Materials and Design 92 (2016) 590–601

Contents lists available at ScienceDirect

Materials and Design

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

Design procedure and experimental study on fibre reinforced concrete segmental rings for vertical shafts

Lin Liao [a,b], Albert de la Fuente [a,*], Sergio Cavalaro [a], Antonio Aguado [a]

[a] Civil and Environmental Engineering Department, Universitat Politècnica de Catalunya (UPC BarcelonaTECH), Jordi Girona 1-3, 08034 Barcelona, Spain
[b] Department of Underground Engineering, Taiyuan University of Technology, 79 Yingze West Street, 030024 Taiyuan, China

ARTICLE INFO

Article history:
Received 17 August 2015
Received in revised form 7 December 2015
Accepted 14 December 2015
Available online 18 December 2015

Keywords:
MC 2010
Optimal design
Vertical shafts
Precast segments
FRC

ABSTRACT

Structural fibres are used to replace partially or totally the passive reinforcement in precast concrete segments for tunnel linings constructed with TBM, showing several advantages. Fibre reinforced concrete (FRC) could also be applied with similar benefits to vertical shafts. However, to the author's knowledge, this material has not been used in such application yet. The Model Code 2010 gathers an approach for the design of FRC structural elements. This approach should be adapted according to the structural needs of precast segment, for which the transient load stages are often the most critical and specific ductility requirements should be established. The objective of this paper is twofold: propose a general analytical formulation to assess the minimum mechanical requirements that FRC must fulfil in case of partial or complete substitution of the steel rebars and confirm that it is possible to replace the rebars by using fibres in vertical shaft linings. First, the general analytical formulation is proposed. Then, the segments of the Montcada vertical shaft (Barcelona) are redesigned considering the total substitution of the traditional reinforcement by fibres. Finally, two full-scale tests of the FRC precast segments were performed to verify the suitability of the analytical formulation proposed.

1. Introduction

Structural fibres are commonly used in precast segments for the lining of tunnels constructed with tunnel boring machines (TBM). These structures usually remain under compression in service, presenting tensile stresses primarily during transient stages (demoulding, storage, transport, handling, and installation). Under these conditions, the partial or even the complete replacement of traditional bar reinforcement by an adequate amount of structural fibres becomes attractive from an economic and technic standpoint.

Currently, several codes and guidelines include fibre reinforced concrete (FRC) as a structural material; highlighted among them the MC 2010 [1]. Furthermore, many experimental campaigns [2–9] from the literature (Table 1) have focused on the production, full-scale bending tests, and numeric simulations of segments made of concrete with compressive strengths f_c ranging from 20 to 150 N/mm^2 and structural fibre contents (C_f) ranging from 30 to 236 kg/m^3. Moreover, [10–16] present a set of real experiences in tunnels constructed with TBM in which FRC is used. These experiences have promoted the application of FRC, demonstrating that the material is competitive at the structural level compared with other traditional solutions.

Until now, the design of FRC segments has been addressed by means of numerical methods [3,17–27]. To the authors' best knowledge, no analytical expression that describes the design of segments reinforced only with fibres or with hybrid reinforcement (fibre + bars) is found in the literature. Furthermore, the authors have been unable to find any reference in which these types of segments are used in vertical shafts constructed with a vertical shaft machine (VSM). Like in many tunnels, in this case the segments are generally subjected to reduced stresses during the transitional phases and compression predominates during service. Therefore, despite the absence of previous experiences, the use of structural fibres instead of bars may also be competitive.

The aim of this study is to provide a response to the two absences mentioned in the previous paragraph. On one hand, the objective is to demonstrate that the complete replacement of the bar reinforcement by fibres is also possible in shaft linings constructed with VSM. On the other hand, the objective is to propose an analytical and general formulation to assess the minimum mechanical requirements that the FRC must fulfil in elements with complete or partial substitutions of the traditional reinforcement.

First, the analytical formulation based on the MC 2010 is proposed for the structural design of FRC segments. This formulation is then applied to the redesign of the segments from Montcada Shaft, which was originally conceived with traditional reinforcement. After that, in the context of full-scale construction work (Montcada Shaft, Barcelona) and a research project, a characterization campaign of conventional and self-compacting concretes reinforced with fibre quantities (C_f) between 30 and 60 kg/m^3 was performed to evaluate the optimum amount for

* Corresponding author.
E-mail address: albert.de.la.fuente@upc.edu (A. de la Fuente).

http://dx.doi.org/10.1016/j.matdes.2015.12.061
0264-1275/

Table 1
Experimental campaigns and numerical simulations collected from the scientific literature regarding FRC segments for tunnels created with a TBM.

