Composite Structures 152 (2016) 607–616

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Shear behaviour of hybrid composite-concrete beams: Experimental failure and strain analysis

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ARTICLE INFO

Article history:
Received 6 May 2016
Accepted 23 May 2016
Available online 24 May 2016

Keywords:
Short-span beams
Four-point bending
Textile Reinforced Cement (TRC) composite
Principal strains
Rosette analysis
Deflection

ABSTRACT

The combination of high performance composites and concrete results in hybrid composite-concrete elements which no longer resemble the traditional reinforced concrete structures. Consequently, these hybrid elements have a different structural behaviour that requires new evaluation procedures. This paper focusses on hybrid TRC-composite-concrete elements which are used as a substitute for reinforced concrete beams within a floor system. Their shear behaviour is experimentally investigated by the examination of ten short-span hybrid beams with different geometries.

Visual inspection shows that shear failure occurs by an inclined flexural shear crack in the concrete. A rosette strain gauge analysis proves that the principal strain and stress orientations are in accordance with theoretical predictions. Finally, the small influence of shear deformation on the total deflection of these beams is illustrated.

1. Introduction

Hybrid composite-concrete elements possess different advantages over traditional steel reinforced concrete (RC) elements, most important ones being an improved durability in an aggressive environment and a reduced self-weight, leading to lower foundation requirements, a decrease in transportation cost and an increase in construction speed. These advantages of combining high-performance composites with concrete have stimulated the design of several innovative hybrid geometries (beams [1–6]; floors [7]). The flexural behaviour of these hybrid elements is already widely investigated, however few research exists on their shear behaviour. These few studies focus on the interface debonding between the composite material and the concrete [8–10]. Moreover, when these hybrid concepts – often a combination of concrete and Fibre Reinforced Polymers (FRPs) – are extended with Textile Reinforced Cement (TRC) composites [11–13], their structural behaviour becomes even more complicated.

With the current state-of-the-art literature about the shear behaviour of TRC-FRP-concrete beams, the shear failure is unpredictable. Therefore, this paper has three main objectives. (i) It elaborates on the shear failure location, the composite-concrete interaction at high shear loads and the material behaviour, which are parameters needed to set up design formulas for the shear capacity in hybrid beams [14]. (ii) Besides, a better understanding of the shear failure and the orientation of the major strains is required for future more efficient hybrid beam designs. This paper compares the experimentally observed strain pattern to the analytical predictions. (iii) Finally, this paper also quantifies the contribution of the presence of thin composite elements within these hybrid geometries to the shear deformation of hybrid beams.

This paper presents the experimental investigation of the shear behaviour of ten TRC-composite-concrete beams. Four composite box elements and six hybrid beams with a span of 700 mm are tested under multiple point loading. A detailed analysis of the shear behaviour – failure, principal strains and deflection – is made, based on visual inspection, load cell data, rosette strain gauges, linear strain gauges and displacement transducers. This paper first gives a brief overview of the specimen geometries, their material properties and the test set-up (§ 2). Afterwards, the failure load and failure mode are discussed, based on experimental observations (§ 3.1). Next, a strain gauge analysis is performed to determine the magnitude and orientation of the principal strains (§ 3.2), which is then linked to the observed failure mode. Finally, the relative contribution of shear deformation to the total deflection is illustrated in load–deflection graphs (§ 3.3).

2. Materials and methods

2.1. Specimen geometries

The hybrid beam design (Fig. 1) is composed of two major parts: a hollow composite box at the bottom (in tension) and a concrete

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http://dx.doi.org/10.1016/j.compstruct.2016.05.075
0263-8223/

layer on top (in compression). This composite box consists of a Textile Reinforced Cementitious (TRC) tube, reinforced at the inside with a Carbon Fibre Reinforced Polymer (CFRP) strip. A series of ten beams (five different types) is tested to investigate the shear behaviour of the hybrid cross-sections.

The height of the concrete and the amount of CFRP are varied to identify their contribution to the shear capacity (Table 1). All beams have the same outer-box dimensions (box width: 100 mm (w); box height: 75 mm (h_b)) but a different TRC (t_b), carbon strip (h_{ca}) and concrete (h_{co}) thickness. Based on their configuration, the ten tested beams are subdivided into three smaller groups: (i) four plain TRC Boxes (**B**-yy-z), (ii) four Unreinforced Hybrid Beams (**UHB**-yy-z) and (iii) two CFRP Reinforced Hybrid Beams (**RHB**-yy-z) (Table 1). The plain TRC boxes have a variable amount of textile layers, varying from four (B-**4L**-z – corresponding to a thickness of 2.5 mm) to eight layers (B-**8L**-z – corresponding to a thickness of 5 mm). All hybrid beams (UHB and RHB) are made of eight glass fibre mat layers. These hybrid beams contain a concrete layer of 25 mm (UHB-**25C**-z) or 50 mm (UHB/RHB-**50C**-z) on top of the TRC box. The reinforced hybrid beams (RHB), with a concrete layer of 50 mm, are strengthened with one carbon strip of 1.5 mm thick and 75 mm wide (w_{ca}) at the inside bottom of the TRC box. To prove the repeatability of the experimental results, two identical specimens of each configuration are tested (xx-yy-**1/2**).

