High Speed Railway Milan – Genoa, implementation of coupled analysis to estimate thermo-mechanical effects produced by the fire on the TBM segmental lining.

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ABSTRACT: The Stretch of the Italian High Speed Railway between Genoa and Milano is currently under construction with more than 78 km running tunnels and will be completed by 2021. More than 20 km of the tunnel excavation will be executed by EPB TBM, with overburden ranging from 5 to 600 m and geomechanical condition varying from hard rock to soft marble. Segmental lining, in precast concrete and polymeric fibers, is characterized by outer diameter of 10 m and thickness of 40 cm. The paper describes the implementation, by FLAC thermal code, of coupled analysis to estimate thermo-mechanical effects produced by fire on TBM segmental lining cross section, applying on the intrados the EUREKA (2008/163/CE) and the RWS (UNI 11076) fire curves, for 120 minutes. Analysis starts from stress-strain conditions at the end of tunnel excavation and permits to model thermal damage and degradation of concrete, with progressive increase of temperature, in accordance with Eurocode 2. The analysis of fire effects on exposed segmental lining are carried out by combining the thermal actions with the rock mass pressure around the excavation, taking into account the presence of segmental joints during thermal analysis.

1 INTRODUCTION

The study of the tunnel final lining behaviour under fire conditions has become certainly one of the most discussed technical topic during the last years. International standards are becoming increasingly aware of the importance of fire events in structural design due also to several accidents occurred in Europe in the recent past.

Figure 1. Damage to structure and vehicles in the Gotthard tunnel Switzerland (2001)

Tunnel behaviour under fire conditions becomes more interesting from a technical point of view since the average lining thickness is decreasing due to the wider application of TBM excavation technology. In this construction method the tunnel lining, usually made of precast reinforced concrete segments, is generally from 250 and 500mm thick.

Simplified models are often a good choice to achieve accurate results and to produce reasonable designs at the same time. However, phenomena such as fire response of structures, mainly in tunnel design, are intrinsically non-linear and simplifications could lead to section oversizing (Cucino *et al*., 2010).

As it is known, the effects of fire exposure are not only related to material degradation under high temperatures or to concrete spalling, but also to the coactions that can arise due to differential thermal expansion.

Several authors have recently dealt with this issue in a complete and detailed way, by performing complex numerical analyses able to well simulate the actual response of the tunnel under fire conditions. The relevant problem of soil-structure interaction is usually taken into account in these works coupling it to the degradation of concrete parameters associated to high temperatures.

In some cases (Lilliu and Meda, 2013) concrete has been modelled with a rotating total strain crack model, in which the stress is defined as a function of the total strain, in order to obtain a more realistic time dependent response of the structure.

In this paper, the design procedure for structural analysis and verification of the "Terzo Valico" TBM lining under fire conditions is described. Analyses are performed with the FDM software FLAC (Fast Lagrangian Analysis of Continua, Itasca 2011) using the thermal option. In the analyses the soil structure interaction coupled with concrete lining degradation parameters (non-linear thermo-mechanical behavior with temperature dependent proprieties) is considered. All failure criterion and advanced constitutive model could be applied to soil or rock surrounding the tunnel, both during stage construction analysis and thermal analysis. Finally the numerical model provides the tunnel lining stress-strain field that could be easily used to carry out static verifications.

The present article outlines a possible modelling procedure that can be applied to fire analysis of reinforced concrete tunnels; this procedure has provided a realistic model response and accurate results if compared with common data available in literature. However, the approach allows the overall structural performance verification, also under fire conditions, maintaining costs and time in the common design range (usually 15 hours for a new completed construction stage analysis and thermo-mechanic fire condition phase, including structural verifications). As it is described below, this issue could be significant if the number of analyses to be performed is high (i.e. different geomechanical contexts or overburden that have to be analysed).

The numerical models also allow to consider the non-continuous geometry of the precast segmental lining of the tunnel through the use of interface elements following a pure friction material model with tension cut-off set to zero.

The development of spalling mechanism during rapid heating of concrete could be considered in the model with two different approaches. On one hand it is possible to consider a cross section reduction according to the estimated spalling depth only in the verification phase: this could be a good alternative for modest section reduction and lead to conservative results. On the other hand, it is possible to model the section reduction directly in the model during fire exposure by a progressive mesh modification deleting elements of the inner layer when typical temperature of spalling is achieved.

2 TERZO VALICO TBM TUNNELS

The Milan–Genoa railway line is included as one of the 30 European priority projects approved by the European Union, known as the "Bridge between two Seas" Genoa–Rotterdam (Pagani and Cassani, 2016). The line runs along the Genoa-Milan route reaching Tortona, and proceeds along the Genova-Alessandria-Turin route up to Novi Ligure, crossing the provinces of Genoa and Alessandria. The "Terzo Valico" (third pass) spans a distance of approximately 53 km and presents particular challenges in terms of construction because of the presence of long tunnels traversing approximately 34 km of the complex Apennine range located between the Piedmont and Liguria.

