Evaluation of the response of concrete tunnel linings subjected to fire: a three-dimensional approach

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Abstract

This work is focused on the development of a refined nonlinear constitutive model for the analysis up to failure of concrete elements subjected to fire, able to account the main features governing concrete behavior, i.e. cracking and crushing. In particular, the model is applied to the structural assessment of unreinforced concrete tunnel linings in order to deal with all the different stages of tunnel life, from its construction to its service conditions, also taking into account the possible development of a fire and its effects on the lining system. The reliability and accuracy of the proposed model are checked against analytical closed-form solutions.

1 Introduction

Finite Element (FE) analysis represents a powerful tool that allows solving different types of structural problems, and it is experiencing an increasing diffusion even for tunnel design. While in the past the study of tunnel behavior was often afforded through empirical methods and closed-form analytical solutions, nowadays two-dimensional FE models are ordinarily used for the evaluation of ground settlements, as well as for the determination of the stress field in temporary and final support systems (among others, e.g., [1]–[3]). Even though tunnel excavation is a three-dimensional problem, especially near the excavation face, the diffusion of 3D FE analyses has been instead quite limited in the past, mainly due to their complexity and long calculation times [4]. Nowadays this type of approach is becoming more common especially in the research field, thanks to the recent advancements in computing resources, together with the unquestionable advantages related to the generality of the method. 3D analyses allow indeed a detailed representation of tunnel excavation and support installation phases, taking into account in a realistic way the ground-support interaction, the actual geometry of the opening, the presence of different geo-mechanical units around the tunnel, as well as realistic constitutive laws for the involved materials (e.g. [5], [6]).

More or less sophisticated FE models also represent the main strategy to deal with another relevant research topic related to tunnel design, i.e. the analysis of lining behavior during and after fire development. The scientific community, together with the designers, is showing an increasing interest towards this problem, due to need of mitigating fire hazard in transportation structures, which has grown due to the rapid urbanization and to the increase in shipping of fuel and chemical products [7].

When considering unreinforced concrete linings, the most critical design issue is represented by cracking [8]; thus the use of sophisticated constitutive law for concrete able to represent the most important nonlinear effects and parameters, such as crack width, is mandatory.

Aim of this paper is the development of a refined non-linear constitutive model for the analysis up to failure of concrete elements subjected to fire, able to account the main features governing concrete behavior, i.e. cracking and crushing. To this aim, an existing total-load secant-stiffness formulation suitable for Non-Linear Finite Element Analysis of in-plane stress elements is herein extended to manage the behavior of concrete under high temperatures. This model, which is based on a smeared, fixed crack approach, enables to account in a realistic way all the resistant mechanisms that take place after crack formation, giving a reliable estimate of crack width.

The developed model is applied to the structural assessment of concrete tunnel linings by performing 3D FE simulations, so as to manage all the different stages of lining construction and use, that is to say its installation during the excavation process, its service life after the completion of the excavation phase, and the possible occurrence of fire spreading. The problem is tackled by performing a nonlinear structural simulation that considers both ground-lining interaction and temperature-induced effects (i.e. thermal strains, as well as the decay of strength and stiffness of concrete during heating).

Thanks to its generality, the work described in this paper could represent the first step in the development of a comprehensive methodology for simulating, analyzing and assessing the structural response of unreinforced concrete tunnel linings, to be used for handling complex design cases. However, in this initial stage, it has been chosen to apply the above described modeling strategy to a simplified theoretical case study, so to allow an easy check of its reliability through comparison with analytical approaches [9]–[11], obtaining promising results.

