Safety in tunnel : the suspended emergency escape route

A. Focaracci
Prometeoengineering.it srl, Rome, Italy

ABSTRACT: In this article will explain the design of enclosed walkway, suspended from the crown of a tunnel that is a particularly effective and innovative means of providing emergency escape routes. The suspended emergency escape route is an enclosed walkway that is large enough to provide an easy escape route. Access to it is along connecting stairways sited inside side chambers or at parking areas. The walkway is trapezoid or rectangular in shape and it is fixed to threaded bars or bolted plates. The structure is in concrete or steel and it is protected with materials designed to resist high temperatures such as mortars, plasterboard or similar materials. The exit to the walkway may be near the tunnel portal, where special areas are set aside and equipped for emergency rescue operations. The walkway is therefore designed to fully meet requirements for the emergency evacuation of tunnel users, because it is fully enclosed (prevents the passage of flames, gas and smoke), thermally insulated (it limits the transfer of heat) and conserves its structural integrity (it will maintain its structural integrity for at lease 120 minutes in a fire). In other words it constitutes an REI 120 structure to all effects and purposes. This structure provides the following advantages over conventional solutions: industrialised construction, low production costs, rapid installation. In the 2009 a full scale test was therefore performed inside the S. Croce Tunnel on the "Strada dei Marmi" at Carrara. The results obtained were very good, consequently the suspended emergency escape route was built for some bidirectional tunnels: the Monte Greco Tunnel 2400 m long and Macina Tunnel 947 m long. Actually the solution in under construction inside Sellero Tunnel bidirectional 5047 m long and it is under design for Serralunga Tunnel 1300 m long.

1 INTRODUCTION

In the field of tunnel safety during operation, the new regulations, both at European and national level, have responded in an innovative methodological way to the need for substantial improvement in the security strongly felt by the public as a result of serious accidents occurred in recent years (Monte Bianco, Gottardo, Frejus).
The new regulatory framework has adopted the new design approach based on the quantitative and probabilistic risk assessment.
Thus were created the necessary conditions to launch an impressive program of safety interventions for the road, rail and metro tunnels based on engineering judgments and not related to the sensitivity of the "experts", or worse, dictated by emotions produced by major accidents. The main normative reference is the Directive 2004/54/EC "on minimum safety requirements for tunnels in the trans-European road network", which provides that the security measures are based on a systematic consideration of all aspects of the system, namely the infrastructure, operation, users and vehicles; the directive also provides mandatory guidance for all underground infrastructure longer than 500m.

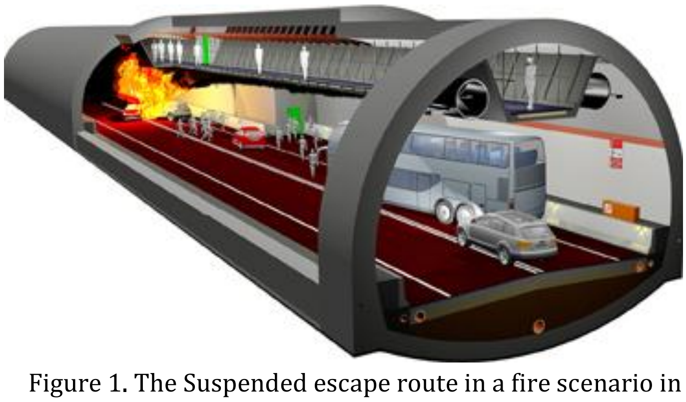

Figure 1. The Suspended escape route in a fire scenario in the tunnel

It identifies the security objectives to be pursued, identifies a set of security parameters to consider, establishes groups of minimum safety requirements to be met, suggests a systematic approach for the design of safety by identifying risk analysis as an analytic tool to be used to determine the safety level of a tunnel.
The objectives of the Directive 2004/54/EC, that is to ensure a minimum sufficient level of safety for road users in all galleries that are part of the Trans European Road Network. In the event of an accident, the consequences must be tackled with effective protection measures enabling users involved to rescue themselves and at the same time, allowing immediate intervention of all those not directly to prevent further damage.

