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Structural safety assessment of concrete tunnel lining subjected to fire

D. de Silva [a,*], M. Andreini [b], A. Bilotta [a], G. De Rosa [a], S. La Mendola [b], E. Nigro [a], O. Rios [b]

[a] Department of Structures for Engineering and Architecture, University of Naples Federico II, via Claudio 21, Naples, Italy
[b] European Organization for Nuclear Research (CERN), Occupational Health and Safety and Environmental Protection Unit, Occupational Health and Safety Group, Infrastructures and Buildings Section (HSE-OHS-IB), CH-1211, Geneva 23, Switzerland

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ABSTRACT

The basis of a possible fire design and verification approach to the linings of RC tunnels, using the performance-based approach, is presented. Starting from an extensive literature review, a selection of the most relevant tunnel fires was analysed. The study of structural consequences of these real fires may be considered as experimental data of tunnel in fire, to define the possible fire damage levels. Back analyses were carried out to define the main parameters controlling each damage state, whose temperature range is determined via fluid-dynamic analyses based both on fire zone models and Computational Fluid Dynamic Modelling. Therefore, the novelty of this paper is that the proposed methodology introduces the structural damage levels for the tunnel lining in fire, according to a performance-based approach.

In the second part of the paper, the proposed approach was applied to a real concrete tunnel to assess its potential fire damage level. First of all, the expected damage level of the underground structure was identified through the gas temperatures reached during different real fire scenarios, where no fire damage was observed. This result was confirmed by analysing both the temperatures and the stresses of the structural lining, through advanced thermo-mechanical analyses.

1. Introduction

Fire in tunnels is a worldwide problem that can cause infrastructural deficiencies and huge economic and human losses. Despite all efforts made to control and prevent human errors, and to detect technical problems, accidents will occur, and without efficient fire extinguishing capability, some of these accidents will develop into catastrophes. Indeed, the structural conformation of the tunnel makes fighting fires complex, in particular because of the limited escape possibilities and difficulty of intervention by rescue teams, while the generated heat is intense and the heat loss is limited.

For these reasons, the evacuation and life safety aspects are widely studied in the in literature, indeed Riess et al. [1] studied the main factors controlling smoke propagation in a tunnel and their impact on design and dimensioning of longitudinal ventilation to guarantee a safe people evacuation; while Ronchi et al. [2], described an evacuation experiment performed for understanding how the smoke can influence human walking speeds, underlining that fires may quickly become devastating due to the confined tunnel environment and the fire development may be rapid causing a quick deterioration of evacuation conditions.

However, the reaching of high temperatures during a tunnel fire does not affect only the evacuation conditions and the rescue team interventions, but also the tunnel lining can be damaged from the structural point of view and loss of bearing capacity and durability problems may occur [3].

For these reasons, in recent years several studies have focused on the development of sophisticated approaches a realistic degradation estimation of strength and stiffness of tunnel linings exposed to fires. The extension of the ‘‘beam-spring’’ model towards consideration of effects associated with tunnel fires was proposed by Savov et al. [4], using layered finite beam elements for the discretization of the lining, allowing consideration of spalling by deactivation of layers following a pre-specified spalling scenario. Sakkas et al. [5] presented the fire assessment of a cut & cover tunnel, using finite element analysis and for the evaluation of the spalling rate, depth and time, an in-situ fire test was selected as an optimum solution. Vitek [6] compared different fire protection of the tunnel lining, underling that the design of protection against fire in a specific tunnel should be based on a detailed evaluation of many influencing factors.

* Corresponding author.
E-mail addresses: donatella.desilva@unina.it (D. de Silva), marco.andreini@cern.ch (M. Andreini), antonio.bilotta@unina.it (A. Bilotta), gabrie.derosa@studenti.unina.it (G. De Rosa), saverio.la.mendola@cern.ch (S. La Mendola), emidio.nigro@unina.it (E. Nigro), oriol.rios@cern.ch (O. Rios).

