, tensile, compressive and shear properties were obtained after extensive material characterization tests performed on a minimum of 5 coupons for each test (see Fig. 2a–e). The obtained mechanical properties and corresponding standards are summarized in Table 1.

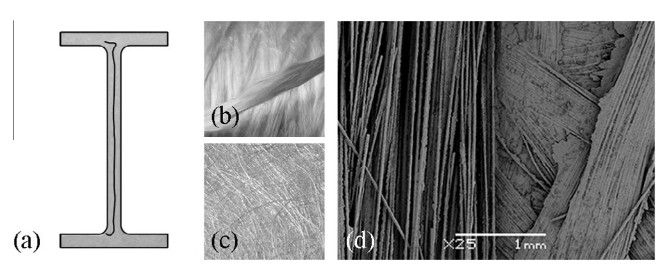

Fig. 1. GFRP structural profile: (a) cross-section structure and geometry; (b) fiber roving; (c) non-woven CSM; (d) microscopic anisotropic structure of web-flange junction.