Both conventional and mechanized excavation will be used for the Terzo Valico tunnels. More than 6,5 km of Serravalle Tunnel will be realized entirely with mechanized excavation, using two 9.73 m diameter EPB TBMs. On the contrary, the excavation of the Valico Tunnel will be carried out using both technologies: conventional excavation from the southern entrances and from the four access adits, and mechanized excavation, using two EPB TBMs of 9.77 m diameter, from the northern entrances. The tunnels are lined with pre-cast 40 cm thick segments in reinforced concrete, connected by circumferential and radial joint connectors and EPDM gaskets to insure water tight conditions. Each ring 1.8 m long consists of 6 "normal" elements plus one "key" segment that allows the closure of the ring. The "universal" ring permits to adapt the ring to any alignment radius, from the minimum to the linear one, by a simple rotation of every ring along the tunnel axis (see Figure 2).

The injection of mortar behind the segments, performed immediately at the beginning of the excavation procedures, helps to avoid the superficial collapse and ensures the correct confinement/bedding of the lining.

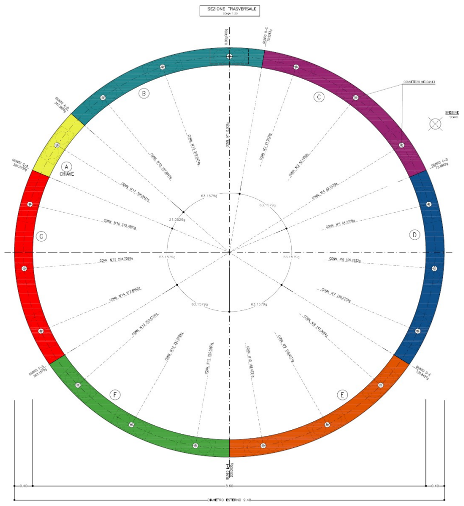

Figure 2. Tunnel lining configuration

The foreseen concrete class is C35/45, except for special local conditions (high overburden) in which a top class equal to C40 / 50 is foreseen. All the segments are reinforced with polypropylene fibres to limit the spalling of the precast lining.

The ring reinforcement has been designed taking into account the variable geomechanical context and overburden. Three different reinforcement sets have been developed with a medium steel ratio ranging between 100 and 135 kg/m3.

From a geomechanical point of view the studies have revealed that the Tunnels cross an area of exceptional geological complexity.

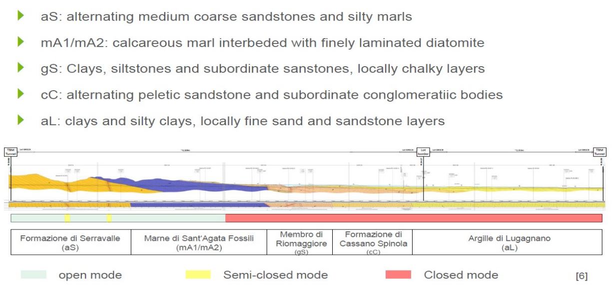

Figure 3. Longitudinal Profile - Serravalle tunnel

In Serravalle tunnel, for more than 3000 m from the north entrance, the thickness of the overburden is lower than the tunnel diameter, and the formation encountered at the face is the one of Lugagnano clays (clayey silt with sandy and arenitic intercalations), which exhibits poor mechanical strength properties (see Figure 3). In the south area, proceeding with the excavation, the overburden increases up to more than 100 m; the tunnel passes through Serravalle (aS) sandstones and Sant'Agata Fossili marls (mA). These are alternating medium coarse sandstones and silty marls (aS) and calcareous marl interbedded with finely laminated diatomite (mA). Starting from the north entrance, Valico tunnel is excavated through the marls of the Rigoroso Formation and the Costa Areasa Formation. Silty, clayey marl with intercalations of fine sandstone (Rigoroso Marls) and flyschoid formation consisting of poorly cemented silty marl, cemented marl carbonates, poorly cemented sands and fine sandstones (Costa Areasa Formation). The rock fracturing degree is medium to high.

In the following stretch the tunnel is excavated in the conglomerates of the Molare Formation, consisting of polygenic conglomerates in benches and strata in an arenaceous matrix (see Figure 4).

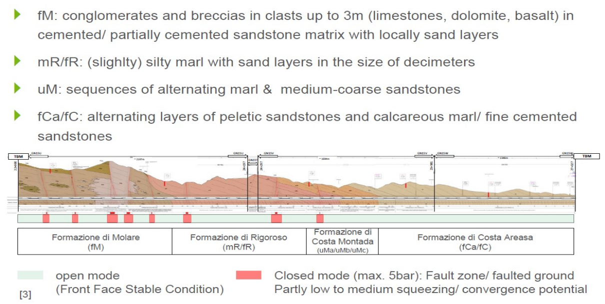

Figure 4. Longitudinal Profile – Valico tunnel

At the end, the tunnel overburden reaches more than 400 m and material encountered at the face presents important resistances (monoaxial compression strength greater than 30-40 MPa).