2 Case study and modelling procedure

As mentioned before, the proposed procedure is applied to the simplified case of a circular tunnel supported by an unreinforced concrete lining, subjected to standard fire. The following assumptions are made: deep circular tunnel with 5.15 m external radius and 100 m overburden; natural isotropic stress state ($K_0 = 1$); support system only constituted by a 300 mm concrete ring (which can be regarded as a single shell spayed concrete lining [12]); standard ISO 834 fire curve. For the surrounding ground, which is assumed to correspond to a marble rock mass with a GSI index of 30, the most recurrent values suggested in technical papers and handbooks for a similar rock type are adopted. The main mechanical properties assumed for the rock mass and the concrete lining are summarized in Table 1.

Table 1 Mechanical properties assumed in FE analyses for the rock mass and the concrete lining.

Rock mass					Concrete lining	
γ_r [kN/m^3]	E_r [MPa]	ν_r	ϕ	c [MPa]	$\gamma_{c,20}$ C° [kN/m^3]	$f_{c,20}$ C° [MPa]
25	5200	0.25	50	0.30	25	37

2.1 Simulation of excavation and lining installation phases

The attention is initially focused on the simulation of tunnel behavior during its realization and service life, before fire development. The main goal of the analysis is limited here to the evaluation of soil-structure interaction and to the determination of the stress state within the lining system; however, the same procedure can be also used to face other design issues. For example, it allows the evaluation of an effective and safe unsupported distance between the excavation face and the lining, or the assessment of the influence of the adopted protective measures on possible ground settlements (especially for shallow tunnels) and face deformations.

Figure 1 shows a general view of the adopted FE mesh, which is kept the same for all the phases of simulations. Since symmetric loading conditions are assumed in this study, only one-half of the transverse cross-section of the tunnel and of the surrounding ground is considered. The extent of the FE mesh in the transversal direction is chosen so as to reach steady-state conditions and to eliminate almost any influence of the outer boundaries [5], [6]. Almost the same extent (approximately equal to 5 diameters) is also considered in the vertical direction, above and below tunnel axis. The surcharge due to the overburden not explicitly included in the model is taken into account by applying an external pressure to the upper boundary of the FE mesh.

The rock mass and the concrete lining are respectively modeled through 6-node triangular prismatic elements (Fig. 1a) and 4-node shell elements (Fig. 1b), connected to each other by means of surface-based ties placed on the perimeter of the opening. In this way, all the active degrees of freedom for the pair of surfaces (i.e. lining and ground surfaces) are made equal during the simulation by connecting the corresponding nodes of the two reference surfaces, so avoiding any relative motion between them. Since the default reference surface of the shell elements coincides with their mid-surface, an offset is assigned between the shell middle plane and the reference surface in order to properly represent the lining thickness and avoid element interpenetration. Still concerning shell elements, a reduced integration technique – with one Gauss point – is adopted in the element plane, while 19 Simpson integration points are considered throughout the thickness. The use of a high number of integration points within lining thickness is not strictly needed for the analysis of lining behavior during the installation stage, but it becomes necessary when considering fire load, so as to properly describe the temperature distribution within the concrete ring and the related hoop stresses. A refinement of the integration points is provided near lining intrados, where the maximum temperatures and stress gradients are expected, by subdividing each shell element into several layers with decreasing thickness towards the bore side.