2 SAFETY PROJECT

The Directive requires each member state to adopt a methodology of risk analysis. Italy has implemented a risk analysis methodology consistent with IRAM (Italian Risk Analysis Method) norm.
IRAM is the Italian method for the design and verification of safety in tunnel, it uses a Risk Model of Classic Bayesian type, integrated with the analysis of random and epistemic uncertainties associated with the variables and models that describe the state of tunnel in an emergency. The state variables, treated as statistical quantities and characterized in terms of specific distribution functions are the variables that appear:
- in statistical models stimulating the flow of thedanger caused by a probabilistic set of hazard scenarios;
- in statistical models stimulating the escape process of users from the structure;
- in models of traffic evolution;
- in the statistical definition of security systems performance.

The Method of Risk Analysis from IRAM allows:
- the verification of acceptability of the risk associated to an infrastructure;
- the identification of alternative and additional measures to the group of minimum safety requirements, as prescribed by the standard for a specific tunnel,
- the verification of equivalence, that is, of risk reduction achieved through the adoption of alternative and additional measures with respect to risk level insured by meeting the minimum safety requirements;
- the application of ALARP principle of risk reduction through the cost-safety analysis.

From the point of view of users salvageability in the tunnel among the most feared incidental events, for the severity of its consequences, is without doubt the fire: the toxic fumes and gases, developed at high temperatures, retain dangerous levels of concentration even at distance, creating difficulties not only for people who are already in the tunnel but also for the supervening rescuers.
Safety in tunnels is therefore a complex topic able to create both varied and well-structured research fields, regarding in particular:
- the behavior of users in case of emergency
- the infrastructure characteristics (construction typologies, exits, entrances, ...);
- the operation characteristics: the type and operation of plant and safety equipment (fire-fighting safety, ventilation, lighting).

Therefore, the design and preparation of safety projects for many new or existing tunnels led to the development of a lot of innovative solutions. In addition to the regulatory framework, among safety equipment, ample emphasis is given to escape facilitation measures both of infrastructure and plant type. Higher efficiency measures, as demonstrated by the application of IRAM risk analysis methodology (Italian Risk Analysis Method) to the safety project of more than 300 km of tunnels and highways are linked to infrastructure measures for facilitating the escape defined by the Directive as follows:
-Emergency exits (54/2004/CE § 2.3): "allow tunnel users to leave the tunnels without their vehicles and reach a safe place ... (omission).

3 MEASURES FOR FACILITATION OF ESCAPE: THE EMERGENCY EXITS

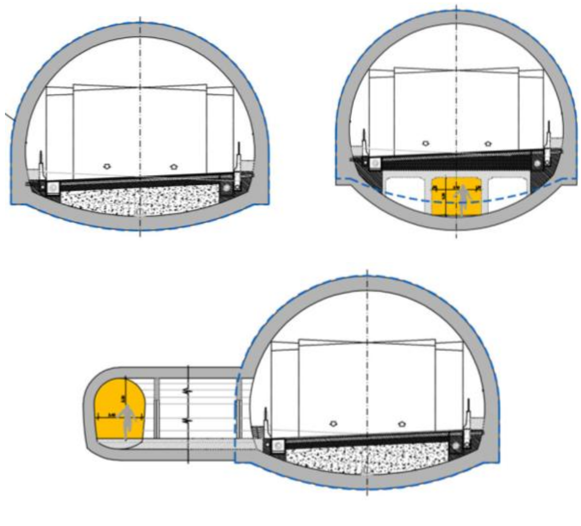

Figure 2. Various arrangements for escape routes

The discovery through the many risk analysis developed at national and international level that escape routes are the most effective measure for the salveagibility of users in tunnels in consequence of a serious accident in general and of fire and release of fumes in particular, has led security operators to seek innovative solutions both from the functional and technology point of view.

