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Experiences in Barcelona with the use of fibres in segmental linings

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ABSTRACT

This paper presents the most outstanding experiences regarding the use of fibres as the main reinforcement in precast segmental linings in the metropolitan area of Barcelona. It is known that the addition of structural fibres improves, on the one hand, the mechanical behaviour of the structure during its construction, especially in cases such as the thrust of the jacks, and on the other hand it leads to a reduction of the global costs by reducing the conventional passive reinforcement. The aim of this paper consists in presenting three real experiences that are representative of the application of FRC in urban tunnels and a design methodology to take into account the structural contribution of the fibres. Two particular cases of the application of this design method are presented. In the first case, the use of 25 kg/m^3 of fibres has led to a reduction of 70% of the conventional reinforcement initially proposed in the project. In the second one, which was planned to employ fibres but without considering its structural contribution, the parametric study reflected the possibility of reducing up to a 38% of the rebars adding 25 kg/m^3 of steel fibres in the concrete mixture. In light of good results, construction companies in Spain have become aware of the advantages of using fibres in these structures and have carried out experimental stretches. This attitude has also been influenced by the approval of the new Spanish Code, which includes the FRC as a construction material with design purposes.

1. Introduction

Fibre reinforced concrete (FRC) is a composite material that has proved to be a competitive material in many types structures (di Prisco and Toniolo, 2000; di Prisco et al., 2009; Walraven, 2009; de la Fuente et al., 2010a). In particular, there are many advantages when using FRC in the manufacturing of segmental linings of tunnels built by means of a Tunnel Boring Machine (TBM) (Waal, 1999; Blom, 2002; Plizzari and Tiberti, 2006; Burguers et al., 2007). In this field, the use of steel fibre reinforced concrete (SFRC) improves the mechanical behaviour of concrete enhancing: (1) toughness; (2) resistance to fire; (3) resistance to fatigue and (4) its response facing impacts and concentrated loads that can be occur in stages prior to the placement of the segments (curing, transport and handling), during its assembling (thrust of the jacks) and during service stage (contact between joints).

Likewise, the use of SFRC may lead to the total or a partial removal of rebars, improving the production efficiency and ensuring economic competitiveness with regards to the traditional solution. There are many studies both experimental (Caratelli et al., 2011) and numerical (Plizzari and Cominoli, 2005; Plizzari and Tiberti, 2006; Burguers et al., 2007; Tiberti et al., 2008; Tiberti and Plizzari, 2008; Chiaia et al., 2009a,b) in which the advantages associated to the use of SFRC in precast segments are proved as well as the use of steel bar reinforced concrete (RC) and SFRC in the same precast concrete segment (RC-SFRC, hereinafter).

In the last 8 years, the construction of more than 120 km of tunnel has started in the metropolitan area of Barcelona (Spain), some of which are still under construction. The internal diameter (D_i) of these tunnels ranges from 6.00 m to 10.9 m, with aspect ratios ($\lambda = D_i/h$) of even 31 as in the Can Zam stretch of the Line 9 Subway of Barcelona. Basically, the applications were either related to railways, metro lines or for hydraulic conduits.

The use of SFRC began at several stretches of Line 9 Subway of Barcelona (started in 2003). Nevertheless, the structural contribution of the fibres was not considered in the design due to the lack of regulations in the Spanish Code regarding the use of FRC. Conversely, they were considered to improve the toughness and enhance the cracking control during handling and assembling operations, while rebars kept the main resistant function. In this sense, the most advanced regulations currently available when these first applications were carried out in Barcelona did take already into account the structural contribution of the fibres, but they were too recent (DBV, 1992; RILEM TC 162-TDF, 2003; CNR DT 204/2006, 2006; Model Code 2007). Nowadays, the Spanish regulation CPH (2008) includes SFRC as a material with a structural responsibility.

Subsequently to the beginning of the construction of the Line 9 Subway of Barcelona, several experimental applications of SFRC precast segments were performed in various stretches. In these cases, 60 kg/m^3 of steel fibres were used to replace the steel rebars. However, two groups of stirrups similar to the ones used in the

