Composites Part B 90 (2016) 1–13

Contents lists available at ScienceDirect

Composites Part B

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

Shear behaviour of new beams made of UHPC concrete and FRP rebar

E. Ferrier [a, *], A. Confrere [b], L. Michel [a], G. Chanvillard [b], S. Bernardi [c]

[a] LGCIE Site Bohr, Université Claude Bernard Lyon I, Domaine Scientifique de la DOUA, 82 Boulevard Niels Bohr, 69622 Villeurbanne Cedex, France
[b] Lafarge, LCR, Saint Quentin Fallavier, France
[c] Lafarge, Corporate, Paris, France

ARTICLE INFO

Article history:
Received 10 April 2015
Received in revised form
18 September 2015
Accepted 4 November 2015
Available online 17 December 2015

Keywords:
A. Carbon fibre
B. Mechanical properties
B. Stress transfer
C. Analytical modelling
D. Mechanical testing

ABSTRACT

The primary objective of this study was to develop a new type of high-performance lightweight beam with improved performance over conventional reinforced concrete (RC) by adding fibre-reinforced polymer (FRP) reinforcing rebar to ultra-high-performance concrete with microfibre reinforcement (UHPC-SFR). This new type of beam was designed to be lightweight, to have high compressive and tensile strength, to be able to sustain large bending moments, and to be resistant to shear. The main objective was to verify the mechanical behaviour of the beams and to compare it with the behaviour of typical RC beams. An experimental program was designed to identify its failure modes and bending behaviour. The results indicate that the behaviour of such RC beams is comparable to typical RC beam behaviour to a certain extent. An analytical model for validating this concept is presented here, which is based on the typical material behaviour law hypotheses of nonlinear mechanical beam behaviour. The load−displacement and moment−curvature relationships predicted using this model were compared to the experimental results obtained for several large-scale specimens. The comparisons revealed a good correlation between the analytical and experimental results and illustrate the potential of these composite beams in civil engineering structures.

1. Introduction

Research and development on the application of high-performance materials in the field of civil engineering has progressed significantly throughout Europe and the world in recent years, which has included the study of advanced materials such as ultra-high-performance micro-fibre-reinforced concrete (UHPC-SFR) and fibre-reinforced polymer (FRP). UHPC-SFR is strong under both compression and tension and can contribute to the mitigation of the effects of environmental exposure due to its low permeability. Thus, the use of this material is expected to increase, especially when sustainable development principles are considered [1]. In addition, the use of UHPC enables designers to create thinner sections and longer spans that are lightweight, graceful and innovative in both geometry and form, with low permeability and good durability with respect to corrosion, abrasion and impact [2]. Shear stirrups can be eliminated, which enhances safety, reduces weight and allows for faster construction. Furthermore, its durability reduces the maintenance requirements and extends the service life. All of these factors contribute to reductions in cost [3]. Finally, use of UHPC in construction has increased significantly throughout the world to such a degree that new ways to optimize its use are now necessary [4,5].

Recently, the use of fibre-reinforced polymer (FRP) rebar to replace steel rebar has emerged as one of the many techniques proposed to enhance the corrosion resistance of reinforced concrete structures. It has already been used for strengthening, rehabilitation and new construction. In particular, FRP rebar offers great potential for use in reinforced concrete construction under conditions in which conventional steel-reinforced concrete has exhibited unacceptable performance [6,7].

In emerging construction fields, research on hybrid structural members that use FRP materials combined with other high performance materials to yield new structural advantages has markedly increased [7,8]. The objectives of these new designed hybrid members are to enhance global structural performance and corrosion resistance but also to save costs compared to conventional steel construction. A study on the construction of an FRP-reinforced concrete bridge deck in Wisconsin has revealed that conventional construction technology and normal strength concrete can lead to a 57% savings in construction labour costs

* Corresponding author. Tel.: +33 04 72 69 21 21; fax: +33 04 78 94 69 06.
E-mail address: emmanuel.ferrier@univ-lyon1.fr (E. Ferrier).

http://dx.doi.org/10.1016/j.compositesb.2015.11.022
1359-8368/

compared to the construction of a nominally identical steel rebar reinforced deck [9].

Moreover, many studies have focused on the bond-slip behaviour of FRP rebar embedded in concrete to prevent unexpected debonding [10–15]. It has been shown the increased concrete strength corresponds to the increased FRP rebar strength [16]. The use of UHPC could allow the full composite action of the FRP rebar to be developed. The bond behaviour between UHPC-SFR and FRP rebar is not developed in the present study, although this property represents another benefit of combining these two high-performance materials.

Here, we present the experimental results of an investigation of a new type of RC beam composed of UHPC-SFR and reinforced with carbon fibre-reinforced polymer (CFRP).

To minimize the amount of UHPC and to improve the full use of the compressive strength, a specific cross section of the beam is proposed. When the UHPC is associated with FRP rebars, it may develop a higher tensile stress at failure. The level of material stress at failure is improved by the combination of two high-performance materials. The first cross section is a UHPC hollow section designed to avoid shear failure. The second configuration is designed to only include UHPC in areas where strength is essential, such as at the top and bottom for compression and tension resistance. A layer of UHPC is cast in the lower and upper beam parts on a few centimetres. In between, standard C25 concrete is used.