Particular issues can be found in existing single-tube double-track tunnels and in the twin-tube ones in the absence of bypass. Over the years the design of escape routes for tunnel users has undergone some changes both from the point of view of positioning, and regarding the plant equipment:

- escape route coinciding with the entrances
- escape route through bypass and parallel tube
- escape route positioned below the plane of the road
- service tunnel parallel to the main tube
- Such solutions, however, have some negative aspects:
- -a substantial environmental impact because one have to dig a veritable gallery from scratch;
- issues related to the drainage of the water;
- planting of thousands of cubic meters in more excavated;
- major difficulties from the constructive point of view due to the mutual interference of the two tunnels;
- higher manufacturing costs having equal effects on the users safety.

It is obvious that it was needed an innovative solution that would solve at the same time several problems of realization in relation to unforeseen geological and geotechnical issues, processes of industrialization, deadline and cost of performance. So it appeared the idea of a Suspended Escape Route. Such a structure, trapezoid or rectangular in shape, is attached to the crown by bars and plates. It may be made in concrete or steel and is protected with material designed to resist high temperatures.

The suspended escape route addresses and solves all the problems that arise in the initial projects in relation to escape routes, in particular:

- no need for further excavations in addition to the main tunnel, as the escape route is obtained within the tunnel avoiding the issues of environmental and noise impact;
- the structure is made of prefabricated modular and standardized elements that determine fixed deadlines and costs insured by the industrialization process of the operational phases;
- the exits are located at areas easily accessible by rescue teams;
- the plant equipment of the escape route are independent of those of the tunnel and in particular the ventilation system is designed in such a way as to ensure maximum user salvageability.

4 THE SUSPENDEMERGENCY ESCAPE ROUTE

The design of the Suspended Emergency Escape Route required the use of a large amount of resources into the research and development sector of the companies involved, in order to obtain a product able to fulfill the most stringent criteria of safety and at the same time not to allow disproportionate realization costs. The structure of the Suspended Escape Route was designed using precast reinforced concrete elements in trapezoidal shape. The particular shape of the precast segment is designed to better anchor the crown of the tunnel and to allow an easy installation of the equipment.

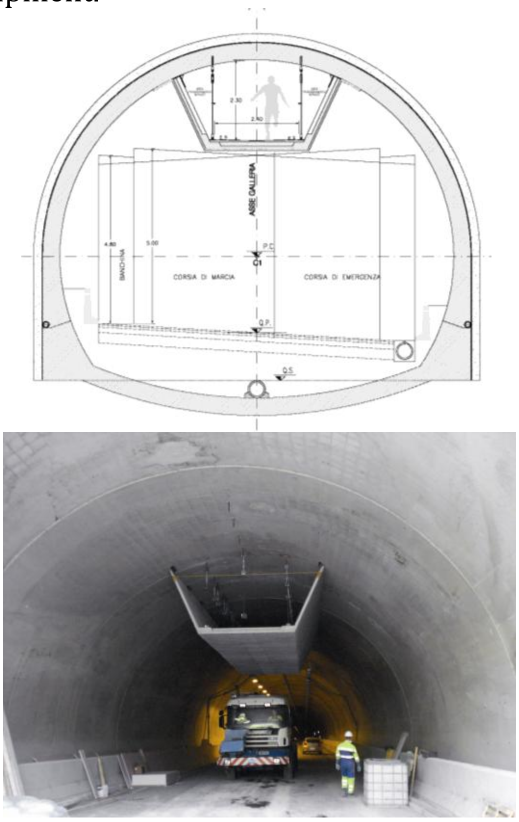

Figure 3. Suspended Escape route within the cross section of Macina tunnel (Carrara)

The elements are connected longitudinally by means of male-female joints in such a way as to form a continuous walkway as shown in the figure. The single precast segment is anchored directly to the crown of the tunnel through four steel tie rods at their turn anchored by plates to the precast elements.