Elements	f_c (MPa)	Dimensions (mm)	Material	C_f (kg/m^3)	Φ_f/λ_f	No	Num. Sim.	Ref.
PS (RT)	75	3640 × 1500 × 200	SFRC	40	0.35/30	1	None	[2]
	45		RC	---	---	1		
PS (RP)	60	2359 × 1400 × 350	PC	---	---	3	None	[3]
			SFRC	30	0.75/60	3		
				40		3		
PS (RT)	45	2406 × 900 × 200	RC	---	---	1	None	[4]
			SFRC	20	0.55/35	1		
PS (MT)	60	4700 × 1800 × 350	SFRC	40	0.75/60	2	None	[5]
				50		2		
PS (MT)	60	4700 × 1800 × 350	SFRC + RC	30	1.0/50	2	Yes	[6]
			SFRC	45		2		
				60		2		
PS (MT)	20	Semi-circle 9700 × 1000 × 300	PC	---	---	1	Yes	[7]
			SFRC	40	0.8/60	1		
			PC	---	---	1		
			SFRC	40	0.8/60	1		
			PC	---	---	1		
			SFRC	40	0.8/30	1		
			PC	---	---	1		
			SFRC	40	0.8/60	1		
PS (RP)	66	2120 × 1500 × 235	RC	---	---	1	None	[9]
	68		SFRC	120	0.75/60	1		
	66	3180 × 1500 × 235	RC	---	---	1		
	68		SFRC + PF	120+	0.75/60	1		
	140	1000 × 500 × 100	UHPC	---	---	1	Yes	
	150	1000 × 500 × 100	UHPFRC	236	0.2/80	1		
PS (MT)	68	2438 × 1500 × 235	SFRC	57	0.75/60	6	Yes	[9]

PS: precast segment; PC: precast concrete; RT: road tunnel; RP: research project; MT: metro tunnel; fc: concrete compressive strength; SFRC: steel fibre reinforced concrete; RC: reinforced concrete; UHPC: ultra high performance concrete; UHPFRC: ultrahigh fibre reinforced concrete; PF: plastic fibres; Φ_f: cross section diameter of the fibres; λ_f: aspect ratio of the fibres.

the complete removal of the traditional reinforcement. Finally, an experimental campaign of full-scale segments subjected to bending was performed with both concrete types to verify the ductile behaviour until failure. This study widens the field of application of FRC, demonstrating the feasibility of a new use. Moreover, it shows new formulations that might support engineers towards the optimal structural design of this type of structures or others constructed with FRC.

2. Brief overview on FRC design

The most common method to characterize post-cracking behaviour of FRC is the three-point test of prismatic specimens with dimensions of 150 × 150 × 550 mm^3, which are notched at the centre (Fig. 1a) according to the EN 14651:2005 standard [28]. During the test, the vertical displacement is controlled and both the load F and the crack mouth opening displacement (CMOD) are measured. The F–CMOD curve obtained (Fig. 1b) may be used to deduce the tensile constitutive law σ–ε of the FRC. The stresses σ are obtained from the residual tensile strength f_{Ri}.

The classification proposed in MC 2010 is based on the characteristic values of the residual tensile strength for CMOD = 0.5 mm (f_{R1k}) and CMOD = 2.5 mm (f_{R3k}). In this regard, the FRC strength class is specified using f_{R1k} to represent the strength interval and the letter (a, b, c, d, or e) to represent the f_{R3k}/f_{R1k} ratio. The strength interval f_{R1k} is established by using a number from the following series: 1.0–1.5–2.0–2.5–3.0–4.0–4.5–5.0–6.0–7.0–8.0 in N/mm^2. The f_{R3k}/f_{R1k} ratios are in accordance with the following series: a if $0.5 \le f_{R3k}/f_{R1k} < 0.7$; b if $0.7 \le f_{R3k}/f_{R1k} < 0.9$; c if $0.9 \le f_{R3k}/f_{R1k} < 1.1$; d if $1.1 \le f_{R3k}/f_{R1k} < 1.3$; and e if $f_{R3k}/f_{R1k} \ge 1.3$. In addition to that, the MC 2010 establishes that when the goal is to replace either partially or completely the traditional reinforcement with an equivalent quantity of structural fibres in ultimate limit state (ULS), the following conditions must be satisfied: $f_{R1k}/f_{Lk} > 0.4$ and $f_{R3k}/f_{R1k} > 0.5$.

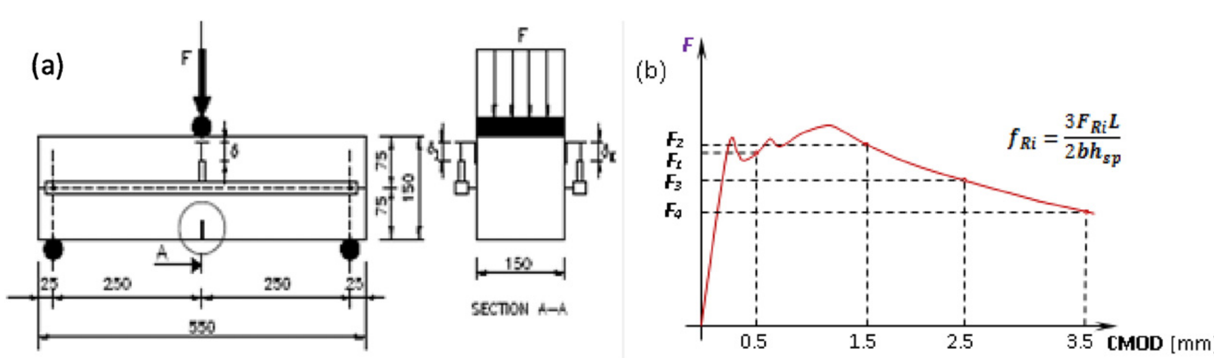

Fig. 1. Three-point test in notched prismatic beams: (a) test configuration (mm) and (b) F–$CMOD$ generic curve.