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It appeared that structural damage can have very serious economic consequences on the capital represented by the tunnel, but also on the safety of the users and rescue teams. Furthermore, complete tunnel protection against the worst possible fire would very often be both very expensive and unnecessary. Consequently, an international refinement of this issue was necessary and the Technical Committee on Road Tunnel Operation (C3.3) of the World Road Association (PIARC) in cooperation with the International Tunnelling Association (ITA) [7] published the design criteria for resistance to fire for road tunnel structures. In particular, the proposed design criteria make a distinction according to the type of traffic (and consequently the possible fire load) and the consequences of a structural failure due to a fire; the ISO curve [8] and either the RWS [9] or the HC_{inc} curves were used for different circumstances, requiring different time resistance according with the type of traffic and with the main or secondary structures. Also, The British Tunnelling Society and The Institution of Civil Engineers published a Tunnel lining design guide [10], including the fire resistance of structures and also in this case the ISO, the RWS and the HC_{inc} curves were indicated for the designing and verification of the tunnel lining.

It is evident that, on one hand, there is no harmonized regulation for designing the tunnel lining resistance in fire situation and on the other hand, all the published guidelines indicate deterministic temperature-time curves, that are used for designing in prescriptive approaches. These curves do not always reflect the real fire conditions in the tunnels and they can be particularly conservative in most real cases in which the fire load is not so high (e.g. complex research infrastructures). Therefore, the main objective of this paper is to apply the criteria of fire safety engineering (FSE) to the design and verification of the tunnel lining, taking into account the real fire risk of the tunnel. Starting from an analysis of the consequences of real fire events on the tunnel linings, several damage levels were defined and fluid dynamic analyses were conducted in order to simulate the gas temperature reached during some of these real cases, in order to link the different structural damage with the temperature regime, reached during the fire.

The proposed methodology was finally applied to a real tunnel, which is analysed using the FSE criteria both from the fluid dynamic and structural points of view. Indeed, several fire scenarios were simulated using Computation Fluid Dynamic analyses, obtaining the natural fire curves, used for a preliminary estimation of the expected damage level. This latter was confirmed by performing several advanced thermo-mechanical analyses, from which the absence of collapse and of structural damages was demonstrated by analysing the temperature and the stresses inside the tunnel lining during the real fires.

2. Principal aspects of tunnel fire dynamic

A fire is a chemical process, but the mode of burning may depend more on the physical state and distribution of the fuel, as well as its environment, than its chemical nature [11,12]. The understanding of fire behaviour, in general, requires knowledge of chemistry, heat transfer, fluid dynamics, etc., and the behaviour of a fire in a tunnel is even more complex. Ingason [13] compared tunnel fires to compartment fires (rooms in buildings) and he stated several differences. First, the maximum heat release rate (HRR) of a compartment fire depends on the natural ventilation, which is determined by the area and height of the openings into the compartment. In tunnels, the natural ventilation depends on the fire size, slope of the tunnel, cross-sectional area, length of tunnel, type of tunnel (concrete lined, rock), and meteorological conditions at the entrance to the tunnel. Tunnels often also have forced longitudinal ventilation, which influences the combustion efficiency as well [13]. Secondly, compartment fires can grow to flash-over within a few minutes, but this is unlikely to happen in a tunnel fire because of great heat losses to the surrounding walls, and a lack of containment of the hot fire gases. Thirdly, in the early stages of compartment fires an upper layer of buoyant smoke is formed, with a cold smoke-free layer below. In case of very low longitudinal ventilation in a tunnel, the same type of smoke layer can be formed in the early stages of a fire. Further away from the fire source, however, the smoke descends to the floor. The distance at which this occurs depends on the fire size, tunnel type, width and height of the tunnel cross-section. Furthermore, in general, combustion can be distinguished into fuel-controlled and ventilation-controlled. Fuel-controlled fire means that oxygen is in unlimited supply, and that the rate of combustion is independent of the mass flow rate of air, but it is instead determined by the mass flow rate of vaporised fuel (fuel supply rate). A ventilation-controlled fire has a limited oxygen supply, and the combustion rate depends on both air and fuel supply rates. The most relevant parameter to characterize a fire is the Heat Release Rate curve (HRR); particular evolutions of HRR for tunnel fires in a realistic and robust way are present in the literature. In particular, Ingason [14] proposes two different exponential expressions of HRR for fuel-controlled and ventilation-controlled fires, validated against several experimental HRR data (Fig. 2).