Figure 4. Interior of the Suspended Emergency Escape Route

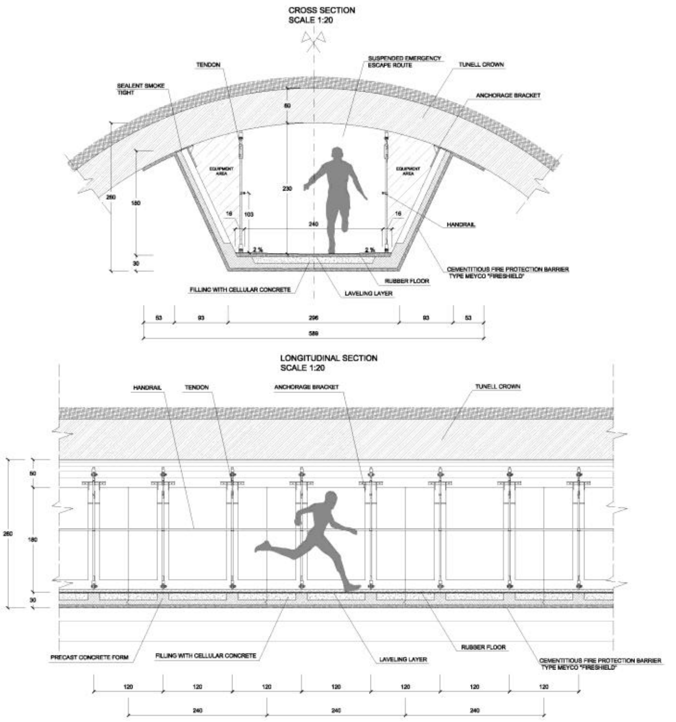

Figure 5. Profile and section of the suspended walkway

On the structure have been designed different fire protection systems made of materials that can reduce temperatures such as mortars, gypsum plasterboard or similar materials;

it is used the RSW fire curve in which the maximum temperature is equal to 1350 ° C after a time of 120 ° C. Subsequently, the validity of this choice in terms of resistance, insulation and airtightness was tested by evidence from real fire. All joints between the prefabricated elements and between these and the cap were sealed to the fumes and heat transfer, via elastic sealant having REI 120 fireproof properties.

The structure is designed considering the loads resulting from the presence of dense crowd and verified by finite element models. Access to the Suspended Emergency Escape Route can be achieved by deriving the ascent to the prefabricated structure within the cross section of the tunnel, in correspondence of widen, or through transverse large rooms to the tunnel specially made.

The access structure must include REI 120 features and must be equipped with all the plant and emergency equipment required, as well as with a lift system for users with disabilities.

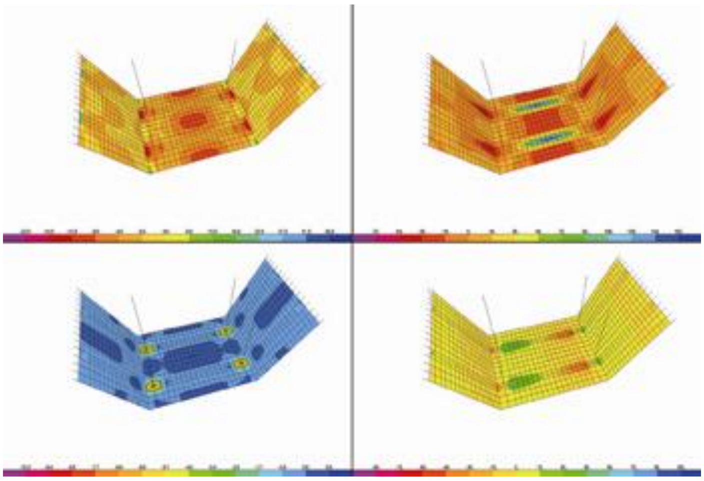

Figure 6. FEM analysis of precast segments

Figure 7. Precast segments of Suspended Escape Route stored on site (Macina and Monte Greco tunnel, Carrara)

Users once they got out using the escape route are directed to the nearest exit from the tunnel entrance.