3 TUNNEL MODEL

3.1 *Hypothesis and standards*

In the research field, the discussion to individuate the most adequate fire curve for tunnels and underground spaces has been intense. This research has also involved tests on real dismissed tunnels and on laboratory samples. Starting from the data obtained, a set of time/temperature curves depending on the exposures conditions have been developed as represented in Figure 5. Two commonly used standards were applied to the numerical models performed: "EUREKA" and "RWS" standard fire curves (T.S.I.s, 2008 and UNI 11076, 2003). The RWS fire curve is usually, even in

Italy, cut after two hours time, because of the estimated time for the rescue intervention.

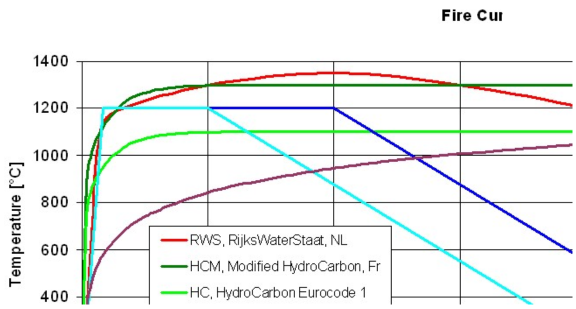

Figure 5. Standard fire curves used in FDM analyses compare with standard fire curve (Promat Tunnel)

In the "Eureka" fire design curve, according to the Technical specifications for interoperability (TSIs, 2008), the temperature rise is very rapid up to 1200°C within 5 minutes. The duration of the 1200°C exposure is shorter than other curves with the temperature drop off starting at 60 minutes for train fires. The 110 minutes cooling period is applied to the curve.

The RWS curve was developed by the Rijkswaterstaat, Ministry of Transport in the Netherlands. This curve is based on the assumption that in a worst case scenario, a 50 m^3 fuel, oil or petrol tanker fires with a fire load of 300MW, lasting up to 120 minutes. The RWS curve was based on the results of tests carried out by TNO in the Netherlands in 1979. The difference between RWS and EUREKA curve is that the latter is based on the temperatures that would be expected from a fire occurring within a relatively open space, where some dissipation of the heat would occur. The RWS curve, on the contrary, is based on the temperature measured when a fire occurs in an enclosed area, such as a tunnel, where there is almost no chance of heat dissipating into the surrounding atmosphere. The RWS curve simulates the initial rapid growth of a fire, using a petroleum tanker as source and the gradual drop in temperatures, to be expected as the fuel load is burnt off. Italy has adopted the RWS standard, according to its legislation (UNI 11076, 2003).

3.2 *Modeling soil and structure interaction*

The tunnel is modelled in 2D, under the assumption of plain strain. A construction phase analysis is performed in order to simulate the initial stress field in the lining of both tunnels using the FDM software FLAC v. 7.0. It allows to apply the presented method in several geomechanical conditions thanks to a wide range of constitutive models (Mohr-Coulomb, Hardening Soil, Hoek & Brown, Strain Softening agents, etc.). The mesh study and generation, even in “cold condition”, is certainly a key part of the analysis. The lining elements are modelled by increasing the mesh density on the internal side of the lining, in order to be able to apply the thermal and mechanical condition to concrete layer. Beam elements are not used in the model.

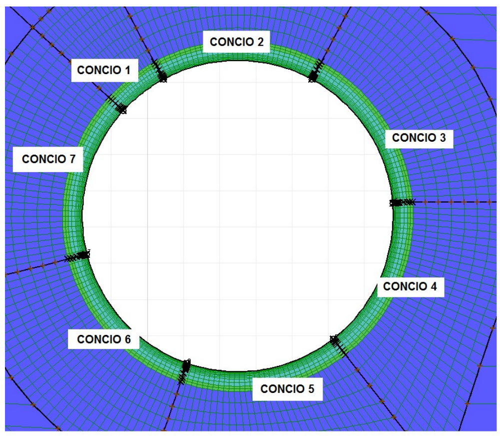

Figure 6. Detail of the FDM model mesh.

As the lining of a TBM tunnel is not a continuous ring structure due to the existence of joints, their effect on internal forces and displacements should be taken into consideration in the lining design. In detail, the joints are modelled by using shell linked with interface elements characterized by frictional behavior and no tension resistance. This structural interface must transmit compression forces only and allow the mutual rotation between two adjacent segments.

3.3 *Modelling of the fire phase*

The thermo-mechanical analysis is performed starting from the stress-strain field evaluated in “cold conditions” as described before. A coupled thermo-mechanical analysis is performed considering a material response depending on time and temperature. The calculation is conducted with an explicit time integration algorithm that solve the mechanical problem and the thermal propagation equations.

In the model the concrete properties are assumed as a function of temperature according to legislation (UNI-EN 1992-1-2). The thermal expansion coefficient α, the thermal conductivity and the specific heat are assigned to lining elements (see Figure 7).