Fig. 1 shows that using the equations for HRR proposed in Ref. [14], the experimental data and the numerical one are very close to each other. These equations were used in this work for calculating the HRR curves in the following fluid-dynamic analyses.

3. Real fires database description

Tunnel fire is one of the most severe global fire hazards and causes a significant amount of economic losses and casualties every year [15]. For this reason, in order to better understand the fire dynamic in tunnels numerous full-scale and small-scale tunnel fire tests have been conducted to quantify the critical fire events and key parameters to guide the fire safety design of the tunnel. In this paper, a deep literature review was conducted in order to collect as much data as possible on the most relevant tunnel fires to study the structural consequences of these real fires as well as experimental tests, on the tunnel structures. In addition, all the experiments conducted were analysed focusing on the damages caused by fire on the structural tunnel lining. In the following, all the considered fires were described.

3.1. *Tunnel fire incidents and experimental tunnel fires*

Analyzing the literature, sixty-six relevant fire events in railway or road tunnels [16–21] were collected in a database. Each fire event has been analysed in terms of temperatures reached during the event, always focusing on the structural damages of the tunnel lining. First of all, the analysed fires were classified according to the year in which they occurred; Fig. 2 shows that:

- between 1959 and 1973, very few cases of fire were recorded;
- from 1973 to 2001 the tunnel fires were increased;
- from 2001 to 2015 a reduction of tunnel fires can be observed.

The reasons of this trend of the recorded fire tunnels in literature can be related first of all to the historical memory of each event, but the growth is both due to the increase of tunnel realization and to the increased traffic, especially of heavy goods vehicle (HGV), to which a bigger fire load is in general related. The reduction, during the last years, in cases of major fires is linked to the increase of active and passive protection systems in the design of tunnels. Indeed, if fires are controlled in their early stages, the consequences can be generally reduced; the detrimental effects of fires become significantly greater and the ability to control them becomes significantly more difficult when fires become fully developed, also hindering the interventions of the rescue teams. Hence, the lining damage was negligible or significantly limited when the intervention of the fire-fighters was immediate or in presence of active fire protection systems that controls or extinguish the fire.

While for real tunnel fires, in most cases it was necessary to indirectly reconstruct the trends of the temperatures reached, for real-scale experimental fire tests this information is available in literature, as

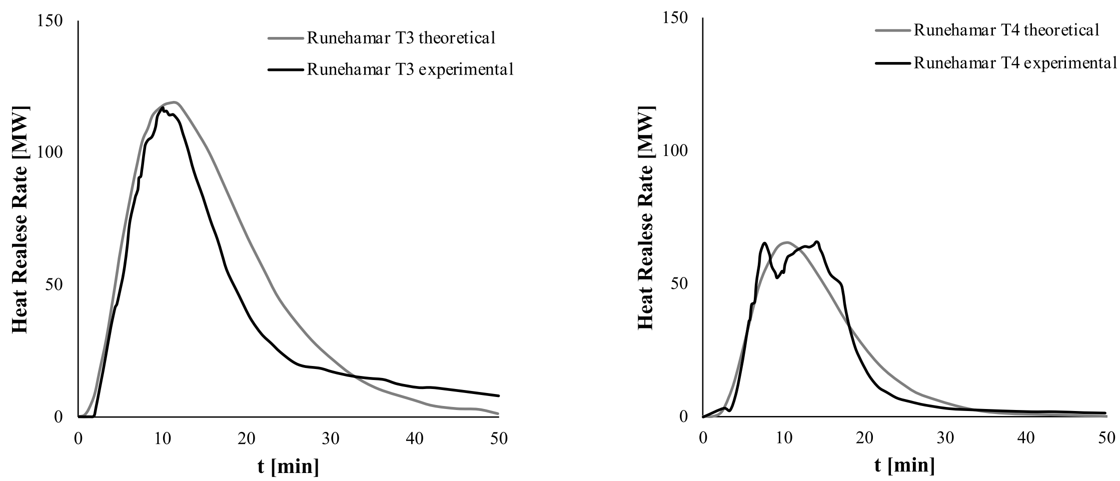


Fig. 1. Comparison to the Runehamar tests (adapted from Ingason, 2005 [14]).