Throughout all the design particular attention has been made to the installation and assembly phases of the structure in the tunnel. In the first stage of the installation, it is necessary to install the anchors and drill the steel bars which are inserted terminals consisting of 4 tie rods. The precast segments are easily liftable, each segment weighs 3.5 tons.

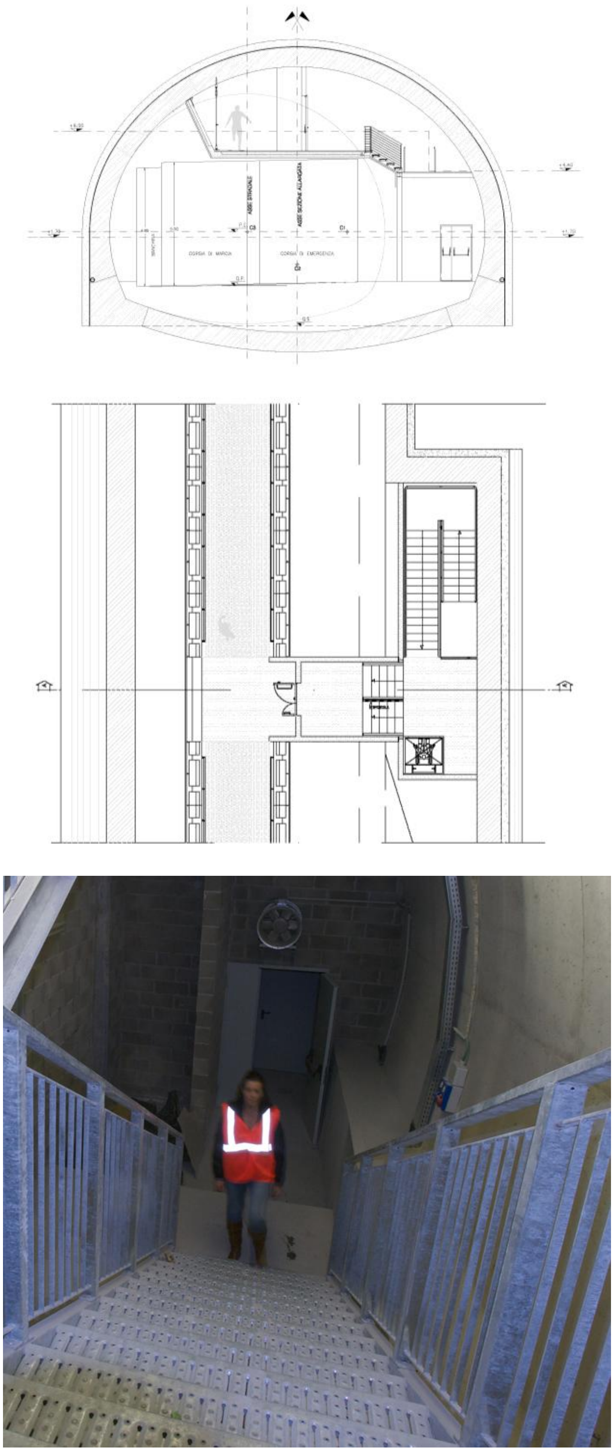

Figure 8. Design of Access structures to the Suspended Escape Route

In the second stage takes place the longitudinal and transverse sealing, while in the final phase the coating with the layer of fire-resistant mortar. The plant equipments of the suspended escape route are independent from those of the tunnel and in particular the ventilation system is arranged in an appropriate facility, in such a way as not to produce problems of loss of overpressure.