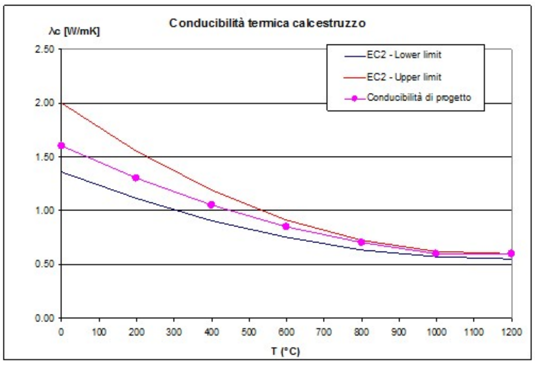

Figure 7. Results thermal conductivity of the concrete function of temperature

Certainly, a special challenge from a numerical modelling point of view has been the developing of a complex temperature dependent stress-strain constitutive model for the concrete that ensured, in the meantime, computational speed compatible with the project schedule. In Figure 8 concrete stress-strain curve as suggested by the Eurocode2 is shown.

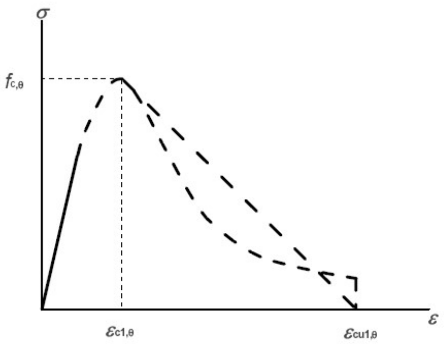

Figure 8. Stress-strain relationships for concrete in compression (UNI-EN 1992-1-2)

In the same code the values of stress-strain evolution depending on the temperature are also given, in the discretization of the 100° temperature range. In the analysis under fire loads the constitutive law shown before has been modelled through the adoption of a strain softening model coupled with Tresca failure criterion, provided by FLAC 7.0 and implemented with a User Supplied Subroutine.

With reference to the constitutive model previously illustrated, the secant modulus of elasticity is provided as the ratio of peak resistance $f_{c,\theta}$ and the associated deformation $\varepsilon_{c1,\theta}$ (see Figure 9). The cohesion value, according to the failure criterion, is set to $f_{c,\theta}/2$ in the model (see Figure 10).

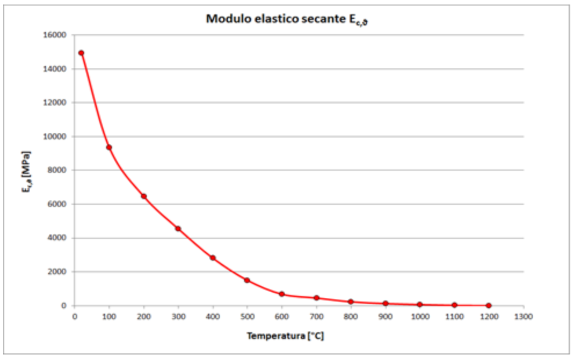

Figure 9. Temperature dependent secant elastic modulus used in the analyses

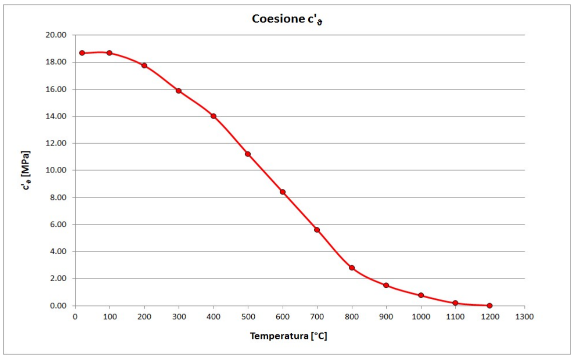

Figure 10. Temperature dependent cohesion used in the analyses.

In the calculation a linearization of the values given by the Norms is assumed for intermediate temperature values. Furthermore the mechanical characteristics of the material are associated with the maximum value of temperature reached by each element during the fire action, not allowing the recovery of mechanical capacity in case of cooling. A tensile resistance with a linear behaviour for limited temperatures is assigned to concrete layers in order to consider the steel bars reinforcement. The steel area and the tensile stress level reached in the model will be checked in verification phase. It is assumed that fire load acts only on the portion of tunnel lining above train level considering that the temperature varies according to the standard fire curves previously described. It is important to remark that the chosen modelling procedure can be adapted to all fire cases or fire curves.

During thermo-mechanical analysis for each fire curve applied (EUREKA and UNI11076) the software can store the model results at time instants defined by the user. In the model the backup of the complete results is performed in the following steps: 5, 60 and 120 minutes for EUREKA curve and 10, 60 and 120 for UNI11076 curve. These steps have been established considering that the decay of material property depends on the maximum value of temperature reached in all the steps performed: taking into account the thermal profile described by the curves, the chosen time steps could be considered representative. Furthermore special control points are defined, in order to record the principal parameters variation (for example temperature and cohesion) throughout the analysis (see Figure 11). As defined before, the mesh is denser in the inner layers: each element has to be 1.5-2cm thick (see Figure 12) in order to well simulate the stress-strain variation due to fire load applied.

