Fiber Reinforced Concrete for Tunnel Linings

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1. INTRODUCTION

Underground infrastructures play a relevant role in the modern society; the pressing need of improving existing public transportation systems and satisfy the increasing transportation demand has brought more and more attention on these infrastructures. Consequently, bored-tunnelling is a good solution in order to reduce the hindrance to infrastructure above ground and to the environment. The excavation process can be done with conventional methods or with mechanized full face methods. When using excavation techniques with Tunnel Boring Machines (TBMs), linings are made of precast segments that are subjected to temporary and final loading conditions [1, 2]. For obtaining a time optimized and cost-effective structure the attention of designers and researchers has been focused on new materials such as High Performance Concrete and, in particular, to Fiber Reinforced Concrete (FRC). For structural purposes, Steel Fiber Reinforced Concrete (SFRC) is widely utilized, even though some types of synthetic fibers have been recently introduced in the market. FRC represents a competitive design alternative for tunnel linings as it would allow time reduction in handling and placing the curved reinforcement that has to be used in ordinary RC elements. Fibers represent a reinforcement spread out everywhere into the lining (both conventional and segmental), including the concrete cover which needs to be often considerably thick for the fulfilment of the fire protection and durability requirements. Structural fibers provide toughness to the concrete matrix, which involves the ability to resist stresses after cracking, improve impact and fatigue resistance, and make the crack pattern more distributed. FRC could be a reliable solution especially for precast elements (segmental lining) since it favours the industrialization of the production process. Cracking phenomena of concrete elements containing fibers can be accurately represented by non-linear FE analyses based on fracture mechanics (NLFM) [3] [4]. After more than 40 years of research [5] [6] [7], guidelines concerning the structural response of FRC elements are now available [8], [9]. Recently, within fib (Fédération Internationale du Béton), the Special Activity Group 5 (SAG 5) is preparing the New fib Model Code [10] that aims to update the previous CEB-FIP Model Code 90 [11]; the latter can be considered as the reference document for many international building codes and, in particular, for Eurocode 2 [12]. The New Model Code includes several innovations and addresses, among other topics, new materials for structural design. Due to a better knowledge of FRC and the significant advantages provided by this material in structural design, SAG 5 decided to introduce some sections on FRC. For this reason, fib TG 8.3 “Fiber reinforced concrete” and TG 8.6 “Ultra high performance fiber reinforced concrete” are preparing the sections concerning FRC characterization.
and design rules [13]. Accordingly, it clearly turns out that FRC is becoming a new material for several structural applications, including tunnel linings.

Tunnel segments are generally reinforced with conventional rebars that are placed in r.c. elements to resist the tensile stresses both at Serviceability (SLS) and Ultimate (ULS) Limit States.

As far as the service conditions are concerned, in recent years durability issues have become of paramount importance. Durability design generally requires rebars protection against corrosion that can be achieved by reducing concrete porosity and crack width. The former can be obtained by using a matrix with a low water/cement ratio while the latter can be achieved by using a diffused reinforcement; to this aim, fiber reinforcement may represent an optimal solution since it is diffused in the concrete matrix.

As far as the ultimate conditions are concerned, localized stresses (due to bending actions) are better contrasted by localized reinforcement (rebars) while diffused stresses are better resisted by diffused reinforcement as fibers. For the reasons mentioned above, since both localized and diffused stresses are present, an optimized reinforcement for tunnel linings can be obtained by using a combination of conventional (rebars) and fiber reinforcement.

The present paper aims to summarize some of the main issues concerning the design process of tunnel linings pointing out the attention to the beneficial effects due to fiber reinforcement.

2. SEGMENTAL LINING

The design process of segmental concrete linings in ground conditions often refers to ring models under the standard load cases of embedded ground condition and of the grouting process. Nevertheless, beside these loading conditions, other possible mechanisms, occurring during the construction process, may govern the structural size and may explain the crack patterns that are frequently observed in practice in tunnel segments. These loading conditions are mainly related to the thrust jack forces applied during the TBM operations or to the torsion effects caused by the out-of-round lining rings outside the TBM shield during the grouting process [14]. Although the application of the thrust jack forces is a temporary loading condition during construction, it may govern the structural size.