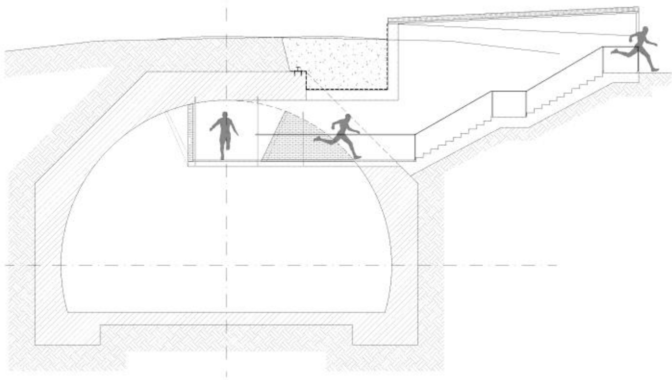

Figure 9. Exit corresponding to the entrances of Sellero tunnel

Figure 10. Exit corresponding to the entrances of Macina tunnel

The safety system consisting of the suspended escape route, in order to perform its function is accompanied by the following equipment:

- ventilation system that allows access overpressure and thermo hygrometric comfort for users during the escape process;
- lighting system that allows an appropriate level of illumination for the entire period of the escape process considering possible malfunctions;
- video surveillance system that allows monitoring of the escape process in the tunnel by rescue workers;

-presence of smoke detection system within the tunnel that allows the monitoring of environmental conditions inside the tunnel;

-system facilitating the escape (emergency active and passive signs, sound diffusion system) that reduces the identification times for the access to the tunnel by the tunnel users and access to the tunnel by the users present in the tunnel.

The ventilation system allows the access pressure and the thermo hygrometric comfort for users in the process of escape.

The lighting system allows a suitable level of illumination for the entire period of the escape process also in case of fault in the electricity network.
The system of escape facilitation constituted by signs capable of directing users and provide information was designed in order to reduce the time of detection of access to the tunnel by users in tunnels and of escape from it.
The design of the escape route also considered, using suitable models of three-dimensional calculation, the time required for escape as determined by the evolution of fire scenarios in the tunnel and by the performance of security systems installed, especially fire resistance.

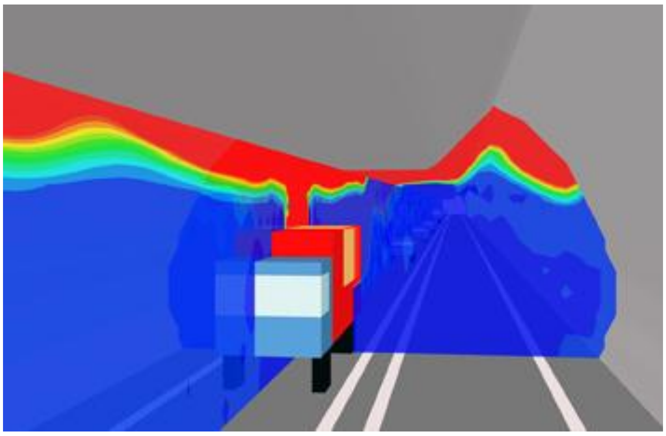

Figure 11. Simulation of escape scenarios in the tunnel

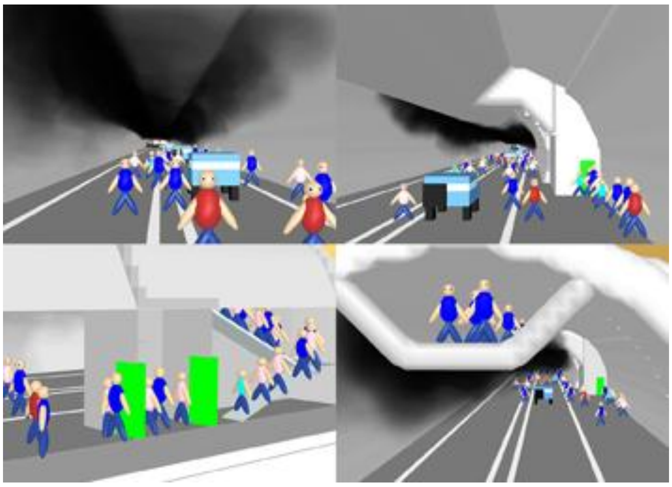

Figure 12. Simulation of escape scenarios in case of fire in the tunnel with Suspended Escape Route

Such an innovative solution, for the salvageability of the tunnel users in the event of a major accident with fire, requires a validation by a highly qualified third party, that checks, on the one hand the static characteristics of the work, on the other hand the REI 120 functionality provided by the standard. For this was made a full-scale test within the S. Croce tunnel on the "Strada dei Marmi" at Carrara. The testing for certification was performed by the Energy Department of the Polytechnic of Turin, which designed and supervised all the tests on site.

