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Reinforcement optimization of fiber reinforced concrete linings for conventional tunnels

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ABSTRACT

Tunnel linings are generally reinforced with conventional rebars that are placed to resist tensile stresses. As far as the service conditions are concerned, in recent years durability issues have became of paramount importance, especially for underground infrastructures. Durability design generally requires rebar 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, discrete fibrous reinforcement may represent an optimal solution. In fact, the addition of fibers into concrete may provide noticeable residual tensile strength at a crack, linking the two adjacent faces of any crack due to the bridging effect provided by its enhanced toughness. The latter also provides a significant resisting contribution against diffused tensile stresses acting in the structural element. However, when localized stresses (due to bending actions) occur, they are more efficiently resisted by localized reinforcement (rebars).

Within this framework, this paper aims at investigating the behavior of FRC final tunnel linings, excavated with conventional method. Numerical non-linear analyses were carried out by considering different load conditions in order to achieve a reinforcement optimization based on the combination of conventional (rebars) and fiber reinforcement (FRC). The procedure is applied to a real case of a road tunnel.

1. Introduction

Fiber reinforced concrete (FRC) is a composite material with a cementitious matrix and fibers as discontinuos reinforcement. FRC is gaining an increasing interest within the concrete community for the reduced construction time and labors costs. Besides cost issues, it is well recognized that fibrous reinforcement significantly improves the mechanical performances of concrete as numerous researches have demonstrated its effectiveness in many structural applications, both with reference to Serviceability Limit States (SLS) and Ultimate Limit States (ULS). For these reasons, many structural elements are now reinforced with fibers as partial or total substitution of conventional reinforcement (rebars or welded mesh, [1]). The recent inclusion of FRC in the *fib* Model Code 2010 [2], in national codes as well as the organization of conferences devoted to FRC [3–5] confirms this positive development.

FRC considerably improves the concrete post-cracking behavior due to the remarkable residual post-cracking strength related to the enhanced material toughness. The latter is a performance based parameter useful for designers and depends on the fiber content, material and geometry as well as on the concrete matrix [2]. FRC toughness can be determined by means of fracture tests [6–8]. However, fibrous reinforcement in combination with conventional rebars is particularly effective in terms of crack control, since a more distributed crack pattern characterized by reduced crack widths could be achieved [9]; this solution is also quite suitable in terms of structural strength since both diffused (resisted by fibers) and localized (resisted by rebars) stresses are generally present.

In the field of tunneling, the construction of tunnel lining in a short time (to remain within the project schedule and budget) and in safe condition is a crucial issue in order to reduce the hindrance to infrastructure above the ground and to the environment as well as to guarantee durable and economic concrete structures. For these reasons, fibrous reinforcement can be a competitive solution in linings for tunnels excavated with both conventional and mechanized methods [10–14].

Conventional tunneling is generally carried out in a cyclic execution process of repeated steps of excavation followed by the application of relevant primary support, both of which depend on the existing ground conditions and ground behavior. The void should be fully stabilized with the first phase support (primary support system), which is designed to maintain a stable excavation

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so that a permanent lining can be placed [15,16]. The latter usually consists of cast-in-place lightly reinforced massive concrete structure subjected to bending and axial actions and is designed to stand for the whole life of the structure (final lining).

While FRC is already widely used in primary support system as sprayed concrete (shotcrete), it is not commonly used in cast-in-place final linings and only just few experiences are reported into the literature [17–19]. Some studies concern design provisions of final lining cross-section to evaluate the benefits from steel fibers on crack control [20,21].

Actually, the presence of fibrous reinforcement allows for time reduction in fabrication, handling and placing of the curved rebars that has to be placed in cast-in-place and segmental linings. Furthermore, fibers represent a reinforcement spread out into the structure, which could substitute the reinforcement placed along the longitudinal tunnel axis (secondary reinforcement) that is generally used for stress redistribution. Since fibrous reinforcement is particularly effective for diffused stresses [11,12] while rebars represent an optimal reinforcement for localized stresses, it is of main interest the evaluation of a proper combination of fibers and rebars in order to achieve a reinforcement optimization, as proposed in other research works concerning precast tunnel linings [13,14,22].

