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Mechanical behaviour of ultra-high-performance short-fibre-reinforced concrete beams with internal fibre reinforced polymer bars

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ABSTRACT

The primary objective of this research was to develop a new type of high-performance lightweight beam providing better performance than conventional beams made of timber, steel or reinforced concrete (RC) by casting fibre-reinforced polymer (FRP) reinforcing bars (rebars) in ultra-high-performance concrete with short fibre reinforcement (UHPC–SFR). This new type of beam was developed to be lightweight, have high compressive and tensile strength, be able to sustain large bending moments and be resistant to shear. The main objective was to verify the mechanical behaviour of the beams and compare it with typical RC beam behaviour. For this purpose, an experimental program was designed to identify the failure modes and bending behaviour. The results indicate that the behaviour of such RC beams can be compared to typical RC beam behaviour to a certain extent. A model to validate this concept is presented in this paper; this analytical model is based on typical material law behaviour hypotheses of beam nonlinear mechanical behaviour. The load–displacement and moment–curvature relationships predicted with this model were compared to the experimental results obtained for four large-scale specimens. The comparisons revealed good correlation between the analytical and experimental results and illustrate the potential of these composite beam configurations in civil engineering structures.

1. Introduction

In recent years, construction with ultra-high-performance short-fibre-reinforced concrete has increased significantly, both in Europe and worldwide. This material is strong in compression, more ductile in tension than plain concrete and can help mitigate the effects of environmental exposure because of its low permeability; thus, the industrial use of this material has increased, particularly when sustainable development principles are considered [1,2]. Use of this material enables a designer to create thinner sections and longer spans that are light, graceful and innovative in both geometry and form, with low permeability and good durability in terms of corrosion, abrasion and impact [3]. The material can be used without ordinary steel reinforcement (rebar). It requires less formwork, labour and maintenance than conventional concrete, therefore, reducing costs [4]. The elimination of shear stirrups enhances safety, reduces the weight of the structure and speeds construction. Its durability reduces maintenance requirements and extends service life. The use of UHPC in construction has significantly increased globally; consequently, new ways to optimise its use are now necessary [5,6].

In the past few years, the use of fibre-reinforced plastic (FRP) rebars to replace steel rebars has emerged as one of the numerous techniques proposed to enhance the corrosion resistance of reinforced concrete structures. In particular, FRP rebars offer significant potential for use in reinforced concrete construction when conventional steel-reinforced concrete has yielded unacceptable service [7–9]. The objective is to mix UHPC–SFR and FRP.

This paper presents the analytical and experimental results of an investigation of a new type of RC beam reinforced with UHPC–SFR.

The RC beams tested in this study were formed by casting FRP rebars in the bottom of an ultra-high-performance short-fibre-reinforced concrete (UHPC–SFR) beam, as shown in Fig. 1. The high-performance concrete, which has a minimum compressive strength of 150 MPa and a minimum tensile strength of 15 MPa, was placed in moulds to obtain beams as lightweight as possible. The elastic modulus of the UHPC–SFR was approximately 50,000 MPa [1,2]. The UHPC–SFR layers were internally reinforced with FRP bars to increase the tensile strength of the bottom portion of the RC beam [10].

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Nomenclature

A_c	area of the UHP concrete (mm^2)	m_r	internal bending moment in rebars (Nm)
A_r	area of the rebars (mm^2)	M_u	ultimate bending moment (kN m)
A_w	area (mm^2)	m_w	internal bending moment in wood (Nm)
b_w	width of the beam (mm)	w_f	web thickness (mm)
d_c	depth of the concrete layer (mm)	V_u	ultimate shear load (kN)
d_r	depth of the rebars (mm)	z_g	neutral axis position (mm)
$E_{1\%}$	initial Young's modulus of UHPC (MPa)	$\varepsilon(z)$	strain at depth z (m/m)
E_c	Young's modulus of UHPC (MPa)	$\varepsilon_{0,3}$	elastic concrete strain in tension (m/m)
E_{ci}	Young's modulus of layer i of the UHPC (MPa)	ε_{bc}	ultimate strain in UHPC (m/m)
E_r	Young's modulus of the rebars (MPa)	ε_c	ultimate concrete strain (m/m)
F_c	force applied to the concrete (N)	ε_{cj}	concrete strain in layer j (m/m)
f_{cc}	compressive strength (MPa)	ε_{lim}	strain limit (m/m)
f_{ct}	ultimate tensile strength of UHPC (MPa)	ε_r	strain in the rebars (m/m)
f_{ctj}	ultimate tensile elastic strength (MPa)	ε_{sup}	strain at the bottom of the beam (m/m)
h	thickness of the laminate (mm)	$\varepsilon_w\ (i)$	strain in the concrete in layer i (m/m)
h_{c1}	thickness of the lower plank (mm)	ρ_c	volume percentage of UHPC (%)
h_w	depth of the beam (mm)	σ_c	compressive stress in concrete (MPa)
l_c	UHPC crack length (mm)	σ_r	rebar stress (MPa)
M	applied moment (Nm)	τ_w	maximum shear stress (MPa)
m_c	internal bending moment in concrete (Nm)	$w_{0,3}$	crack width of UHPC (mm)
m_{ext}	external bending moment (Nm)		

