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# Combining fiber-reinforced concrete with traditional reinforcement in tunnel linings

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ABSTRACT

New procedures to design cast-in-situ steel fiber reinforced concrete (SFRC) tunnel linings are briefly presented in this paper. The ductile failure of such cement-based structures is ensured by adding a suitable amount of steel fibers to ordinary steel bars. The capability of SFRC to carry tensile stresses, also in the presence of cracks, allows designers to reduce the minimum area of ordinary steel reinforcement, generally computed in compliance with American or European code requirements. In the serviceability stage, to evaluate crack widths more accurately, a suitable block model is introduced. This model is able to take into account the bridging effect of fibers, as well as the bond slip between steel bars and concrete in tension. The proposed approaches have been successfully applied to the design of tunnel linings in Italy.


## 1. Introduction

In the field of tunneling, steel fiber reinforced concrete composites (SFRC) are mainly adopted for shotcrete, which is a concrete mixture carried under pressure into a closed pipe system, projected against the application surface where it realizes a supporting shell. Only for the last twenty years, have fibers been largely adopted in tunnel linings, as shown by several precast SFRC tunnel segments built all around the world [1].

For the concrete structure of linings, mainly subject to normal and bending actions, usually only minimum reinforcement is required. Thus, their cross-sections reach the ultimate limit state as the first crack grows in the tensile zone. Under these conditions, the maximum tensile force carried by the steel bars is more or less equal to that of SFRC in tension. In fact, due to the presence of fibers, tensile stresses can be present also on the surfaces of wide cracks. This contribution cannot be neglected and can be computed by means of non-linear fracture mechanics approaches [2]. For instance, Rilem TC-162 TDF [3] suggests a smeared approach for the structural analysis of steel fiber reinforced concrete. It is based on the stress–strain relationship ($\sigma$–$\varepsilon$) depicted in Fig. 1, where the post-cracking stage under tensile actions consists of a bilinear softening branch ($\varepsilon > \varepsilon_1$).

By means of the constitutive relationship of Fig. 1, it is possible to define the interaction domains $M$–$N$ (i.e. all the possible combinations of bending moment $M$ and normal force $N$ which a given cross-section is able to bear) of SFRC structures, also in the presence of steel bars (R/SFRC). Such domains have been largely adopted in designing steel fiber reinforced tunnel segments. Due to the presence of fibers, the area of rebars, the thickness of the segments, as well as the global cost of tunneling, can be considerably reduced [4]. Moreover, from a structural point of view, thinner linings are desirable if buckling failure under service and local crushing produced by the TBM jack loads do not occur. In this way, it is possible to reduce bending moments, increase the membrane effect, and induce a greater support reaction of the soil [5].

Several laboratory tests performed on arches and curved beams, under load-control or displacement-control methods, have shown the effectiveness of steel fiber reinforcement. This is evident both at failure and during the serviceability stage, with and without ordinary reinforcement in tensile zones [6,7]. Therefore, in SFRC precast tunnel segments, the conventional amount of steel bars can be significantly reduced, and sometimes can be eliminated completely [4]. However, during the excavation of a tunnel, precast segments are subjected to compression loads produced by the tunnel boring machine (TBM), whose direction is orthogonal to soil actions. Frequently, due to an unpredictable discrepancy between the axis of the TBM thrust and the reaction of the elements already in place, segment failure can occur. Only with the presence of

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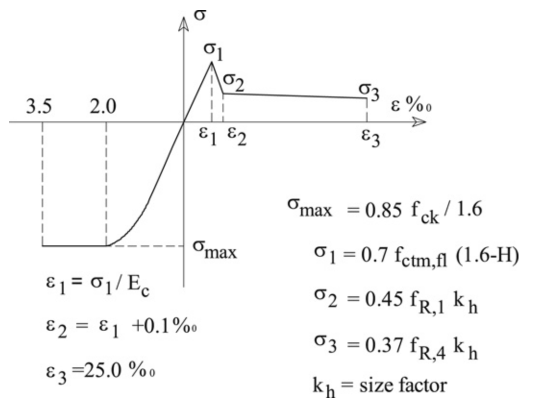


**Fig. 1.** The stress–strain relationships of SFRC proposed by Rilem TC 162-TDF [3].

conventional reinforcement, can such a failure be avoided [8]. However, a suitable combination of normal reinforcement and fibers can reduce the total amount of steel, which could be limited to bars along the borders of segments, where the TBM thrust is applied [9].

'Although the design of cast-in-situ tunnel linings appears simpler than in the case of precast segments, just few experiences of cast-in-situ SFRC linings are reported in the existing literature [10, 11], in which however neither the design procedures, nor the structural advantages of using steel fibers are described. Nevertheless, if steel fibers are added to reinforced concrete (RC) structures, steel reinforcing bars, as well as construction time, can be significantly reduced. In fact, the reduced reinforcement can be placed only in the tensile zone of the covering structure. This solution, obtained by means of pre-curved self-sustaining steel meshes, provided a very rapid advancement of the lining structure [12].

In this paper, new design procedures, successfully applied in Italy in two different cast-in-situ SFRC tunnel linings, are described.

