Experimental Behaviour of Precast Tunnel Segments in Steel Fiber Reinforcement with GFRP Rebars

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Abstract

The interest in using fiber reinforced concrete (FRC) for the production of precast segments in tunnel lining, installed with Tunnel Boring Machines (TBMs), is continuously growing, as witnessed by the studies available in literature and by the actual applications. The possibility of adopting a hybrid solution of FRC tunnel segments with GFRP reinforcement is investigated herein. Full-scale tests were carried out on FRC segments with and without GFRP cage, with a typical geometry of metro tunnels In particular, both flexural and point load full-scale tests were carried out, for the evaluation of the structural performances (both in terms of structural capacity and crack pattern evolution) under bending, and under the TBM thrust. Finally, the obtained results are compared, in order to judge the effectiveness of the proposed technical solution.

Keywords

Tunnel segments, hybrid solution, Fiber reinforced concrete, GFRP reinforcement, full scale tests.

1 Introduction

In the last few years the adoption of fiber reinforced concrete (FRC) in precast tunnel segments, has encountered a great interest, as witnessed by theoretical and experimental studies (Plizzari and Tiberti, 2008; Caratelli et al., 2011; Liao et al., 2015), and actual applications (Kasper et al. 2008, De La Fuente et al., 2012, Caratelli et al., 2012). The solution of FRC elements, without any reinforcement, provides the great advantages, in terms of cost and precast production. Nevertheless, in some part of the tunnel, for particularly loading condition (typically under prevalent bending actions, as in cross-passage or shallow tunnel), the FRC solution could not satisfy the requirement. In this the adoption of a hybrid system, with the addition of rebars, could be a realistic solution.

The possibility of adopting glass fiber reinforced polymers (GFRP) reinforcement in precast tunnel segments in ordinary concrete was investigated (Caratelli et al., 2016; Caratelli et al., 2017; Spagnuolo et al., 2017). GFRP rebars in concrete structures can be proposed as an alternative to the traditional steel rebars, mainly when a high resistance to the environmental attack is required. Indeed, GFRP reinforcement does not suffer corrosion problems and its durability performance is a function of its constituent parts (Micelli and Nanni 2004; Chen et al. 2007). From the mechanical point of view, the GFRP rebars are characterised by an elastic behaviour in tension, and, with respect to the steel ones, present higher tensile capacity, lower elastic modulus, and lower weight (Nanni 1993; Benmokrane et al. 1995; Alsayed et al. 2000). The compression strength is often neglected, due to its low value. GFRP is also electrically and magnetically non-conductive, but sensitive to fatigue and creep rupture (Almussalam et al. 2006). Furthermore, the structural effects of the low elastic modulus and bond behavior (Cosenza et al. 1997; Yoo et al. 2015, Coccia et al., 2017) have to be considered. Due to all these aspects, this type of reinforcement is not suitable for all applications, but it appears appropriate for tunnel segments, both for provisional and permanent elements.

In order to evaluate the synergic effect of the above mentioned composite materials, tunnel segments, with a typical metro tunnel geometry, made in FRC with and without GFRP bars were cast and experimentally tested. Both bending and point load tests are carried out, in order to evaluate the structural performances, both in terms of strength and crack width. The obtained results are finally compared and discussed.