The optimized reinforcement for tunnel segments provides the necessary flexural capacity by means of the rebars and enables a better crack control and a significant reduction of stirrups (necessary for shear and splitting stresses) by means of fiber reinforcement [15].

In order to evidence the benefits from an optimized reinforcement in tunnel segments, the particular case of the thrust jack phase is considered herein.

Nonlinear numerical analyses based on smeared crack approach [16] were carried out by considering different loading and boundary conditions as well as reinforcement combinations.

The TBM is pushed forward by thrust jacks acting on the last ring placed in the lining. These forces are required to compensate the friction forces on the shield and the ground and water pressure present at the front of the machine. Previous research works clearly evidenced the beneficial effects of SFRC in presence of load concentrations and splitting phenomena that arise in tunnel segments because of the introduction of thrust jack forces [17], [18]. In fact, splitting cracks may occur, and, although there is no danger for tunnel collapse, these cracks may cause leakage. In addition, because of the thrust jack forces, spalling of the segment edges may occur; this is the result of high concentrated forces in the concrete cover, which is not reinforced when using conventional reinforcement; on the contrary, in SFRC segments fibers are spread also in the small concrete covers and may contrast spalling cracks.

Some examples of cracks that typically appear in segmental tunnel linings are shown in Figure 1: it should be noticed that the concrete cover can be spalled off along the edges of the segments and that longitudinal cracks may occur over almost the entire depth of the ring. Possible causes of these cracks could be the eccentricity or the inclination of the thrust jacks with respect to the longitudinal axis; in fact, by considering these possible irregularities, a different local splitting and spalling behaviour is expected.

Moreover, it is expected that segments belonging to the same ring can hardly stay in a perfect plane because of the irregularities that are normally present (Figure 2a). Generally designers study this temporary stage by referring to an ideal loading condition where the thrust jacks are perfectly placed and also the supports on the rear face of the segment are exactly located on the bearing pads. Since different thrust jack configurations can be used (French, German and Japanese), the stress concentrations in the tunnel lining may take place differently.
Figure 1. Cracks that typically appear in segmental tunnel linings during the construction phase.

(a) (b)

Figure 2. Possible gap between rings due to a no-perfect placing process (a); possible irregular support configuration, so-called un-even supports (b).

In practice, the tunnel segments are not supported uniformly by the previous ring and a bending moment may arise (un-even supports of the segments in the ring joints; Figure 2b). This moment, in unfavourable cases, may be a cause of further cracks; therefore, a concentration of rebars is required along the longer segment edges (chords) in order to resist the tensile stresses provoked by the additional bending actions due to the irregularities.

Cracking phenomena in tunnel design can be limited by adopting a further control of the jack position and alignment as well as of the ring planarity; since this is not easily attainable in practice, cracks can be reduced by using a proper combination of SFRC and conventional reinforcement localized in the critical regions. By adopting a proper combination of rebars and fibers, the total amount of reinforcement is generally less or equal to that use in segments reinforced with traditional rebars.

By performing numerical analyses based on non-linear fracture mechanics, the crack development in the segment can be reproduced [19]; numerical results show that the regions where cracks mainly tend to arise are the following:

- under the thrust jacks (loading area) due to splitting stresses;
- between the loading areas due to the spalling stresses. These cracks are principally caused by the curved shape assumed by the segment at this location;
- under the bearing pads.

Each crack type requires special considerations by designer in order to provide a proper reinforcement solution. The solution proposed herein is presented in Figure 3a and is based on:

- a minimum amount of conventional longitudinal reinforcement ($\rho_c=0.2-0.3\%$) to guarantee the necessary flexural capacity at ULS. The longitudinal rebars are concentrated in the chords in order
to guarantee a better behaviour with respect to spalling cracks that can appear in the segment in the normal conditions but can further increase when irregularities occur. The conventional longitudinal reinforcement is particularly adequate to withstand also the flexural stresses arising during the thrust jack phase in case of very unfavourable supports conditions.