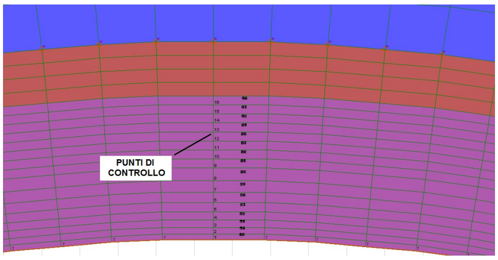

Figure 11. Calculation mesh and control points

3.4 *Verification phase*

The verifications in fire condition are carried out through the definition of the fire resistant domain with a specific calculation software. The change in material properties (steel and concrete), according to the maximum reached temperature, are taken into account for the definition of the resistant domain. The section considered in the verification is 180 cm wide (out-of-plane ring dimension) and 37cm high. The reduction of 3cm of the bearing section is taken into account conservatively in order to simulate spalling (see figure 12).

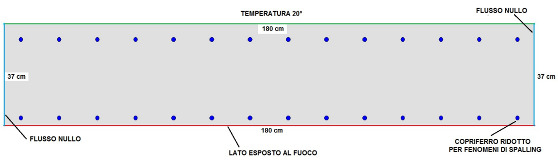

Figure 12. Segment modelling and thermal condition

Heat flow in the longitudinal direction of the gallery is considered zero (plane section analysis). The program leads to a set of resistance domain depending on temperature exposure: a specific thermal analysis is performed in order to define the temperature distribution in the section, during the application of fire curves (see Figure 13).

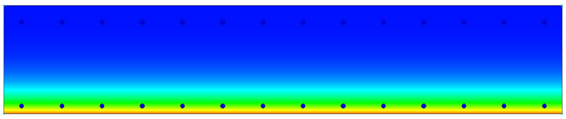

Figure 13 Temperature distribution in segment

The verification consists in comparing the analysis stresses in fire condition with the corresponding resistant domain (see Figure 14).

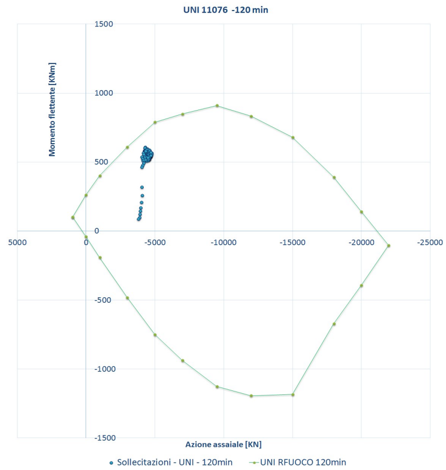

Figure 14. Verification under fire: stress and fire resistant domain

4 KEY RESULTS ACHIEVED

The procedure described has reached the goal to perform several analyses in static and fire condition with sectional verifications in short time: it not only enables to design all representative scenarios for railway tunnel “Serravalle” and “Valico” respecting project schedules, but also creates a rich database to investigate how fire load, tunnel depth and soil could affect analysis results. The following picture shows some curves plotted for the control points set: in particular the cohesion variation within the lining thickness during the analysis (see Figure 15). The data collected from analyses in different contexts brought essentially to define two different types of stress-strain behaviour under fire condition. When the excavation is performed in high overburden and high quality rock mass with elevate elastic properties, a significant compression stress field in lining is produced in “cold conditions”.

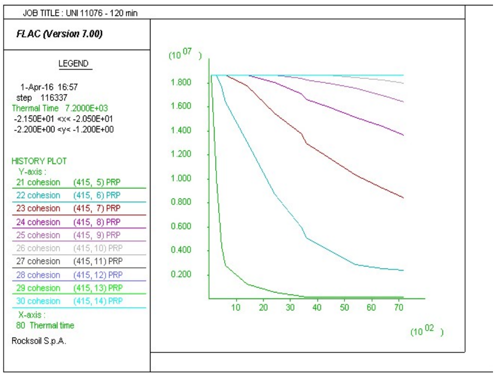

Figure 15. Cohesion variations during time within the segment (control point set)

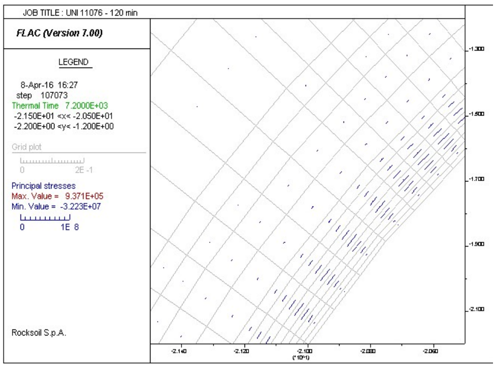

Figure 16. Stress distribution within lining - T = 120min curve UNI11076 – high overburden