2.2. Materials

The carbon strips [15] have a fibre volume fraction of at least 65% and exhibit a linear stress–strain relation up to failure (Fig. 2). All CFRP tensile material properties (tensile strength and elastic stiffness – Table 2) are the experimental mean values of three tensile tests. The compressive CFRP characteristics are taken equal to the tensile properties, but the strength is limited by the used glue [16]. The mean concrete compressive strength of 42 MPa is based on the average of three compressive tests on cylindrical specimens (diameter: 100 mm; height: 220 mm – according to EN 12390-3 [17]) and converted into the compressive strength of standardized cylinders (diameter: 150 mm; height: 300 mm) [18]. These material tests are performed after 28 days of concrete hardening and thus at the same age as the tests on the hybrid beams. All other concrete properties are calculated according to EN 1992-1-1 [19]. The concrete behaviour is modelled as a parabola-rectangle diagram [19] (Fig. 2).

The TRC used in this design is a Glass Fibre Reinforced Inorganic Phosphate Cement (GFR.IPC). The cementitious IPC matrix [20] is reinforced with randomly in-plane oriented glass fibre textiles, being chopped strand mats with a surface density of 300 g/m^2. This random fibre orientation results in in-plane isotropic material properties. All tensile properties (Table 2) are experimentally determined by tensile tests on six rectangular specimens. Due to the brittleness of the cementitious matrix, tensile loading will initiate cracks in the composite material at relatively low stress levels, leading to a non-linear constitutive behaviour in tension that can be characterized in a bilinear approach ([21] – Fig. 2). In compression, the stiffness is equal to the initial tensile stiffness and is assumed linear until failure. The compression strength value is based on previous research [21].

Table 1
Dimensions of all hybrid beams.

	w [mm]	w_{ca} [mm]	h_{ca} [mm]	t_b [mm]	h_b [mm]	h_{co} [mm]
B-4L-1/2	100	–	–	2.5	75	–
B-8L-1/2	100	–	–	5	75	–
UHB-25C-1/2	100	–	–	5	75	25
UHB-50C-1/2	100	–	–	5	75	50
RHB-50C-1/2	100	75	1.5	5	75	50

2.3. Methods

To investigate shear, a four-point bending test is executed on the short-span (700 mm) beams because of the clear distinction between bending- and shear cracks for this test set-up. Consequently, a constant moment without shear forces is created in between the two point loads (central zone of 300 mm in length). On the other hand, a linearly reducing moment and constant shear force occurs between the point loads and the supports (two outer zones of 200 mm length). However, loading the plain TRC box 'B-8L-1' with only two point loads (Fig. 3 bottom; black point loads) yields local indentation of this box underneath these loads. Therefore, beams 'B-4L-1/2' and 'B-8L-2' are loaded with 6 point loads in order to distribute the local stresses (Fig. 3 bottom; combination black and grey point loads). For all beams the loading is displacement controlled (0.4 mm/min) and applied by an electromechanical actuator with a maximum capacity of 250 kN. One LVDT (Linear Variable Differential Transformer) is placed underneath the specimens to measure the deflection at mid-span. For the hybrid beams with a concrete compression layer of 50 mm ('UHB-50C' and 'RHB-50C'), four rosette and four linear strain gauges are applied on the beam's cross section. The four linear strain gauges (concrete: PL-60-11; GFR.IPC: FLA-30-11 and PFL-30-11 [22,23]) are glued [24]

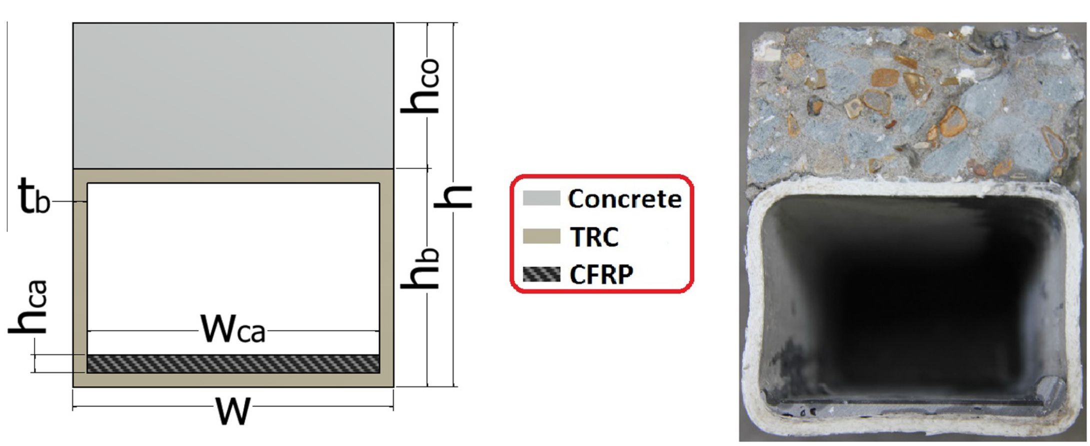

Fig. 1. The hybrid beam design: a CFRP reinforced TRC box bears the tensile forces, while the concrete on top is compressed. A schematic representation of the hybrid cross-section with all parameters (left) and the experimental cross-section of beam RHB-50C-1/2 (right).