- A minimum amount of stirrups is adopted only for practical reasons in order to better control the tensile stresses arising from the longitudinal curved rebars and to properly place the two chords in the mould. This minimum amount can be further reduced. In fact, by considering the shear forces arising in the lining in case of the embedded ground condition and grouting process, the stirrups can be entirely replaced by SFRC.

![Figure 3. Optimized reinforcement solution proposed for tunnel elements, RCO+steel fibers (a); tunnel segment reinforcement configuration adopted by designers, RC (b).](image)

This optimized reinforcement solution (Figure 3a) is compared with a traditional solution, Figure 3b. The main advantages coming from the use of the optimized reinforcement are the following:

- less storage areas are necessary for the conventional reinforcement;
- the proposed chords are easier to handle and to prepare;
- the fiber reinforcement can be easily introduced in the casting process of the segment, enabling a faster industrialization process.

Besides the advantages listed above, the structural behaviour of the segment tends to improve also in case of unfavourable loading conditions represented, for instance, by eccentricity applied to the lining. An eccentric placement of the thrust jack in radial direction (e.g. caused by a misplacement of the previous assembled ring) may represent a significant loading condition. In particular, the presence of an eccentricity on the outward part of the lining provokes a rotation of the tunnel segment (Figure 4). Consequently, cracks may occur in the middle of the segment because of the superposition of the tensile stresses due to a bending moment related to the segment rotation (Figure 4). Furthermore, splitting cracks under the loading areas seem to occur earlier since the eccentricity determines an applied higher pressure on the outward part of the segment.

![Figure 4. 3D scheme of the dominant mechanism in case of outward eccentricity. Notice that the lining behaviour tends to be governed by bending moments.](image)

Figure 5 shows the development of spalling and splitting cracks in the segment when an outward eccentricity equal to b/6 (b=bearing pad thickness) is present. The comparison between specimens reinforced with fibers only (without rebars) having two different volume fractions (50/1-V_f=0,57% and
50/0.75-Vf=0.32%), the proposed combined reinforcement (RCO+50/0.75-Vf=0.32%) and the solution based on rebars only (RC) is presented. The splitting and spalling crack openings are represented by the relative displacement between two points positioned astride the crack. It is evident that the presence of fiber reinforcement only cannot compete with the longitudinal rebars especially in the regions of the segment between the jacks (Figure 5a). The combined reinforcement proposed (Figure 3a) enables to better control these cracks because of the presence of local longitudinal rebars (concentrated in the chords). In fact, this solution guarantee the same local behaviour of segments with traditional reinforcement. A similar tendency has been found with respect to the development of splitting cracks, as shown in Figure 5b.

The un-even supports (also called non-smooth support) in the ring joint occur for several possible reasons. Beside the no-perfect placement of the last segment (loaded by the TBM's thrust jacks), the non-smooth configuration of the ring joint can be the consequence of the trumpet shape [14]. One of the most severe un-even support configuration corresponds to the missing support in the middle of the segment. This loading condition has been investigated referring to a case study of a railway-tunnel in order to further verify the optimized reinforcement solution proposed (RCO+50/0.75-Vf=0.38%). For studying this very severe loading condition, two supports were localized at the ends of the tunnel segment, as shown in Figure 6, acting on a surface of about 300 x 300 mm² (each); these boundary conditions have been maintained during all the thrust phase (no further supports could arise in the middle of the segment where the deflection is maximum).

![Eccentricity outside](image)

**Figure 5.** Estimation of the development of spalling cracks between the loads (a) and splitting cracks under the load (b).

Figure 7a shows the numerical results in terms of load (from the three actuators of the central segment) versus the deflection measured in the mid-span of the segment; it can be noticed that, although the very
severe loading condition, RCO+50/0.75-Vf=0.38% specimen is able to carry the thrust j act force without failing.

Figure 6. Un-even support configuration adopted for the central precast tunnel segment of the invert.