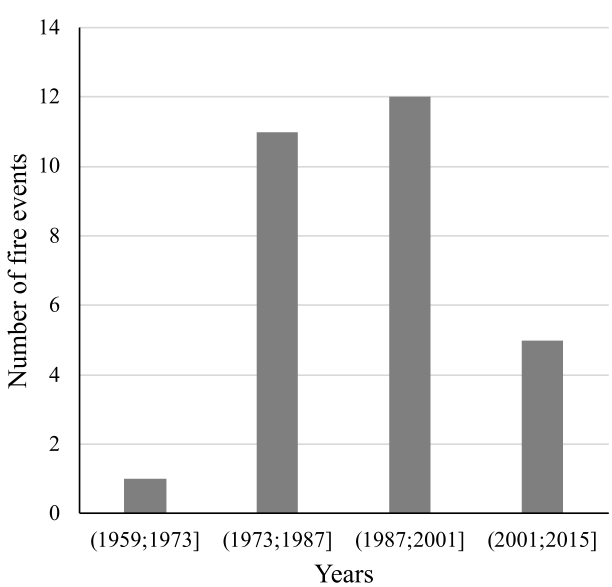


Fig. 2. Analysed fires divided by years.

soon as all the parameters related to the fire have been measured. Therefore, the real-scale experimental fire tests were analysed in order to highlight and quantify the structural damage induced by the fire; in particular, the Runehamar Tunnel Fire Tests [22] and the Large-Scale Fire Tests in the Second Benelux Tunnel [23] were deepened. In the following a brief summary of the two experiments is reported.

3.1.1. Runehamar tunnel fire tests

Five large-scale fire tests, including one pool fire tests (T0) and four HGV mock-up fire tests (T1-T4), were carried out in the Runehamar tunnel in Norway in year 2003 [22].

These real-scale fire tests have significantly improved the community knowledge about the fire dynamics in large tunnel fires. Simple and robust theoretical models were developed to estimate and predict heat release rate (HRR), gas production, fire spread, fire growth rate, gas temperature, flame length, radiation, fire spread, gas production, ventilation, backside wall temperature and so on.

In particular, as also briefly described above, based on the Runehamar fire test results, a simple method to estimate the maximum heat release rate was proposed where the maximum heat release rate in a well-ventilated tunnel fire is directly proportional to the burning rate per unit fuel area, heat of combustion and the total fuel areas, provided the fuel is fully involved in the fire. A theoretical approach to model the fire growth rate in a ventilated tunnel fire was proposed [22].

The thermal inertia, heat of combustion, wet diameter and mass burning rate per unit area of the fuel play important roles in the fire growth rate and the ventilation velocity is proportional to the fire growth rate. In this work, the parameters affecting the structural lining stability were considered, such s the ceiling gas temperatures. Maximum ceiling gas temperatures in the tests were investigated and they show a very rapid increase after ignition. A robust equation was proposed which correlate all the important parameters, including heat release rate, ventilation, tunnel geometry and fuel geometry, with the maximum ceiling gas temperature. Table 1 summarises the main information about the two tests considered for the following fluid-dynamic analyses.

3.1.2. Large scale fire tests in the Second Benelux Tunnel

Fourteen full-scale fire tests were carried out during 2000/2001 in the Second Benelux Tunnel near Rotterdam in the Netherlands and were supported by several parties [23].

An essential issue in tunnel fire safety is the choice of the most efficient combination of measures that will enhance the possibility of self-rescue of escaping tunnel users. To achieve this goal detailed information is required about the real conditions that can arise during a tunnel fire.