In this case the lithostatic pressure can counteract the expansive effect produced by the temperature increase, and it generates an additional stress at the intrados (see Figure 16). This increase does not appear only in the layers on the internal side, where the high reached temperature causes an extreme reduction of the concrete properties. Furthermore in fire condition a remarkable decrease of compressive stress at the extrados occurs. It is due to the earth confinement that limits the effect of thermal action. From the deformational point of view, the expansion produced by the fire load generates radial deformation in the structure. The strain integration provides the trend of the internal forces along the ring development, shown in the Figure 17. Bending actions increase significantly, compared to the static phase results: the tension side is placed at the extrados with a substantially constant value for all areas exposed to fire action. The axial force diagram shows a lower but still noticeable increase. Shear stresses achieve low values; the maximum is located in the bottom area, where fire load is not applied.

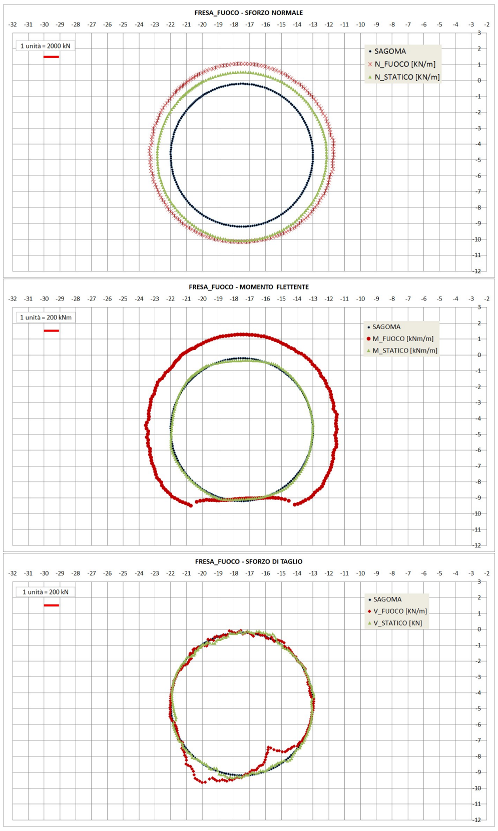

Figure 17. Internal action diagrams - High overburden

In the other case, when the excavation is performed with low overburden and in weak soil, the lithostatic pressure is not able to counteract the expansive effects of the thermal action and it results in a clear ovalization of the lining.

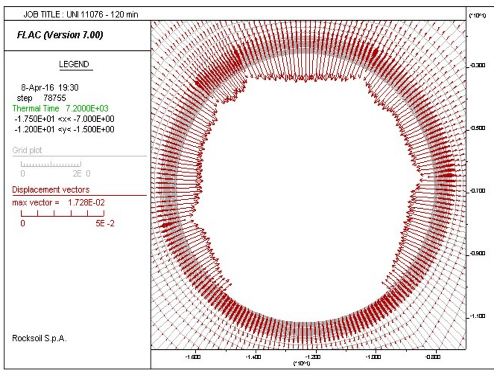

Figure 18. Deformed configuration– low overburden

In Figure 18 deformed configuration in final step is shown: the most evident effect is the inward displacement of the lining inner layer where temperature exceeds 1000° and consequently the concrete properties become null; it should be remarked that this phenomenon is associated only to the first layer at the intrados, that is the first 1-2 cm of thickness. The compression stress distribution increase at the intrados similarly to the other case. On the contrary, at the extrados tensile stresses arise: the initial static pressure is therefore not sufficient to confine the expansion and to limit the stresses induced by the action of fire (see Figure 19).

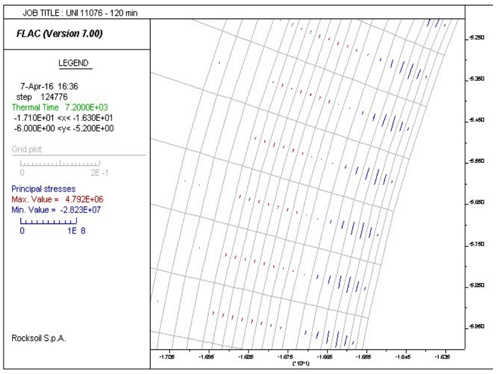

Figure 19. Stress distribution within lining – T=120min curve A UNI11076 – low overburden

Compared to the previous case, the tensile stress that arises at the top of the surface causes a different behaviour in the distribution of internal actions. The joint modelling, by the use of interface elements that are not tensile resistant, allows the rotation between two neighbouring segments (see Figure 20).