To this aim, in the present paper several combinations of reinforcement have been investigated by means of non-linear numerical simulations, which are suitable for taking into account the residual strength provided by fibers after cracking. The numerical analyses have been developed by using a global load progressive increment up to failure. In order to evaluate the bearing capacity, the development of crack patterns, the post-cracking stiffness as well as the collapse mechanism, the structural analyses refer to a real case study of a cast-in-place final lining. Based on the initial design solution [23], the typical static loading conditions were numerically simulated. It is shown that, by adopting a combination of steel fibers and traditional reinforcement placed in appropriate regions, an optimized solution can be achieved, which guarantees the required structural performance at both SLS and ULS, by reducing the amount of reinforcement globally used. Besides reinforcement savings (in terms of weight), this reduction also allows labor savings and limited areas for the reinforcement storage.

2. Case study: Turina tunnel

The "Turina" road tunnel, which is part of the infrastructures of a 3.5 km long road project, is taken as a reference case study herein. The road section is 13 m wide and is made of two 3.75 m lanes, a hard shoulder (1.50 m wide) and a wide curb for each lane (1.25 m wide). The "Turina" tunnel is 665 m long, with an internal diameter of 12.6 m (Fig. 1a) and it is excavated by means of conventional tunneling method.

The tunnel is located in a geo-mechanical group consisting of poor rock mass conditions and alluvial deposits. The most critical sections investigated are positioned in layers of detritus with poor mechanical properties and alluvial deposits having an unsure location with respect to the surrounding sub-layer of weak rock. The average tunnel overburden for these sections is approximately 40 m. Due to these uncertainties and the severe ground conditions, the injection-type fore-poling method (umbrella) was suggested by designers in the preliminary tender project [23]. Fig. 1b shows the longitudinal profile of the tunnel; it is evidenced that the injection-type fore-poling method (umbrella) was adopted. Steel pipes with a length of about 12 m, a diameter of 114.3 mm and a thickness of 10 mm were driven at the tunnel crown. Consequently the thickness of the arch (crown) cyclically varies along the tunnel layout as shown in Fig. 1a and b. On the contrary, the invert thickness is constant and is equal to 900 mm (Fig. 1a).

More in details, the following construction sequence was considered:

- Placement of sub-horizontal steel pipe umbrella and fiberglass bolts for providing temporary support and face reinforcement, respectively.
- Excavation of the heading of the tunnel.
- Construction of the early stage lining (primary support) consisting of fiber reinforced shotcrete and steel ribs.
- Casting of the temporary invert.
- Excavation of the invert of the tunnel and construction of the corresponding first phase lining.
- Casting of the invert of the final lining.
- Casting of the benches and subsequently of the arch (crown) of the final lining.

The present study focuses on the behavior of the final lining with particular reference to the static load due to the surrounding ground. In particular, both symmetrical and asymmetrical loads were considered; the latter load distribution represents lining sections along the track, which exhibit asymmetrical lateral ground cover, in proximity of the valley walls.

3. Materials

In the first final lining design [23], the minimum concrete characteristic cubic strength required ($f_{ck,cube}$) was 30 MPa. In order to quantify possible benefits from the use of FRC, an experimental campaign [24] was developed at the laboratory for testing materials of the University of Brescia on fibrous and non-fibrous

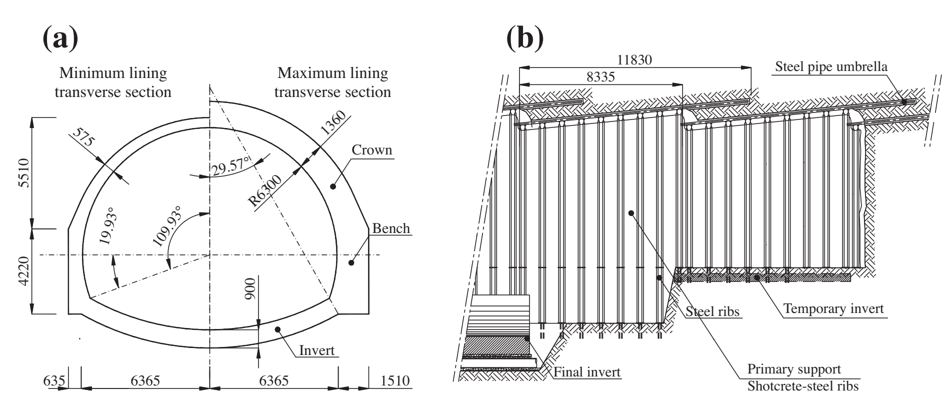

Fig. 1. Scheme of the transverse section of the final tunnel lining (a); simplified scheme of the longitudinal tunnel profile with evidenced the fore-poling method (b).