Many of the fire tests that have been undertaken throughout Europe and the rest of the world have focused in general on fires in small and empty tunnels and with the fire source located at the center of the tunnel. However, during a real fire, the burning vehicle is not likely to be situated in the center of the tunnel. Also, during congested traffic conditions it might not be possible to evacuate the traffic and therefore other vehicles could surround the burning vehicle.

Due to these issues the Dutch Ministry of Transport initiated the ‘Safety Test’ project, addressing specific fire safety questions for Dutch road tunnels. The project consisted of a series of full-scale fire tests and human behavior experiments in the Second Benelux tunnel.

So, the objectives of the fire tests were to assess the tenability conditions for escaping people in the case of a fire in a Dutch road tunnel and to study the effect of mitigating measures on these conditions. Several types of fire sources were used: fuel pans, cars, a van and covered truck loads, in different ventilation conditions. Temperatures, radiation levels and optical densities in the tunnel were measured, as well as smoke velocities and heat release rates. The information

Table 1
Runehamar test information useful for the nex analyses (Ingason et al., 2003 [22]).

Test no.	Description of the fire load (target not included)	Target	Total weight (kg)	Theoretical calorific energy (GJ)	Maximum HRR (MW)	Maximum ceiling gas temperature (°C)
T1	360 wood pallets measuring 1200X800 × 150mm^3, 20 wood pallets measuring 1200X1000 × 150mm^3 and 74 PE plastic pallets measuring 1200X800 × 150 mm^3; 122 m^2 Polyester tarpaulin	32 wood pallet and 6 Pe pallets	11010	244	202	1360
T2	216 wood pallets and 240 PUR mattresses measuring 1200X800 × 150mm^3; 122m^2 polyester tarpaulin	20 wood pallets and 20 PUR mattresses	6853	135	157	1313

collected about the effect of the fire development, and the use of longitudinal ventilation and sprinklers, was used to evaluate the possibility of self-rescue for escaping people.

The traffic tube in which the tests were performed has a rectangular cross section with a height of 5.1 m, a width of 9.8 m and a length of 840 m. The tunnel was equipped with longitudinal ventilation consisting of jet fans near the ceiling and has escape doors at intervals of 100 m.

The test series included 14 tests and it was divided into three categories, each category primarily addressing one of the six issues mentioned in the objectives above.

The first set of testes (Category 1) aimed to investigate the effect of longitudinal ventilation on the heat and smoke propagation in the tunnel in the early stages of a fire. The objective of Test 5 to 10 (Category 2) was to study the effect of forced longitudinal ventilation on the rate of heat release of the fire and the effect of the ventilation on the tenability conditions in the tunnel. The third set of tests (Category 3) aimed to investigate the effect of a normal open deluge sprinkler system.

The results of these tests were useful for this work mainly for fluid-dynamic model calibration, indeed, in accordance with standard procedures for new tunnels in the Netherlands, the tunnel ceiling and part of the walls were sprayed with insulation to enhance the fire resistance of the tunnel structure, so no structural damages were found.

4. Lining damage

4.1. Effects of fire on concrete structures

The fire resistance of structures and their performance in fire are closely related to the thermal and mechanical properties of the structural materials. Among the structural materials having the best performance in fire, concrete is certainly the main one. In particular, the advantages of using concrete in fire are [24]:

- it is incombustible and so it does not emit any toxic fumes or smoke;
- possessing a low thermal conductivity, it is a good insulating material, acting as an effective fire shield.

This excellent performance is due to the main constituents of its composition, namely cement and aggregates. However also the concrete can suffer during a wilful fire, indeed the high temperatures can cause the deterioration in mechanical properties and the explosive spalling, causing reduction in section size and the direct exposure of the steel reinforcements to fire. These two problems can greatly affect the load-bearing functions of the concrete members in general and also the concrete tunnel lining. Both material and structural behaviour of concrete are well described in the literature [24]. [25] and in the technical standards [26] and well known to the scientific community. However, a general overview is presented in the following for completeness.