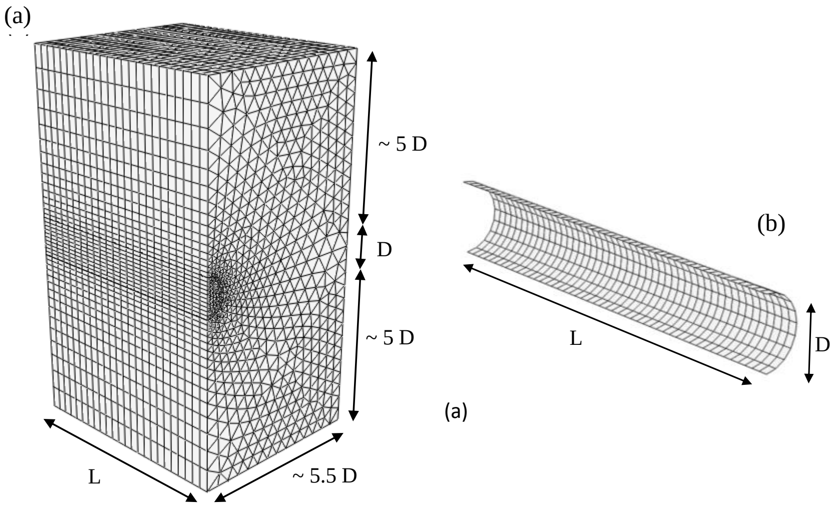


Fig. 1 (a) Adopted 3D FE mesh; (b) Detail of lining discretization.

2.1.1 Material constitutive laws

Ground behavior is modelled by using a Mohr—Coulomb elasto-plastic constitutive law with the parameters reported in Table 1, assuming drained conditions.

The nonlinear response of concrete in both tension and compression, together with the two associated failure mechanisms (that is cracking and crushing, respectively), is instead managed through 2D-PARC model, implemented as a User MATerial (UMAT) subroutine within the adopted FE code ABAQUS, (see [13], [14] for details). This model represents a very versatile tool for analyzing unreinforced, reinforced and fiber-reinforced concrete structures, and can be successfully adopted also in case of tunnel analysis, to improve/refine the design procedure [6]. For example, 2D-PARC is able to represent, in a realistic way, all the resistant mechanisms that take place after crack formation. It provides a reliable estimate of crack width, which is a variable of paramount importance not only for unreinforced concrete linings and sprayed concrete ones [8], [15], but also in presence of reinforcement, for the fulfillment of durability issues [6], [16]. Moreover, 2D-PARC model can be used to simulate the progressive hardening of concrete during the construction phases, which can be a quite important aspect in the evaluation of the performances of shotcrete temporary linings, as well as of sprayed concrete permanent linings. To this aim, concrete strength and stiffness are varied during tunnel advancement, by inserting concrete properties as a function of time in the adopted algorithm, so taking into account the time dependent development of stiffness and strength according to EC2 relations [17].

2.1.2 Loading sequence

Tunnel excavation and subsequent lining installation are modeled through a step-by-step procedure [5], [6]. At the beginning of the analysis, all the shell elements representing the lining are deactivated, and the lithostatic load is applied to the rock mass. From the second step on, the model simulates the progressive stages of excavation and support installation, so reproducing the stress-strain field deriving from the advancement of the excavation face. Tunnel excavation starts from the external cross-section of the model (Fig. 1), through a progressive deactivation of solid elements corresponding to tunnel opening (one "slice" of rock elements is switched off in each step of the analysis). Meanwhile, lining installation is simulated by switching on a ring of shell elements, hypothesizing an unsupported distance from the excavation face equal to 2.5 m. These excavation and lining installation phases are then repeated alternatively until the tunnel is fully excavated.

2.2 Simulation of fire effects

The study of the structural response of concrete linings under fire cannot be performed by simply applying the former nonlinear analysis procedure, but some extensions and modifications are required, especially related to material constitutive relations.

The analysis procedure followed in this work is based on the basic assumption that the temperature distribution in the studied element is independent from its structural behavior, namely the thermal field affects the stress and displacement variables, but not vice-versa. In this way, it is possible to first perform a heat-transfer analysis, and subsequently pass the temperature solution – which varies with time, as well as with position, in the lining thickness – to the mechanical analysis as a predefined field. In this way a so called "sequentially-coupled thermo-mechanical analysis" is performed so determining the stress evolution in the lining during fire exposure.

2.2.1 Thermal analysis

The heat-transfer analysis takes into account all the three mechanisms ruling heat-transfer: conduction, convection and radiation. This requires the specification of material thermal properties as input parameters, by exploiting the relations suggested by Eurocode 2 [18] for concrete (referring to a moisture content of 1.5% by weight, and to the lower limit of the thermal conductivity), and assuming typical average values taken from technical literature for the surrounding ground.