2 Segment geometry and materials

Four full-scale fiber reinforced concrete segments were cast in moulds available at the Laboratory of the University of Rome Tor Vergata. The specimens have an external diameter of 6400 mm, thickness of 300 mm, and width of about 1400 mm (Fig. 1). Two of the four segments were further reinforced with a perimetric GFRP cage.
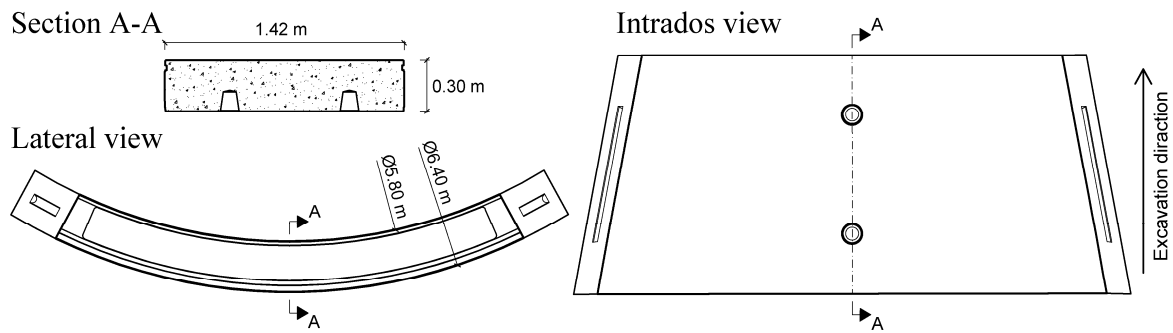
Figure 1:   Segment geometry

Steel fibers Bekaert Dramix 4D 80/60BG were added to the concrete matrix with a content of 40 Kg/m³. The average compressive strength, measured on 6 cubes having 150 mm side, was equal to 62.35 MPa.

The tensile behavior was characterized through bending tests on eight 150x150x600 mm notched specimens according to the EN 14651. The diagrams of the nominal stress versus the crack mouth opening displacements (CMOD) are plotted in Figure 2.
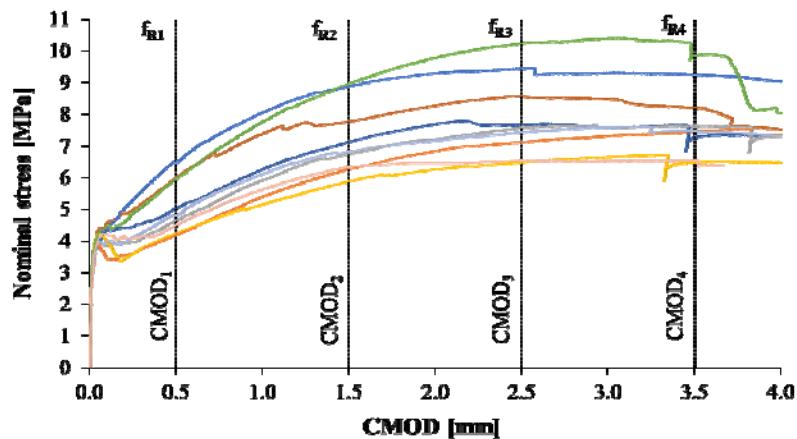

Figure 2:   Results of the beam bending tests

Two fiber reinforced segment, named SFRC-GFRP, were further reinforced with a perimetric Glass Fiber Reinforced Polymeric (GFRP) cage, as shown in Figure 3. The GFRP bars have a nominal diameter of 18 mm, and are characterized by Young's Modulus of about 40 GPa, and ultimate tensile strength equal to 1000 MPa.
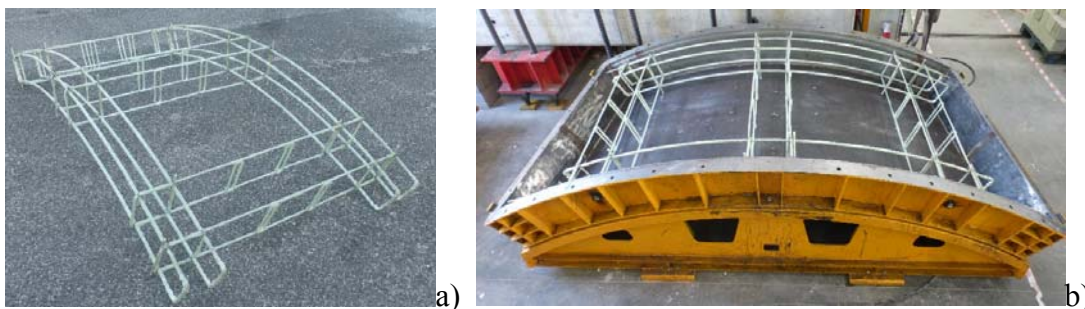