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Nomenclature

A_c	total concrete area	N_k	characteristic axial force
$A_{s,i}$	area of the *i*th steel bar	N_u	ultimate axial force
dA_c	differential of concrete area	n_s	number of steel bars
C_f	amount of steel fibres	x_n	depth of the neutral axis
c_r	cohesion of the soil	y_c	ordinate of the gravity centre of the concrete area element
D_i	internal diameter of the tunnel	y_{cdg}	ordinate of the gravity centre of the section
d	effective depth of the tensioned steel rebars	$y_{s,i}$	ordinate of the *i*th steel bar
d_f	diameter of the fibre	w	crack width
E_{cm}	average Young modulus of concrete	w_{max}	maximum crack width
E_f	Young modulus of the fibre	w_k	characteristic value of the crack width
E_r	Young modulus of the soil	ø	steel bar diameter
E_s	Young modulus of steel	Φ_r	friction angle of the soil
f_c	compressive strength of the concrete	γ_r	specific weight of the soil
f_{cm}	average compressive strength of concrete	ε_c	concrete strain
f_{ck}	characteristic compressive strength of the concrete	ε_{co}	strain for the maximum compressive stress of the concrete
$f_{ctm,fl}$	average flexural strength of the concrete	ε_o	strain of the bottom fibre
$f_{ctk,fl}$	characteristic flexural strength of the concrete	ε_{cu}	maximum strain of the compressed concrete
f_{fu}	failure tensile strength of the steel fibre	ε_i	*i*th post-cracking tension strain of the SFRC
$f_{R,i}$	*i*th post-cracking residual flexural strength of SFRC	ε_s	strain of the steel
f_{yk}	characteristic yielding strength of steel	$\varepsilon_{s,i}$	strain of the *i*th steel bar
h	height of the cross section of the segment	ε_y	yielding strain of the steel
K_o	coefficient of lateral earth pressure	λ	aspect ratio of tunnel (D_i/h)
k_h	size factor	v_r	Poisson ratio of the soil
l_f	length of the fibre	σ_c	concrete stress
M	applied external bending moment	σ_i	*i*th post-cracking tension strength of the SFRC
M_{cr}	cracking bending moment	σ_u	compressive stress of concrete at maximum strain
M_d	design bending moment	σ_s	stress of the steel
M_k	characteristic bending moment	$\sigma_{s,i}$	stress of the *i*th steel bar
M_{max}	maximum bending moment	χ	sectional curvature
$M_{0.3mm}$	bending moment associated with a crack width of 0.3 mm	χ_{cr}	cracking sectional curvature
M_u	ultimate bending moment	χ_u	ultimate sectional curvature
N	applied external axial force		
N_d	design axial force		

analysis of the Line 1 Subway of Valencia (Venezuela) (Plizzari and Tiberti, 2006) were maintained in order to confine the concrete.

Currently, some experiences concerning precast concrete segments reinforced only with fibres have been done (see Table 1), but the great majority of them are related to values of λ generally smaller than those used in the Line 9 Subway of Barcelona. Examples of these applications are: a tunnel for the transportation of water in Ecuador (Vandewalle, 2005), Gold Coast and South East Queensland in Australia (Angerer and Chappell, 2008), Heating Tunnel from the Island Amager to Copenhagen in Denmark (Kasper et al., 2008), Line 4 Subway of Sao Paulo (Telles and de Figueiredo, 2006), CLEM Jones Tunnel in Brisbane (Rivercity, 2008), Hobson Bay Sewer Tunnel in New Zealand (Maccaferri, 2009) and Bright Water Sewer System Seattle Tacoma in USA (Jones, 2009).

The challenge in the recent experiences carried out in the metropolitan area of Barcelona was to analyze the feasibility of exceeding the diameters previously reached. Thus, the purpose of this article is, on the one hand, to present these experiences. On the other hand, this article also aims at showing the design methodology used for the optimization of the amount of fibres (C_f) in SFRC and RC-SFRC precast segments.

2. Pioneer experience in the metropolitan area of Barcelona

The first pilot test for the application of SFRC in precast segments was carried out in the year 2004, in the Can Zam stretch of the Line 9 Subway. It must be highlighted that the execution and the working conditions in this first experience were highly adverse: descending stretch and water leaks with a temperature of up to 60 °C. The solution adopted in this case was a ring with a D_i = 10.9 m, divided by an intermediate slab separating two independent levels (one for each traffic direction). The thickness of the segment was 0.35 m, and a FRC with 60 kg/m^3 of steel fibres dosage was used. A total of thirty rings were constructed; three of them were instrumented in order to carry out a loading test for simulating the soil pressure in the field conditions by means of jacks (Molins and Arnau, 2011; Arnau and Molins, 2011).

In Fig. 1a the instrumented specimen is presented. Notice, that the conventional reinforcement was limited to the stirrups (a similar solution was developed by Plizzari and Tiberti (2006)). Likewise, Fig. 1b shows the hydraulic flat-jacks placed in the extrados of the segment to perform the loading test.

As previously mentioned, the working conditions were adverse. As a matter of fact, some splitting cracks and local failures appeared. Fig. 2a shows the crack pattern generated during the assembling of the segments. This cracking was due to the high eccentricity of the load transmitted by the jacks in the descending part of the stretch (Burguers et al., 2007; Cavalaro, 2009; Cavalaro et al., 2011). Fig. 2b also shows the existence of water leaks. Nonetheless, there was no concrete detachment thanks to the presence of fibres bridging the cracks.

Even considering the problems already mentioned, which also took place in the stretches with traditional reinforcement, the results from the loading test were satisfactory (Molins et al., 2009). In spite of the success achieved, the solution was not generalized in the whole tunnel for several reasons, many of them bearing no relation to the technical reasons.