Temperature evolution with time is ruled by a proper standard fire curve, representing a "nominal" fire scenario. Since Eurocode 2 [18] does not provides explicit suggestions for tunnel fire loading, the classic ISO 834 curve is first applied, by considering a fire duration of 120 min. As known, ISO 834 fire curve is largely adopted for structural applications and testing, and it is also suggested for tunnel design by ITA-AITES Guidelines [19], at least when the expected traffic type is mainly represented by cars and small vans. However, numerical analyses are also repeated by considering the RWS fire curve, which was specifically conceived for fires developed by large vehicles, such as trucks or tankers, in an enclosed environment; thus, it is able to represent the initial and fast temperature increase, typical of tunnel fires. For sake of simplicity, in this work the prescribed temperature field is uniformly applied to the inner surface of the lining, along its whole perimeter and length. This choice is related to the need of checking the effectiveness of the numerical model developed in this work with analytical closed-form solutions, which are based on simplified assumptions (e.g., axisymmetric problem, temperature distribution only dependent from the radial coordinate, and not from the angular one). However, by exploiting the three-dimensional features of the model, a more realistic fire scenario could be considered, e.g. through the application of sophisticated fire safety engineering methods.

2.2.2 Mechanical analysis

As regards the mechanical analysis, it is structured into two main steps, corresponding to the excavation phase and the installation of concrete lining (according to the procedure already described in Section 2.1), and to the subsequent application of fire loading. In this latter step, the transient temperature field derived from the thermal simulation is read by the structural analysis, so allowing the evaluation of the thermal strains in the materials, together with the decay of their mechanical properties.

The simulation of lining behavior under fire conditions is managed through a new developed constitutive model, named "2D-PARC FIRE", which represents an extension of the adopted constitutive law for concrete at ambient temperature (namely 2D-PARC, see Section 2.1.1). As regards the surrounding ground, no modifications are required, since rock mass usually remains at ambient temperature, thanks to the good insulation properties of the lining itself. By properly modifying 2D-PARC algorithm, the additional features connected with fire spreading as regards concrete (i.e. thermal strains and the degradation of mechanical properties due to high temperatures) are correctly managed in 2D-PARC FIRE. The representation of crushing and dilatation are properly adapted for the case of high temperatures, by calibrating the parameters governing the post-peak behavior of concrete, as well as by revising the expressions of the convergence checks of the algorithm. A suitable simulation of these phenomena is mandatory for the analysis of tunnel linings, since concrete may experience high compressive stresses, especially during fire. In order to include thermal strains, the equilibrium and compatibility equations governing the model are reformulated and the material stiffness matrix is consequently rearranged. The followed procedure is herein shortly reported for the considered case of an unreinforced concrete lining; see [20] for further details.

In the uncracked stage, for each integration point, the stress field is derived starting from concrete mechanical strain, thus obtaining:

$$\{\sigma_c\} = [D_c] \left(\{\varepsilon_c\} - \{\varepsilon_{th}\} \right) \tag{1}$$

where $[D_c]$ represents the secant stiffness matrix. The nonlinear isotropic concrete model implemented for the evaluation of matrix $[D_c]$ is herein properly calibrated based on the stress-strain relation of siliceous aggregate concrete suggested in EC2 [18]. The terms of this matrix are indeed properly updated as function of temperature T (previously obtained from the heat-transfer analysis), so as to take into account the dependence of the main concrete mechanical properties on temperature. Vectors $\{\varepsilon_c\}$ and $\{\varepsilon_{th}\}$ in Eq. (1) respectively represent the total strain of concrete and the free thermal strain. This latter, which has a positive sign according to 2D-PARC FIRE conventions, is assumed stress independent and isotropic, with shear component equal to zero, while the other terms are computed as function of temperature T according to EC2 [18]. It is worth noting that transient creep strain (i.e., the additional strain that develops irrecoverably during first-time heating of concrete under load, compared to concrete loaded at elevated temperature [21]), which is generally relevant for tunnels, is implicitly taken into account in the model through the adoption of the Eurocode 2 [18] uniaxial compressive stress-strain relation for concrete at high temperatures.