Figure 3. a) GFRP cage; b) casting phase

For both the segment typologies (SFRC-steel fiber reinforced segments without any reinforcement and SFRC-GFRP), both flexural and point load full-scale tests were carried out, for the evaluation of the structural performances (both in terms of structural capacity and crack pattern evolution) under bending, and under the TBM thrust.

3 Bending tests

The bending tests were performed with the loading set-up illustrated in Figure 4, in displacement control, by adopting a 1000kN electromechanical jacket, with a PID control and by imposing a stroke speed of 10 µm/sec.

The segments were placed on cylindrical support with a span of 2000 mm and the load, applied at the midspan, was transversally distributed be adopting a steel beam as shown in Figure 4. The measure devices, consisting in three potentiometer wires and two LVDTs, are shown in Figure 4.

Figure 4. Bending test set-up and instrumentation

3.1 Bending test results

The behaviour of the segments SFRC and SFRC-GFRP are compared in Figure 5, where the average value of the displacement, measured by the three potentiometer wires, is plotted versus the load. The first cracks appeared for a load value of about 125 kN and 120 kN, for the SFRC and SFRC-GFRP segment, respectively. In both the cases the first cracks were opened on the lateral surfaces close to the midspan and propagates on the intrados.

After a first comparable almost elastic response, the SFRC-GFRP segment presented a peak load about 63% higher than the SFRC one (367 kN against 225 kN of the SFRC segment). The maximum crack widths, measured at different load steps, are compared in Table 1. The obtained results clearly show the synergic effects of the two materials in reducing the crack widths, with respect to SFRC solution, of about 60%. Finally, the evolution of the crack patterns, at the intrados surface, are compared in Figure 6.
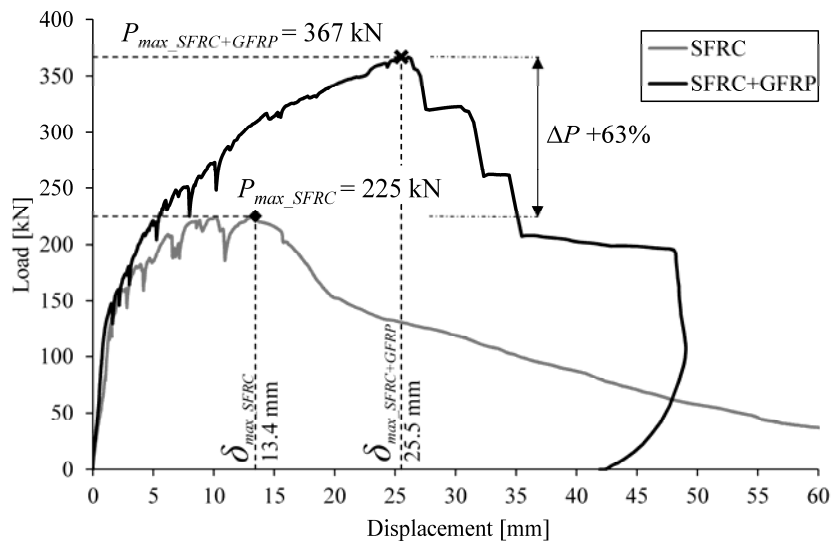
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Figure 5. Bending test. Load- average displacement: comparison between SFRC and SFRC-GFRP segments.