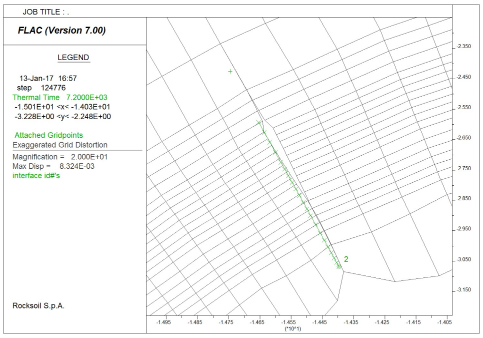

Figure 20. Interface model – joint rotation permitted

It causes discontinuous bending moment diagram shown in Figure 21. This behaviour cannot obviously occur in the first case at high overburden, in which the section is totally compressed. An intermediate behaviour compared to the two previous cases was found in models characterized by medium coverage and stiff soil. In cases like this, the initial stress in the lining is quite reduced and the increase of tension due to fire condition in not onerous, and in addiction the soil stiffness helps to reduce the expansive effects.

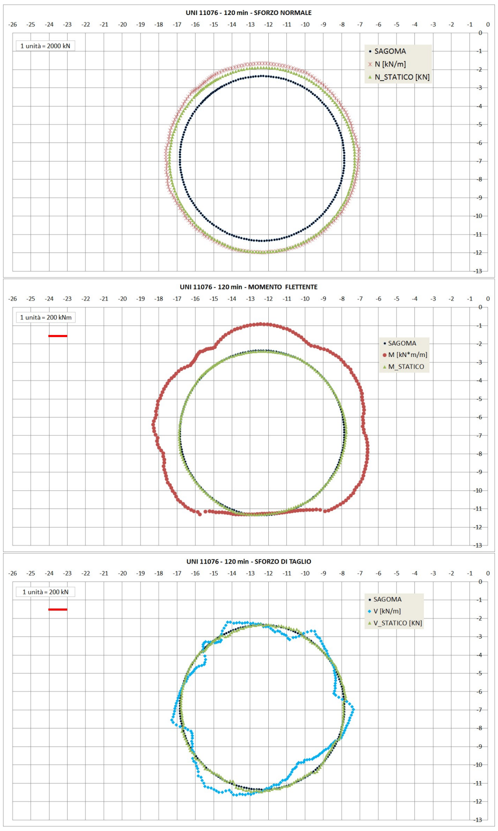

Figure 21. Internal action diagrams - low overburden

5 THE SPALLING PHENOMENA

Spalling of concrete is be defined by Khoury (2008) as "the violent or non-violent breaking off of layers or pieces of concrete from the surface of a structural element, when it is exposed to high and rapidly rising temperatures as experienced in fires".

The "spalling" consists in a localized damage of the concrete and a consequent reduction of bearing section, due to the interaction with high temperatures and vapor migration into the material. It may occur in two specific ways: "not violent" and "violent" spalling. In the first one the material detachment from the structural element surface is gradual; the maximum dimensions of detached material is 20÷30 mm ("surface spalling"). This phenomenon can be related by the spreading of micro-fractures by thermal stresses. In violent spalling, the material detachment occurs suddenly and immediately, with a substantial energy dissipation ("explosive spalling"). The "explosive spalling" is related with two different processes during rapid heating of concrete: thermo mechanical processes and thermo-hydraulic processes. In this regard, a lot of studies have been carried out, especially focused on the evaluation of influence that internal (damp content, porosity, tensile strength, fiber content) and external (heating rate, applied loads, constraints) material properties have on the aforementioned two processes. The heating produces temperature gradients, which provoke compressive stress states on the exposed surface (restrained thermal dilation results), and tensile stress in the coldest internal regions of material (thermo- mechanic process). On the other hand, the build-up of pore pressure in consequence of vaporization of physically/chemically bound water (thermo-hygrometric process) is considered to have the highest influence on the explosive nature of the phenomena, especially for high-performance concretes. The latter explains the increasing attention on the thermo-hydraulic behavior of concrete subjected to fire, by identifying the build-up of pore pressure as the main mechanism of spalling phenomena. The prediction of the explosive cleft during the heating is appraisable through some nomograms (see Figure 22) able to individualize immediately the zones of cleft and not cleft, taking into account the content of damp and other factors, as for instance the rate of job of the structure.

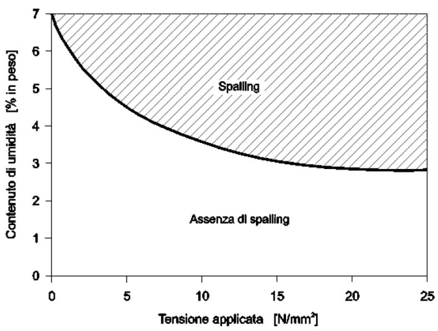

Figure 22. Typical dominion damp-tension applied for sections with rick of explosive cleft (Khoury 2008)

In such sense, referring also to the Eurocode (EN 1992-1-2:2004, §. 4.5.1), it is unlikely that the explosive crushing could occur with damp content of concrete less than k% in weight, recommending the value of k%=3. Above such value percentage, norms suggest to proceed with a more specific damp content evaluation, aggregates selection, concrete permeability and heating rate. In the current case, it is considered to use precast concrete elements with rate of C40/45. Accordingly, damp content could be considered lower than the aforementioned limit (k%=3), and hence it could be excluded the cleft risk described above.