The transition from uncracked to cracked stage takes place when the current state of stress violates the concrete failure envelope in in the region of prevailing tension. The model follows a smeared, fixed-crack approach in conjunction with a strain decomposition procedure; the total strain $\{\varepsilon\}$ is then subdivided into two components, respectively related to concrete between cracks, $\{\varepsilon_c\}$, and to all the mechanisms taking place in the fracture zone, $\{\varepsilon_{cr1}\}$. All the resistant mechanisms developing across crack surfaces (i.e. aggregate bridging and interlock) are express as a function of two main variables, namely crack width w_1 and sliding v_1, and included into the cracked stiffness matrix $[D_{cr1}]$. This matrix retains the same formal expression as that at ambient temperature (see [13] for details); however, in case of fire, the dependence on temperature of the parameters governing the model is introduced in the algorithm. The behavior of concrete between cracks is described analogously to the uncracked stage, by slightly modifying matrix $[D_c]$ (i.e. reducing concrete compressive strength and stiffness to include concrete damaging due to the presence of cracks). The total stress vector $\{\sigma\}$ is obtained by considering equilibrium conditions of concrete between cracks and at crack location, as well as the compatibility equation on total strain $\{\varepsilon\}$; thus obtaining:

$$\{\sigma\} = \left([D_c]^{-1} + [D_{cr1}]^{-1} \right)^{-1} \left(\{\varepsilon\} - \{\varepsilon_{th}\} \right) . \qquad (2)$$

3 Results and discussion

3.1 Tunnel excavation and lining installation stages

The reliability of numerical results relative to the evolution of the stress state in concrete lining during tunnel construction is proven in Figure 2. To this end, the Convergence-Confinement Method ([9], Fig. 2a) is first applied to determine the equilibrium pressure p^* between the ground and the supporting system. In the construction of the support characteristic curve (SCC), the convergence experienced by the tunnel before lining installation is calculated through the relation suggested in [22], by considering that the lining itself is placed at 2.5 m from the excavation face. Starting from the equilibrium pressure p^*, the hoop stress in the lining at the end of tunnel construction σ_θ^* can be analytically determined by adopting the simplified equation reported in Figure 2b; as can be seen, this theoretical value of σ_θ^* is almost superimposed to the asymptotic one provided by the numerical simulation.

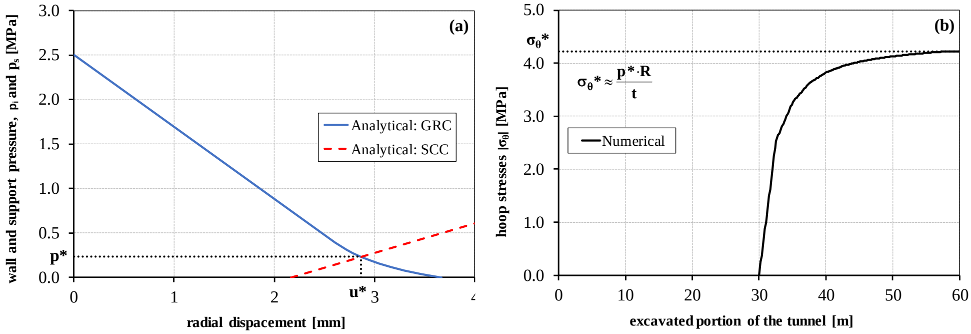


Fig. 2 (a) Analytical [9] representation of the Ground Reaction Curve (GCR) and Support Characteristic Curve (SCC), (b) Numerical hoop stresses in concrete lining.