5 VALIDATION OF SUSPENDED ESCAPE ROUTE BY FULL-SCALE TESTS

5.1 Static tests

The test structure was verified prior to the installation using the following tests:

- heating test corresponding to the tie rods anchorage plate with time course measurement of temperatures in the plate and at the opposite end of the tie rod;
- tie rods static test with test load of 4000 kg with measurement of deflection on each of the twenty tie rods installed;
- heating test of the tie rod loaded with a load of 3000 kg with measurement of deflections and of temperatures in the various points of the tie rod on a tie rod installed ad hoc and used only for the resistance test.

At the end of the equipment preliminary tests, strain gauges were mounted on four tie rods corresponding to the test section that was used for testing resistance to fire. The structure placed in operation was then tested by the following tests:

- load test with a load of 400 kg/m2 on two consecutive segments;
- load test with a load of 400 kg/m2 on two not consecutive segments;
- load test with a load of 400 kg/m2 on two non-consecutive segments with load across the two segments.

The structure placed in operation was also tested by heating in correspondence of one of the fastening plates and the measurement of temperatures in correspondence of the anchorage to time in order to verify the sealing of the resin used for fastening in the crown.

5.2 Fire resistance tests

The following test were conducted on a prototype of escape route specially prepared under the supervision of the Polytechnic of Turin, to verify the resistance to fire of the Suspended Escape Routes:

- pre-thermal stress tighening tests by cold smoke released into the tunnel;
- proof of structural strength and insulation by thermal stress brought about by external burners in open air;

- post-thermal stress tighening tests by open-air fire-fuel pools;
- post thermal stress tightness test by external fuel fire wells.


Figure 13. Structure of full-scale test (Santa Croce tunnel, Carrara)

The pre-thermal stress tightness test was conducted by issuing cold fumes inside the tunnel suitably sealed at the ends. The test was conducted in accordance with appropriate visualization and video capture techniques. The test procedure provided for the hermetic closure of the escape route, the delivery of fumes at regular intervals for a period of 5 minutes, the control by means of video capture of the saturation of the internal environment and the absence of release of smoke from tunnel to the outside, the opening of a window into the tunnel for the release of fumes after 10 minutes from the start of dispensing. The criteria for the tightness verification are: the saturation of the internal environment from the the fumes and the absence of filaments through the walls and the slab of the escape route. The structural resistance test was carried out by performing the local heating of the outer surface of the escape route by means of two oil burners of total heat capacity of 1.5 MW, which allowed the achievement of a maximum temperature in correspondence of the extrados of the product equal to 1000 ° C. The location of the burners was fixed in order to affect, through direct impact of the flame, Both the horizontal surface (slab) and the vertical surfaces (walls) of the product, and the junction area between the two elements, and to heat the area in correspondence of the anchorage of one of the tie rods which support the product.

5.3 Results

The results of the Structural Resistance test, Tightness of the subdivision, Thermal insulation over a period of 120 minutes were as follows:

- the temperature inside the Suspended Escape Route did not exceed 35 ° C, with a fire load in proportion of 70 MW;
- the temperature of the tie rod did not exceeded 45 ° C;
- the temperature at the interface between the insulating material and CLS did not exceed 100 ° C;
- dilation between the joints is less than 0.3 mm;
- elongation of the rod is less than 0.5 mm;
- there were no leakage of fumes outside the structure before thermal stress;
- there were no increases in opacity or concentration of carbon monoxide in the structure after thermal stress;
- the temperature of the internal walls does not exceed 40 ° C;

From the qualitative point of view at the end of the test in which for 120 minutes have been applied more than 1000 ° C on the surface of the body could be observed:

- the insulating coating has not been affected by spalling phenomena,
- the insulating coating did not show any noticeable damage,
- the metal parts have not undergone significant heating,
- the CLS was not cracked or damaged.