Table 1. Maximum crack widths: comparison

Loading							
Load [kN]	125	160	180	210	222	250	270
Crack width							
SFRC	<0.05	0.25	0.35	0.60	1.00	n/a**	n/a**
SFRC-GFRP	<0.05	0.10	0.15	n/a**	0.35	0.45	0.70

n/a*= measure not available since the crack width was not recorded at this load step
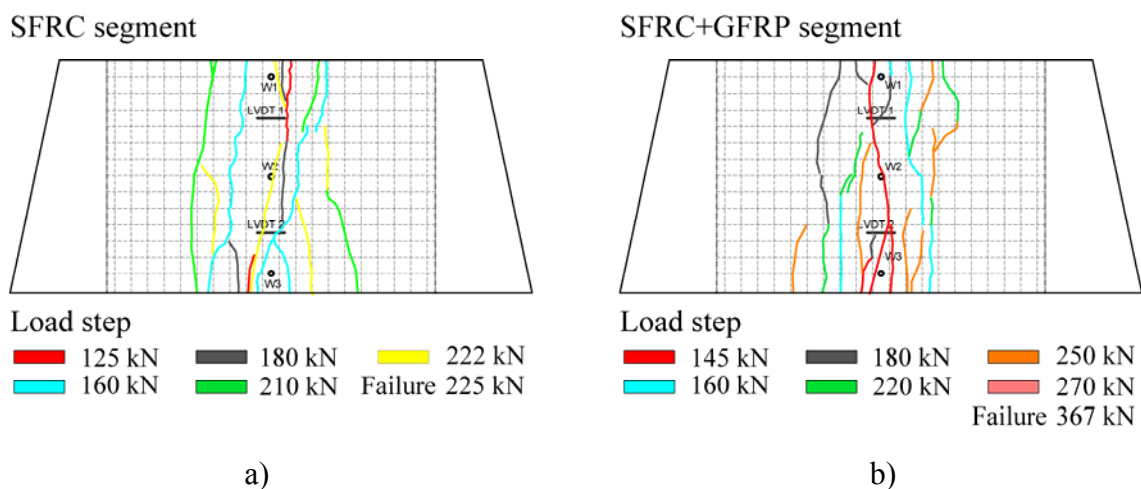n/a**= measure not available since the segment did not reach this load value

a)   b)

Figure 6. Bending test: crack pattern: a)SFRC segment; b) SFRC-GFRP segment

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4 Point load tests

The point load test was performed by applying three-point loads at the segment, and adopting the same steel plates used by the TBM machine (Fig. 7). A uniform support is considered, as the segment is placed on a stiff beam suitably designed (Meda et al., 2016). Every jack, having a loading capacity of 2000 kN, is inserted in a close ring frame made with HEM 360 steel beams and 50 mm diameter Dywidag bars (Fig. 7). The load was continuously measured by pressure transducers. Six potentiometer transducers (three located at the intrados and three at the extrados) measure the vertical displacements, while two LVDTs transducers are applied between the load pads, to measure the crack openings. (Fig. 7).
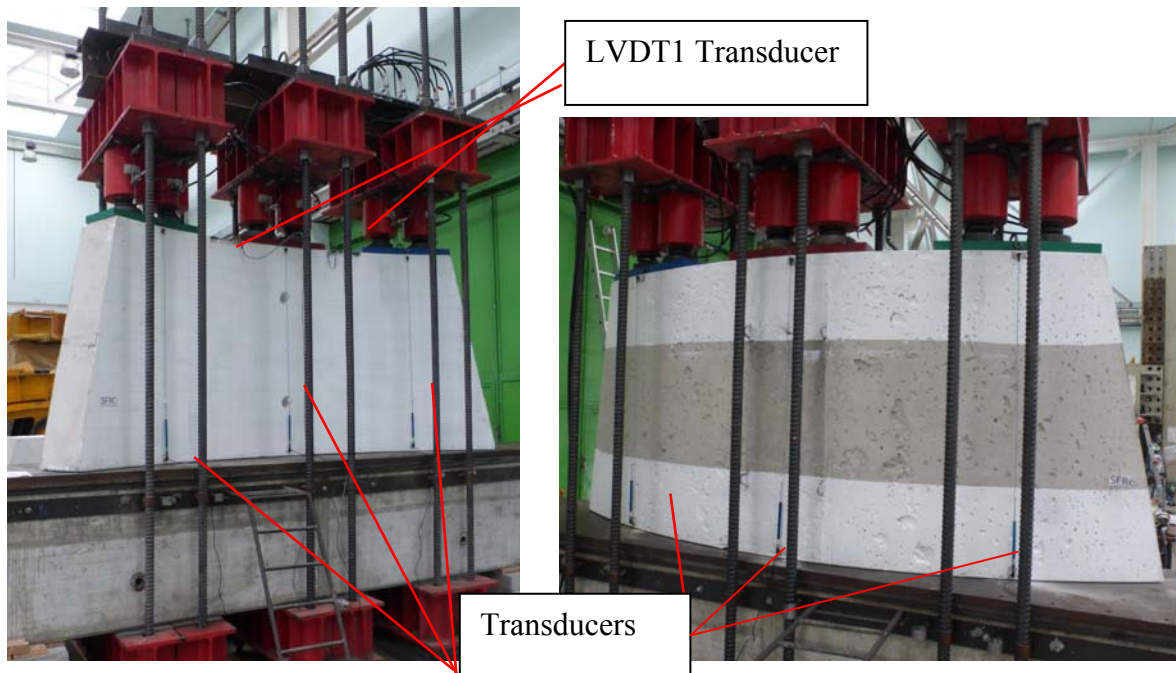