A closer correspondence between numerical and theoretical results can be obtained by considering more refined analytical solutions; for example, see, e.g., [9]:

$$p^* = \frac{\sigma_\theta^*}{2}\left[1 - \frac{(R_e - t)^2}{R_e^2}\right] \tag{4}$$

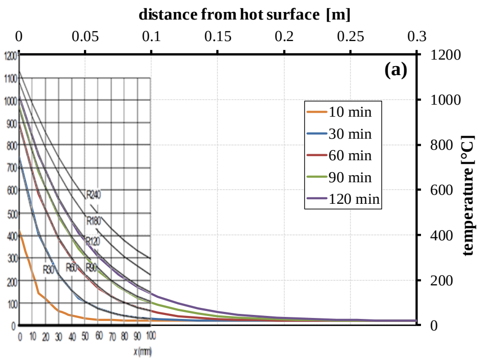
where R_e is the external radius of the support and t is the concrete ring thickness.

3.2 Application of fire load

In this section, the attention is focused on the validation of the modelling strategy adopted for the simulation of tunnel behavior in presence of fire. Numerical results from thermal analysis are compared with solutions provided by design Codes [18], while the main outputs of the mechanical analysis are checked with a closed-form solution based on [10], [11], which has been properly modified in [23].

The nonlinear distribution of temperatures within the lining thickness, for different fire durations (10 min, 30 min, 60 min, 90 min and 120 min), is reported in Figure 3a, showing a close correspondence to the temperature profiles provided in EC2 [18] for concrete slabs. As can be seen, only the first concrete layers (near the opening) are subjected to a high temperature increase, while for the internal parts, nearer to the rock mass, the heating process is very slow due to the good insulation properties of the concrete ring. The corresponding hoop stresses acting within lining thickness are instead reported in Figure 3b, where they are compared with the abovementioned analytical solution [23]. The stress field shows a typical bell-shaped distribution, which is related to the combined effect of the marked decay experienced by concrete mechanical properties at high temperatures – with the consequent stress relaxation near the hot intrados – and of the deformation constraint in the circumferential direction, exerted by the colder extrados. Increasing durations of fire exposure determine a shift of the stress peak along lining thickness, from the hotter layers closer to the heated surface to the colder and farther ones. This translation is attributable to the progressive warming of the concrete ring; the increasing temperatures acting on the exposed surface cause indeed the heat diffusion in the adjacent internal layers, with a consequent degradation of material properties.

Finally, the effects of the application of a more severe fire design curve on lining behavior are pointed out in Figure 4, which compares the temperature distribution within lining thickness, together with the corresponding hoop stresses, produced by the ISO 834 fire curve and by the RWS one. The more pronounced differences can be observed at the beginning of fire exposure, since RWS fire curve is characterized by a faster temperature increase with respect to the ISO curve, together with a higher value of the maximum achieved temperature. For this reason, in the first fire instants (Fig. 4a,d) a larger portion of the exposed lining surface is interested by the fire-induced damage, with a redistribution of stresses within the undamaged colder part of the concrete ring and a consequent translation of the peak of the hoop stress curve. If concrete spalling is not prevented through the adoption proper protection measures, these higher superficial temperatures can also cause a higher spalling rate in the first minutes of fire exposure [24], with a consequent increase in maintenance costs.



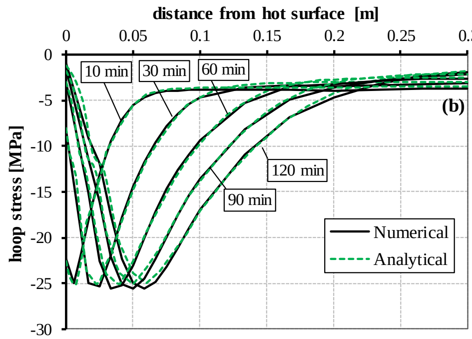


Fig. 3 (a) Temperature distribution across concrete lining thickness: comparison between numerical and EC2 [18] temperature profiles for concrete slabs; (b) Hoop stress distribution across concrete lining thickness: comparison between numerical and analytical [23] results.