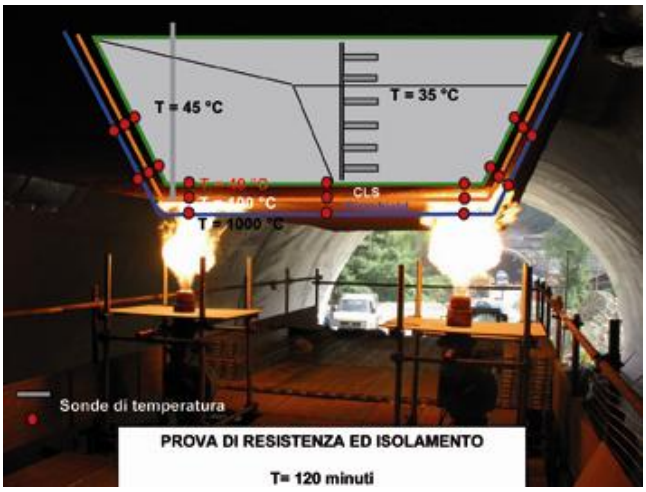

Figura 14. Results of the fire resistance test

6 CASE HISTORY

The positive outcome of the static and fire resistance tests of Suspended Escape Route allowed to introduce such a structure in the field of escape facilitation measures for tunnel users as an alternative to traditional solutions. In particular it has been adopted as a decisive solution of problems related to the construction risks concerning geology and geotechnical, environmental and security issues in operation, on strada dei Marmi where VES has a length of about 2500m, within Macina and Monte Grecco tunnels.

Figure 15. Macina tunnel- Completed Suspended Emergency Escape Route

The walkway made of prefabricated modules was also used in the Sellero tunnel on Strata Statale 42 from Tonale and Mendola for about 300m due to which it was possible to adapt the existing infrastructure with the latest standards for safety.

Figure 16. Sellero tunnel – Detail of the prefabricated structure

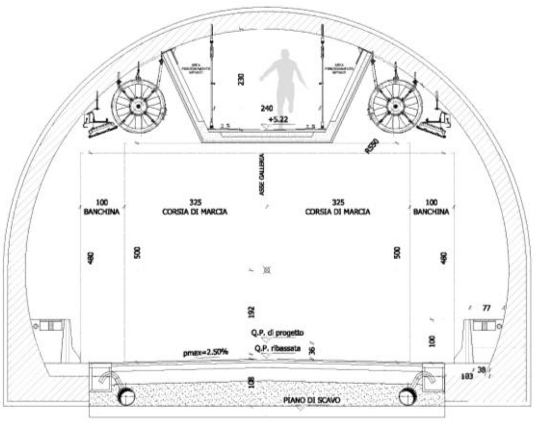

Figure 17. Cross section of Serralunga tunnel line adequate with the Suspended Emergency Escape Route

In addittion, the Suspended Emergency Escape Route is in the advanced design stage for the adaptation of Serralunga tunnel (total length of 1300m and which did not include in the original plan escape routes) where the suspended walkway will be built in two sections from the two entrances in length of respectively 467 m and 332 m, respectively.

7 CONCLUSIONS

The results at the project, experimental and realization level, due to the synergy between the contracting Administration, design engineers and performing companies have made it possible to create a high value engineering work for salvageability of tunnel users. The cases applying to Carrara, the 2.5 km of escape route with their entrances to the outside, made in about 1 year starting from the approval of the project with particularly low costs compared to similar solutions, and to Sellero tunnel, allow to conclude that it was expanded the choice of technical solutions available for the construction of escape routes in the tunnel for both new infrastructure and for the adaptation of existing ones with the latest safety regulations and standards.

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