Figure 7. Point load test and instrumentation

Two cycles were performed, as shown in Figure 8. The chosen reference load levels equal to 1580 kN and 2670 kN (for each pad) refer to the service load and unblocking thrust of the TBM machine.
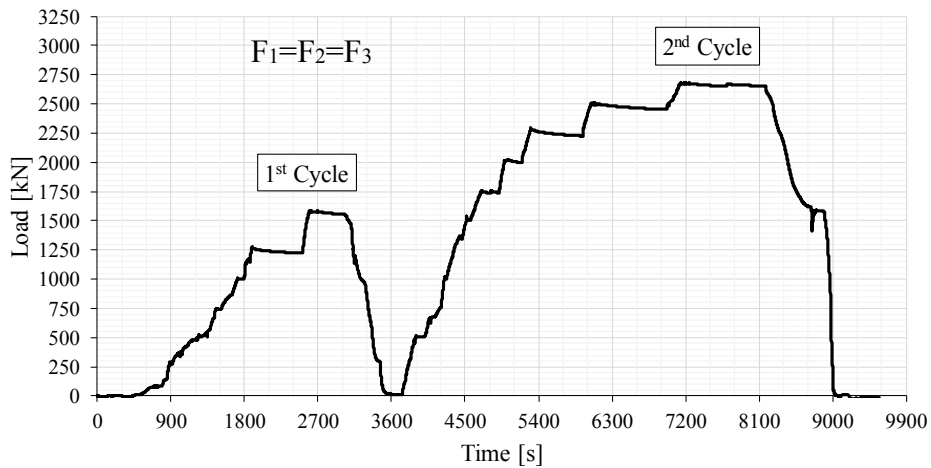
Figure 8. Point load test: Load (single pad) vs Time; a) SFRC; b) SFRC-GFRP segment