From the mechanical point of view, the rise in temperature causes an irreversible loss of stiffness and strength. In particular, the compressive and tensile strength and the Young's modulus can be expressed with respect to the temperature. The decrease of stiffness and strength starts at about 100 °C, and at 600 °C the compressive strength is almost halved; the behaviour is slightly different between siliceous and calcareous aggregates.

Another problem that can occur when concrete is exposed to fire is spalling. This is the phenomenon involving explosive ejection of chunks of concrete from the surface of the material, due to the breakdown in surface tensile strength. It is caused by the mechanical forces generated within the element due to strong heating or cooling, i.e. thermal stresses, and/or, by the rapid expansion of moisture within the concrete increasing the pore water pressure within the structure. Spalling may occur under a variety of circumstances where strong temperature gradients are present, both in the heating and cooling phases. From Ref. [25] we can read that spalling mainly depends on numerous factors such as heating rate, section size and shape, reinforcement and its cover, moisture content, pore pressures, concrete permeability, concrete age, concrete strength, restraint to thermal expansion, compressive stress before and during heating, cracking, etc. In this work, all these described problems were directly considered in the damage state definition of the concrete tunnel lining subjected to certain temperature levels; all the details are described below.

4.2. Damage state definition

The previous overview of all the problems that fire can cause on concrete material/elements, was useful to define in detail the damage levels that a structure can suffer, under a rise in temperature [26].

In this definition, the focusing on the structural damage found during the studied real fires was particularly useful. Five different damage states d_{si} for the concrete tunnel linings, were defined as shown in Table 2, focusing on cracks in the concrete, spalling of the concrete cover and finally on the collapse of the lining it-self [27].

All the collected real fires were investigated and studied in detail in order to classify, according with the defined damage state level of Table 2, the tunnel lining damage.

The real fires were analysed through post fire reports, photos of the event and, in some cases, also through numerical analysis and modelling carried out in literature, such as in the case of New Qidaoliang Highway Tunnel [28], where the structural damages of the lining were investigated and linked to the gas temperature simulated with advanced CFD analyses.

Fig. 3 shows that that in most cases the lining damage was serious and, in very few cases the structural tunnel lining collapsed; also, the frequencies in which moderate and minor damages were observed are quite numerous.

5. Thermo-flud-dynamic simulations of selected real cases

Once the possible damage levels due to the fire in the reinforced

Table 2
Defined damage state level.

ds_0 (None)	ds_1 (Minor)	ds_2 (Moderate)	ds_3 (Serious)	ds_4 (Collapse)
No structural damage	Localised and shallow cracks	Several cracks and localised spalling	Wide and deep cracks, extensive spalling and local collapses	Lining collapse

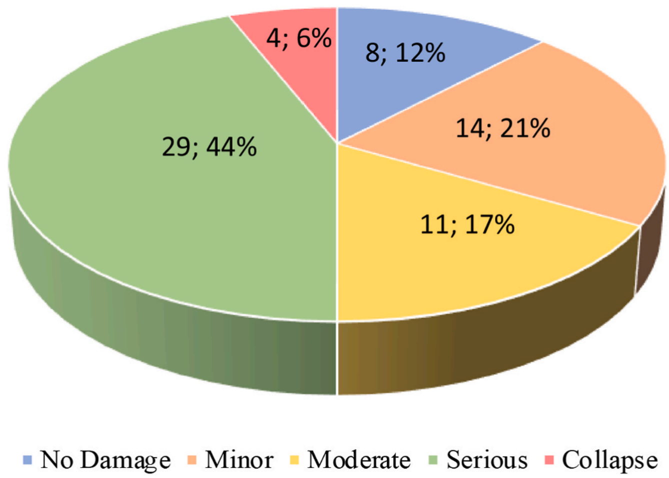


Fig. 3. Frequencies of the damage states defined for the selected real fires [16,17].

concrete tunnel have been defined, some real fire were selected and simulated through fluid dynamic analyses. In particular, for these analyses two different pieces of software were used; in most cases the zone model CFAST [29] was used, while the Channel and the St Gotthard big fires were simulated in FDS [30].