## 2. The minimum reinforcement ratio

In the tensile zone of concrete beams in bending, steel fibers can contribute to sustain stresses, even in the presence of wide cracks. This is particular evident in the experiments of Falkner and Henke [13]. These Authors tested, in four-point bending, two different beams (Fig. 2(a)): the R/SFRC beam is a concrete beam reinforced both with one ordinary reinforcing $\Phi$6 mm bar and with steel wire fibers with hooked ends (40 kg/m$^3$; fiber length $l_f = 60$ mm; fiber diameter $d_f = 0.75$ mm, ultimate tensile strength $f_u = 1050$ MPa). The RC beam is a similar beam without steel fibers. The effect of fibers (segment AB) can be estimated, for a given value of the midspan deflection, by subtracting the load on R/SFRC beam (segment AD) from that on RC beam (segment AC). This difference, depicted in Fig. 2(a), is extremely small at first cracking (during the serviceability stage) and is a maximum at failure. In other words, only for wide cracks is the response of the RC beams substantially modified by the presence of fibers. Therefore the ultimate bending moment $M_u$ of lightly reinforced beams can appear higher than the effective cracking moment $M_{cr}$, in fiber reinforced beams, whereas it is lower in ordinary concrete beams (Fig. 2(b)). As a consequence, the minimum reinforcement area $A_{s,\min}$ of R/SFRC beams can be lower than that required for ordinary concrete structures according to Eurocode 2 [14] and ACI 318-95 [15].

This is particularly true for tunnel linings, whose massive cross-sections require a large amount of steel, if $A_{s,\min}$ is trivially computed with the approaches adopted by the American and European building codes.

To avoid a large amount of steel bars, $A_{s,\min}$ should be evaluated with more rigorous approaches. This is also possible within the frame of Eurocode 2 [14], which states that standard models for a minimum reinforcement area have to be adopted unless more rigorous calculations show a lesser area to be adequate.

For these reasons, in the case of R/SFRC massive cross-sections of tunnel linings, a nonlinear approach has been proposed by Chiaia et al. [12]. It exploits an iterative procedure, where $A_{s,\min}$ is obtained by equating the cracking ($M_{cr}$) and the ultimate ($M_u$) bending moments (Fig. 2(b)). In the model, the effect of fibers, which mainly affect the ultimate stage [5], is modeled through the $\sigma$–$\varepsilon$ relationship shown in Fig. 1. Both with and without steel fibers, $M_u$ is always equal to the yielding moment. Thus, at failure, tensile strains are usually localized in a single crack. With such a definition of failure, the presence of fibers does not reduce the required ductility, as conversely observed in ordinary reinforced concrete beams [16].

Possible values of $A_{s,\min}$, referred to the cross-section depicted in Fig. 3(a), are reported in Fig. 3(c). In the same Figure, the results obtained with the proposed model are compared with those obtained by standard approaches for R/SFRC [3] and RC structures [15]. The mechanical properties of SFRC, used to define the $\sigma$–$\varepsilon$ relationship of Fig. 1, are summarized in Fig. 3(b). If compared to the values provided by the proposed approach, the code requirements seem to overestimate $A_{s,\min}$. The difference increases with the increase of compression actions ($N_{sd}$ in Fig. 3(c)). In presence of high values of $N_{sd}$, steel reinforcing bars even become unnecessary.

The effectiveness of this nonlinear approach can be checked indirectly by observing real scale structures. This is the case, e.g., of the Craviale tunnel in Italy [12], where the cross-sections, made with a combination of FRC and steel rebars and designed in accordance with the proposed procedure, are schematically represented in Fig. 4(a). The lining was cast in 2005, and has been working efficiently since then, without any problems (Fig. 4(b)).

## 3. Cracking control

When steel reinforcement bars are placed in a concrete structure, the evaluation of crack width and crack spacing is generally required in the serviceability stage. Crack width shall be limited in order to avoid corrosion of the steel reinforcement. The presence of fibers in the concrete cast can be a way to achieve this result, since they remarkably increase the bridging action across a crack.

However, new mechanical models are needed to compute these effects, which are generally neglected by the classical approaches [14,15]. Code requirements are based on semi-empirical formulae, in which the average structural performance is analyzed by referring to a single cross-section, instead of a wide portion of an R/SFRC or RC element in bending. As a result, both crack width and crack length are overestimated. In other words, block models, like those proposed by Fantilli et al. [17] for reinforced concrete beams in bending, and by Fantilli and Vallini [18] for R/SFRC members in tension, yield more reliable definitions of crack patterns.

In order to evaluate the possible crack width in R/SFRC tunnel linings, a block model can be also defined for massive structures subjected to combined compressive and bending actions (Fig. 5). In Fig. 5(c) a portion of the beam between two consecutive cracks at incipient cracking is depicted. In this situation, the tensile strength $f_{ct}$ is reached at the central cross-section of the block.

If the constitutive relationship $\sigma$–$\varepsilon$ of the materials, the cohesive law $\sigma$–$w$ (Fig. 5(a)), and the bond slip relationship, $\tau$–$s$, between rebars and concrete (Fig. 5(b)) are known, a discrete structural analysis of the block can be performed. To be more