The experimental testing was conducted on beams with 2- and 4-m spans for which the high performance of this innovative RC structural configuration was demonstrated. Three types of sections were considered. The objective was to develop different failure modes. To accomplish this objective, the geometry of the section was adapted for each case study. We sought to avoid was tensile failure of the FRP reinforcements.

2. Design of FRP-UHPC SFR beams

2.1. Material

2.1.1. UHPC-SFR

The ultra-high-performance concrete used was a Ductal® G2 premix. To evaluate its mechanical properties, mechanical tests were performed on each concrete batch. The beams were cast in four different batches. Six UHPC prisms are subjected to four-point bending tests to measure their modulus of elasticity E_c and flexural strength (Table 1). Six cylindrical concrete specimens were compression tested 28 days after casting, in accordance with the specifications of the UHPC standard from JSCE [17]. A mean compressive strength f_c of 171 ± 1.8 MPa was obtained.

UHPC-SFR has been thoroughly studied regarding tension, and several mechanical laws are available. Won et al. [18] confirmed the properties of UHPC-SFR internally reinforced with micrometallic fibres. An elastic, multi-linear stress–strain relationship for UHPC-SFR proposed by Habel et al. [19] and revised in AFGC 2013 recommendations [2] was used to model the mechanical behaviour of the UHPC-SFR concrete (Fig. 1). For concrete, the strain values corresponding to critical levels on the stress–strain curve are shown in Table 1 and were determined by the equations below, using the low strain hardening law. The tensile stress corresponding to the initial cracking is $f_{ctk,el}/\gamma_{cf}$, with a strain value given by $\varepsilon_{u,el} = 0.02\%$. The maximum point of the tensile stress–strain relationship is defined by the stress corresponding to $f_{ctk}/(\gamma_{cf}\ K)$ with a strain value corresponding to $\varepsilon_{u,peak}$.

$$\varepsilon_{u,peak} = \frac{w_{0.3}}{l_c} + \frac{f_{ctk,el}}{\gamma_{cf} E_{c,eff}} \quad (1)$$

$$\varepsilon_{1\%} = \frac{0.01h}{\frac{2}{3}h} + \frac{f_{ctk,el}}{\gamma_{cf} E_{c,eff}} \quad (2)$$

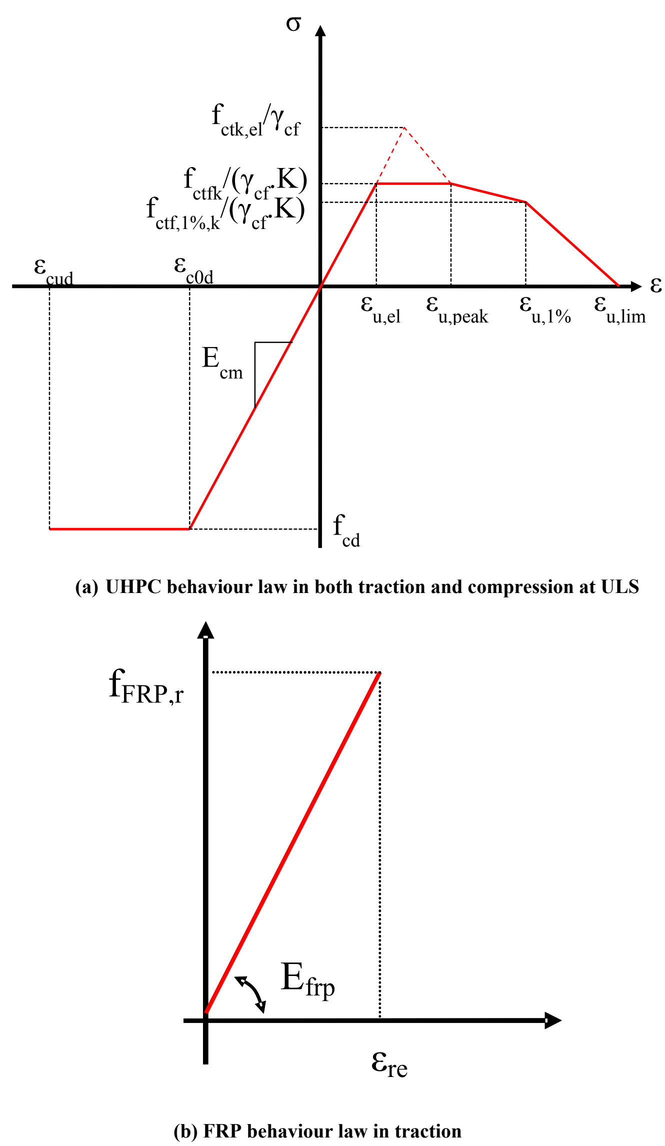

Fig. 1. Stress–strain relationship of the materials.

Table 1
Parameters of the mechanical behaviour laws (mean values).

Material	Property	Parameter	Value
UHPC	Compression	f_{cd} (MPa)	171
		ε_{cud}[a] (%)	0.27
	Tension	$f_{ctk,el}$ (MPa)	13.4
		$\varepsilon_{u,el}$[a] (%)	0.02
		$f_{ct,fk}$[a] (MPa)	25.9
	Young's modulus	E_c (GPa)	53.9
CFRP rebar	Tension	f_{frp}[a] (MPa)	1890
		ε_{rc}[a] (%)	1.35
	Young's modulus	E_{frp} (GPa)	130

[a] Mean values given by manufacturers.