5.1. Selection and description of the case studies

Among all the real fires analysed, several cases were chosen (see Table 3) and thermo fluid-dynamic analyses were performed for understanding the temperatures level reached in the ambient during the fires. The analysed fires were chosen by varying the damage level. In all the analysed cases no forced ventilation is present, so there is only the natural one.

An extended literature review was conducted in order to collect all the fire parameters necessary for performing the analyses; in particular:

- the fire parameters, which are listed in Table 3;
- the HRR curve is considered according with Ingason equation [14];
- the tunnel geometry was obtained from information available in literature and was summarised in Table 4.

5.2. Zone models-CFAST

Zone models assume that a given volume can be vertically subdivided into zones, over which several algebraic equations are solved to determine the relevant flow properties. The upper layer and sometimes a zone are used to represent the plume or ceiling jet in the compartment with the fire. Temperatures, velocities and other properties are assumed to be uniform within these zones; the transfer of mass, energy, momentum and species are tracked from one zone to another via conservation equations.

Table 4
Case studies geometry.

Tunnel fire-	Length (km)	Height (km)
Williams	7	5
Hiltra	10	5
Kaprun	3	3
Baku	3	4
Hovden	7	5
Gudvanga	7	5
Huguenot	7	5
Oslofjord	10	5
Channel	7	7
St Gotthard	8	5

CFAST is a two-zone fire model used to calculate the smoke dispersion, the fire gases dynamics and the temperature throughout compartments of a facility over time; each compartment is divided into two gas layers [29]. In this case, the tunnel was horizontally divided into several fully communicating fictive "compartment", in order to have an estimation of the temperature evolution along the tunnel. For the scope of this research, that is to know the gas temperature evolution during a tunnel fire starting from the HRR curve (see Fig. 4), CFAST is recommended, as it is a quick and user-friendly software.

However, some researchers [30] demonstrate that CFAST models fail in case of high HRR pick, properties of fire with relevant fire load, such as the case of Channel and the St Gotthard fires. For this reason, these last two fires were modelled using Fire Dynamic Simulator (FDS)

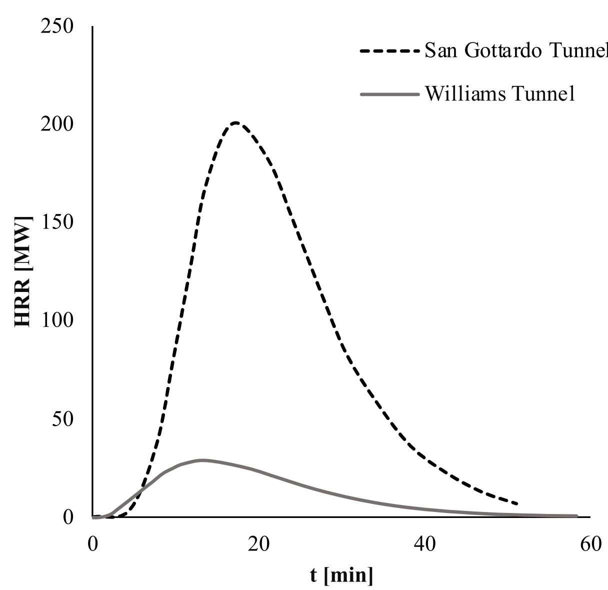


Fig. 4. HRR curve examples used for simulations.

Table 3
Case studies analysed.

Tunnel fire-	Vehicle type-	E tot (GJ)	Q max (MW)	Fire duration (min)	Fire damage-
Williams	1 bus	40	29	50	None
Hiltra	crane engine	7	6	60	None
Kaprun	Funicular train	30	20	60	Minor
Baku	2 metro coaches	80	40	45	Minor
Hovden	2 cars, 1 motorcycle	11	6	90	Minor
Gudvanga	1 HGV	240	200	60	Moderate
Huguenot	1 Bus	40	30	60	Moderate
Oslofjord	1 HGV	300	200	90	Moderate
Channel	10 HGV	2200	200	204	Serious
St Gotthard	13 HGV,10 car	3170	200	480	Collapse

software. All the details are described below.