Figure 7. Comparison of the load-deflection curve (a) and load-crack opening curve (b) obtained from RCO+steel fibers and RC specimens with a two-supports configuration.

On the contrary, RC specimen with conventional rebars is able to carry only 70% of the jack forces; furthermore, the deflection present in the RC specimen is about three times the one measured on the RCO+50/0.75-Vf=0.38% specimen. Figure 7b shows the comparison between the two specimens in term of crack-opening; the latter has been estimated as the relative displacement between two nodes positioned astride the crack (the initial distance between these nodes is 550 mm). The curves clearly evidence the advantages coming from the use of steel fibers, in combination with rebars, allowing for a reduction of the crack-opening. At a load equal to 0.7 times the service load, specimen with optimized reinforcement presents a crack-opening that is ten times smaller than the one present in the RC segment.

3. CONVENTIONAL LINING

The possible advantages offered by SFRC have been preliminary evaluated also for the final lining of a tunnel excavated with conventional method [20]. Generally, these linings are cast-in-place after having previously installed the early stage-linings (e.g.: shotcrete). Besides the main advantages of fiber
reinforcement previously presented for the segmental linings, FRC could also substitute reinforcement along the tunnel (secondary reinforcement) that may be used for stress redistribution.

The behaviour of the final lining has been studied by considering the static load due to the embedded soil by means of a simplified numerical model. In particular, both symmetrical and asymmetrical loads were considered. The regions of the lining between the invert and the benches are crucial, since the tunnel lining section exhibits a change of thickness. Therefore, a reinforcement combination of SFRC (having a volume fraction equal to 30 kg/m$^3$) and conventional rebars, localized in these critical regions was proposed. This optimized reinforcement (RCO+F30) enables a reduction of about 15% of the total amount of steel reinforcement with respect to the configuration usually adopted with conventional rebars (RC), as shown in Figure 8. Notice that rebars are concentrated only in the region connecting the benches and the invert. The proposed reinforcement combines the advantages of rebars for localized stresses, and steel fibers for diffusive stresses.

![Figure 8. Optimized reinforcement proposed for the final tunnel lining based on rebars + steel fibers, RCO+F30 (a); lining with conventional reinforcement only, RC (b).](image)

Since the rebars are basically concentrated in the invert, it turns out that the placement of conventional reinforcement (which is generally quite costly and time consuming) could be limited to the invert. The proposed reinforcement solution for the final lining (RCO+F30) provides the same structural behaviour of the solution with rebars only (RC) and, therefore, allows savings in terms reinforcement weight and construction time.

4. CONCLUDING REMARKS

The present paper shows results of an intensive research on the use of Fiber Reinforced Concrete in both segmental and conventional tunnel linings.

Numerical analyses based on nonlinear fracture mechanics were carried out by using constitutive laws based on the inverse-analysis-method. Similar relationship are present in the draft proposal of fib 8.3 Task Group that is preparing the FRC sections for the new fib Model Code, together with fib TG 8.6.

Due to the presence of both localized and diffused stresses, the optimized reinforcement for tunnel linings is based on the contemporary presence of both rebars and fibers; the reinforcement optimization allows for a reduction of material use and construction time. Fibers are a diffused reinforcement that allows for a reduction of crack width in tensile areas and, as a consequence, an increase of the structural durability. The latter is nowadays of paramount importance due to stringent requirements in terms of service life of the structure and maintenance costs.

In particular, for segmental linings, the optimized reinforcement was verified for severe loading conditions related to the presence of eccentricities of the loading point during thrust jack operations and to the presence of un-even supports in the previous ring. It was demonstrated that the proposed optimized
reinforcement provides the required resistance even under very severe loading conditions while the traditional RC segments do not always provide the required safety. For conventional lining, a combination of SFRC and conventional rebars, localized in the critical region of connection between the invert and the benches, is proposed. This optimized reinforcement enables a reduction of about 15% of the total amount of steel reinforcement with respect to the configuration usually adopted with conventional reinforced concrete (RC).

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