Experimental testing was conducted on beams with 2- and 4-m spans. The high performance of this innovative RC structural configuration was demonstrated in this study.

An I-beam section was considered. The objective was to develop different failure modes. To accomplish this objective, the geometry of the section was adapted to each case study. The failure modes anticipated were tensile failure of the FRP reinforcement (in the beams with 4-m spans), compressive failure (in the beams with 4-m spans) and shear failure (in the beams with 2-m spans). The objective of the modelling conducted in this study was to use the typical analytical model developed for beams that includes concrete cracking and post-cracking behaviour to minimize material quantities by optimizing the UHPC thickness for shear and flexure and the FRP properties (rebar area and elastic modulus), thereby increasing the bending stiffness and ultimate load capacity.

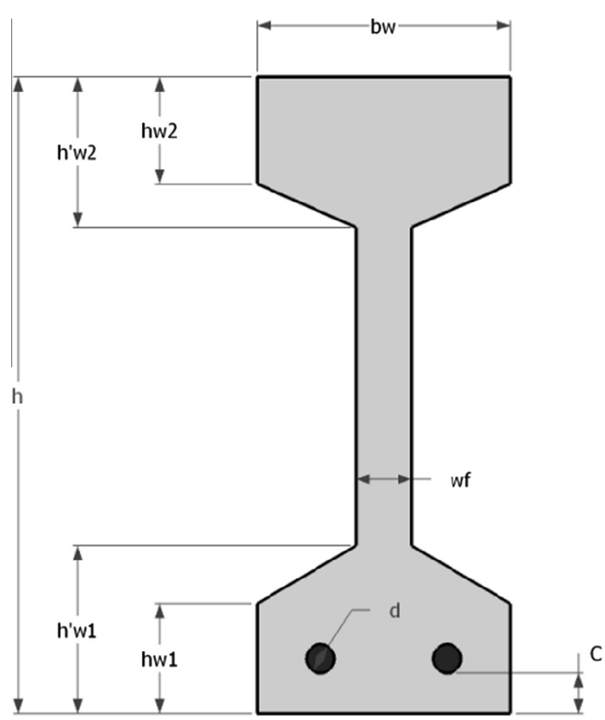

Fig. 1. Geometric parameters of beams.

2. Experimental program

2.1. Test specimens

A typical RC beam, similar to those described previously, is shown in Fig. 1. The length, width and height of a beam are denoted by L_w, b_w and h_w, respectively. The web thickness (w_f) is 22 mm for all beams because of the UHPC use (flow concrete with aggregate size less than 1 mm). The concrete cover of the FRP bars (c) is 15 mm. The thickness of the bottom flange of the beam reinforced with FRP is denoted by h_{w1}. The thickness of the top flange is denoted by h_{w2}. For comparison, the total depth was identical for each beam. Certain parameters were selected to evaluate the efficiency of the beams. Geometric and material parameters, such as beam length, depth and span, depth-to-width ratio, volume percentage of concrete versus short steel fibres, volume ratio of tensile rebar and rebar mechanical properties, including axial stiffness, and mechanical properties of concrete and FRP are all significant. The beam span, depth-to-width ratio and tensile strength of the rebars in the lower flange (Fig. 1) are the parameters investigated in this study. To test a full-scale specimen for building applications, a four-meter span was considered; shorter spans were also considered to study the shear limit of these beams. Four beams were designed for this study (Fig. 2). The geometric properties of the four beams studied are given in Table 2. For the four beams, the volume percentage of short metallic fibres was 2%, and the rebar axial stiffness E_rA_r was 20 and 30 MN for the carbon FRP rebars and 9 and 18 MN for the glass FRP rebars. The geometric and mechanical material properties of the glass (G) or carbon (C) fibre-reinforced polymer rebars are given in Tables 1 and 2. The depth-to-width ratios h/b$_w$ were fixed in the range of 8–9.7 to produce the desired failure modes. The beam span-to-depth ratio L_w/h_w was nine for the four 2-m beams to produce shear failure and 20–22 for the four 4-m beams to produce flexural failure. The