However, in order to mitigate eventual spalling phenomena it is suggested to use polypropylene fibers with an incidence average value equal to 2 kg/m3. Such systems allow to make this detachment phenomena uniform, as far as possible, to avoid localized points of weakness. The beneficial influence of synthetic fibers (see Figure 23) is demonstrated by experimental tests conducted on elements with a pre-existing stress state, before the action of fire (i.e. IBS Institute, R. Winterberg, R.Dietze, 2004, MFPA Leipzig GmbH Test, 2013). It represents the most similar condition, comparable with current state of the case in study. Despite this, the compressive state of the concrete provokes the cracks closing; it limits the vapor migration from the material with consequent increase of the temperature, and the possibility that more intensive and immediate spalling phenomenon occurs.

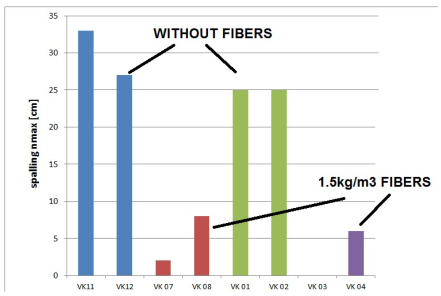

Figure 23. Maximum “spalling” values, with presence and absence of fiber in a pre-existing stress state (IBS Institute, R. Winterberg, R.Dietze, 2004)

In the analyses conducted, it has been taken into account, for safety reasons, the possibility that the “surface spalling” occurs.

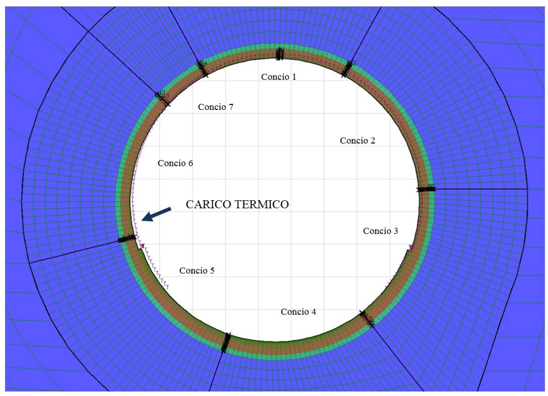

Figure 24 Software model with the presence of “spalling”

As it was said before, the verifying of the stress state is conduced on a reduced section, obtained from a "warm-condition" model (simplified method for spalling modeling). Comparative numerical analyses have been carried out with a progressive reduction (till 10cm) of the bearing section during phase analysis (advanced method for spalling modeling). In this case the application of the fire load is acting on the various structure layers progressively (see Figure 25).

The obtained results show a reduction of the resistant dominoes, but in the mean time a strong decrease of stress states inside the elements. Figure 25 underlines the differences with presence and absence of the simulation of spalling in numerical models.

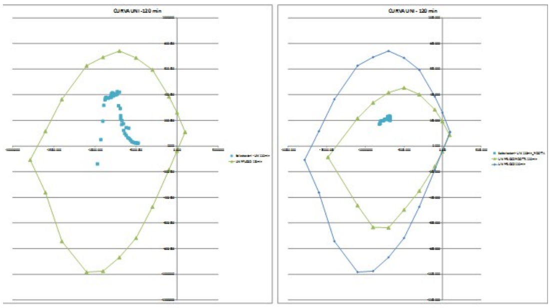

Figure 25. Obtained results with presence and absence of "spalling"

The comparison of the two different approaches confirms that the simplified method, with modest reduction of the section lining (3-5cm) is acceptable and conservatively. On the other hand, if it is necessary to consider a higher value of spalling depth, the advance method has to be used. The simplified approach can lead, in fact, to results extremely conservative.

6 CONCLUSIONS

The response of a tunnel under fire condition is intrinsically non linear; the effects of fire exposure are not only related to material degradation under high temperatures or to concrete spalling, but also to the coactions that can arise due to differential thermal expansion. Therefore, for the tunnel design under fire conditions, particularly for precast segmental tunnel, it could be necessary to perform a coupled thermo-mechanical analysis with soil-structure interaction in order to well simulate the actual response of the tunnel under fire exposure.

The paper presents the procedure developed for analyzing the behavior of TBM tunnels of the new line Av/Ac Milano – Genova both in static and fire condition. The model takes into account all the main problems related to tunnel concrete lining analyses under static (soil-structure interaction, segmental joints modelling) and fire conditions (material degradation, spalling, coactions). Any fire curves (time-temperature curve) can be implemented by the user in the model described.

The presented study underlines how this approach allows the overall structural performance verification maintaining costs and time in the common design range. The development of spalling mechanism could be considered in the model with two different approaches in the verifications phase.

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