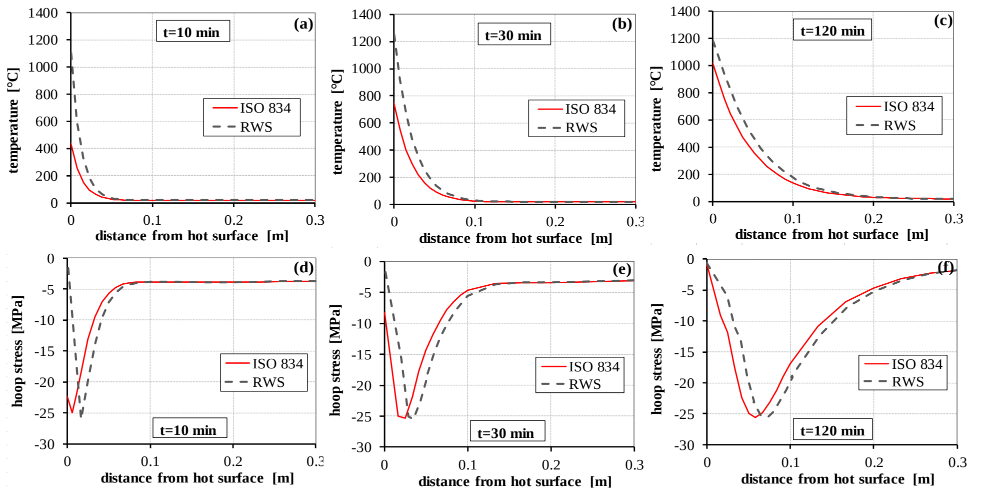


Fig. 4 (a), (b), (c) Temperature distribution and (b), (d), (f) hoop stress across concrete lining thickness at different fire exposure, obtained from 3D numerical analyses considering the ISO 834 and the RWS fire curves.

4 Conclusions

This paper deals with the development of a refined non-linear constitutive model for the analysis up to failure of concrete elements subjected to fire, named 2D-PARC FIRE. In particular, the model is applied to the structural assessment of concrete tunnel linings, both during service life and under fire conditions. Even if the approach described in this paper represents only a first attempt for the development of a comprehensive methodology for simulating, analyzing and assessing the structural response of concrete tunnel linings, the following conclusions can be drawn.

- One of the main advantages of the outlined modeling strategy lies on its generality, since it can be applied to the different stages of tunnel life, from its construction to the possible occurrence of an accidental fire during its normal use. The sequence of soil excavation and tunnel lining construction can be realistically represented through the progressive deactivation/activation of ground and structural elements in the mesh during the analysis steps. Face reinforcing can be taken into account easily by following the same strategy, and also the time dependent development of stiffness and strength of concrete can be considered.

- 2D-PARC FIRE can handle the main features governing concrete behavior, i.e. cracking and crushing, which represent two mandatory phenomena to be considered during the analysis of tunnel linings, both at ambient temperature and under fire load. Within this context, the possibility of correctly managing the occurrence of concrete cracking is very important, since crack control often governs lining design, due to the increasing need of fulfilling durability issues and reducing maintenance costs. On this point, it can be observed that 2D-PARC FIRE model represents an interesting alternative to other constitutive models available in software libraries (as an example, the well-known concrete damaged plasticity in ABAQUS), since it is characterized by a greater computational efficiency and numerical stability, as better discussed in [23]. Moreover, 2D-PARC FIRE is very versatile since it can be also applied to fiber reinforced concrete linings, by simply changing some terms in the stiffness matrices related to concrete [D_c] and to the crack [D_{cr1}], according to [14], without altering its structure, which remains the same described in Section 2.2.2.

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