The final crack pattern after the point load test is shown in Figure 9, for both the segments SFRC and SFRC-GFRP. Similar patterns were registered. The first cracks appeared for a load level of 1250 kN (for each steel pad) between two pads at the top and lateral surfaces (Figs. 9a and 9b), in both the cases. Besides the splitting cracks (between the pads), a bursting crack (under the point load), formed in both the cases.
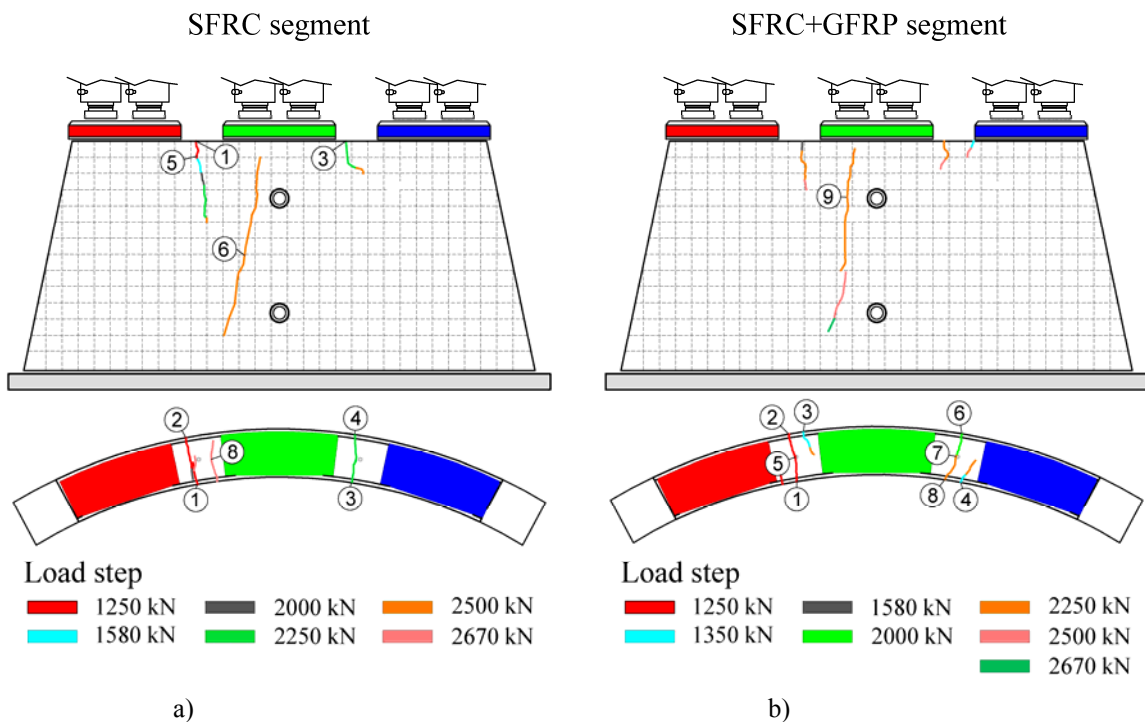

Figure 9. Point load test; Crack pattern: a) SFRC segment; b) SFRC-GFRP segment-

Finally, the crack widths measured for the segments SFRC and SFRC-GFRP, at three significant load steps (related to the first cracking, service load and maximum TBM thrust load), are compared in Table 2.

The addition of the perimetric cage led to halve the crack width under the service load, and to reduce it of about 37.5%, under the unblocking thrust force. Furthermore, a reduction of the crack width of about 33% was measured after the complete unloading.

Table 2. Maximum crack widths: comparison

Load		Maximum crack width [mm]	
		SFRC	**SFRC -GFRP**
1st crack [kN]	1250	0.05	<0.05
Service load [kN]	1580	0.10	0.05
Unblocking thrust*[kN]	2670	0.40	0.25
Unload [kN]	0	0.15	0.10

Note: * For metro tunnel, TBM pushing capacity coincides with unblocking thrust

5 Concluding remarks

The experimental results of full-scale tunnel segments, subjected to flexural tests and TBM thrust actions, presented in the paper, allows to draw the main concluding remarks listed in the following.

1. The results of bending tests, clearly show the synergic effects of the two materials (fibers and GFRP reinforcement) by increasing the peak load and reducing the crack width.
2. The results of the point load test confirm the effectiveness of the solution, since the addition of the perimetric cage led to halve the crack width under the service load, and to reduce it under the unblocking thrust force, and at the complete unloading, respectively.

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