5.3. CFD models- FDS

Computational fluid dynamics (CFD) codes implement the fundamental equations of fluid dynamics over complex domains. FDS is an open source CFD model for fire-driven fluid flows [30]. Due to the accuracy of their phenomenological description and the potential variety of configurations and boundary conditions they can describe, CFD models allow the user to analyse the interactions which occur simultaneously in a fire accident, helping to assess the influence of different parameters on the fire event evolution. Given the complexity of the software and the numerous input parameters, the first FDS model was validated against experimental results. In particular, the Runehamar tests were modelled, to validate the fire parameter of the other models. Five large-scale fire tests, including one pool fire test and four HGV mock-up fire tests, were carried out in the Runehamar tunnel in Norway in year 2003. Heat release rate, fire growth rate, gas temperature, flame length, radiation, fire spread, gas production, ventilation, backside wall temperature, backlayering and visibility were investigated during tests [22]. Therefore, all the information was available to model the Runehamar fire tests through CFD analyses. In this work, the HRR and the gas temperature of the Test1 and Test2 were considered to validate the FDS models; the parameters of these two tests are summarised in Table 1 and the geometry of the tunnel is represented in Fig. 5. Since all the analysis parameters were known (e.g. geometry, HRR fire curve, fire size, ventilation), only the computational grid cell size needed to be defined. A sensitivity analysis was conducted, choosing the tentative range of grid size considered as moderate ($D^*/dx = 10$, see Ref. [29]), in-line with studies conducted in Refs. [31,32]. It was found that, in this case, the mesh grid size did not impact on the result (as absolute temperature quantities), as occurred also in Ref. [33].

Fig. 6 shows a benchmark between the experimental and the FDS simulation results in terms of HRR and of gas temperature; the temperature are in good agreement both for heating rate and for temperature peak (see the solid and the dashed black lines with the red and green ones of Fig. 6b); a good agreement can be observed also between the HRR output curve and the input one (Fig. 6a), thus confirming the correct modelling of the FDS simulations. The theoretical HRR fire curves Q(t) were obtained according to the exponential expressions proposed by Ingason [14], as also explained in section 2.

Once the FDS model had been calibrated it was possible to simulate the Channel (Fig. 7) and the St. Gotthard fires, using the input parameters of Tables 3 and 4.

The results of all the simulations are described in the following, focusing on the gas temperature that could cause different damages on the tunnel lining.

5.4. Discussion and results

All the tunnels examined in this paper are made of concrete, whose fire performance is very often given for granted, because of concrete incombustible nature and ability to function as a thermal barrier, preventing heat and fire spread. However, even concrete presents problems in case of fire. Indeed, there are several physical and chemical changes which occur in concrete subjected to heat, causing the reduction of strength and stiffness of the structural material. The stiffness and the strength start to reduce at about 100 °C, while at about 400 °C the strength reduction factor is equal to 0.75 [26]. In addition, in the case of tunnel lining, the structural behavior may depend on load patterns and boundary conditions given by the interaction with the surrounding soil [3,17].

Furthermore, given the high thermal inertia, concrete structures are not sensitive only to the temperature peak reached during the fire, but also to the duration of each temperature level.

Indeed, observing Fig. 8, it is evident that on one hand high temperature peaks can be reached even if the fire structural damage is low and on the other hand high structural damage can be observed even with not very high temperatures, but always higher than 400 °C.

Thus, considering that the maximum temperature is not the sole influencing parameter, different temperature thresholds ($\theta > x$) have been considered. Each structural damage level has been associated with the periods of time $\Delta t(\theta > x)$ spent above such thresholds; in particular, six $\theta = x$ were fixed (Fig. 9) so that $\Delta t(\theta > 200)$ represents the period of time spent above 200 °C, $\Delta t(\theta > 400)$ the one above 400 °C, and so on up to 1200 °C.

Analyzing Fig. 9, it is possible to observe that:

- fires with temperatures even higher than 1000 °C, but with very short duration, may cause no damage or a minor damage (e.g. Baku tunnel);
- as the damage increases the achieved temperature and the duration of overcoming them increase;
- in the case of the collapse, both temperatures and durations are high;

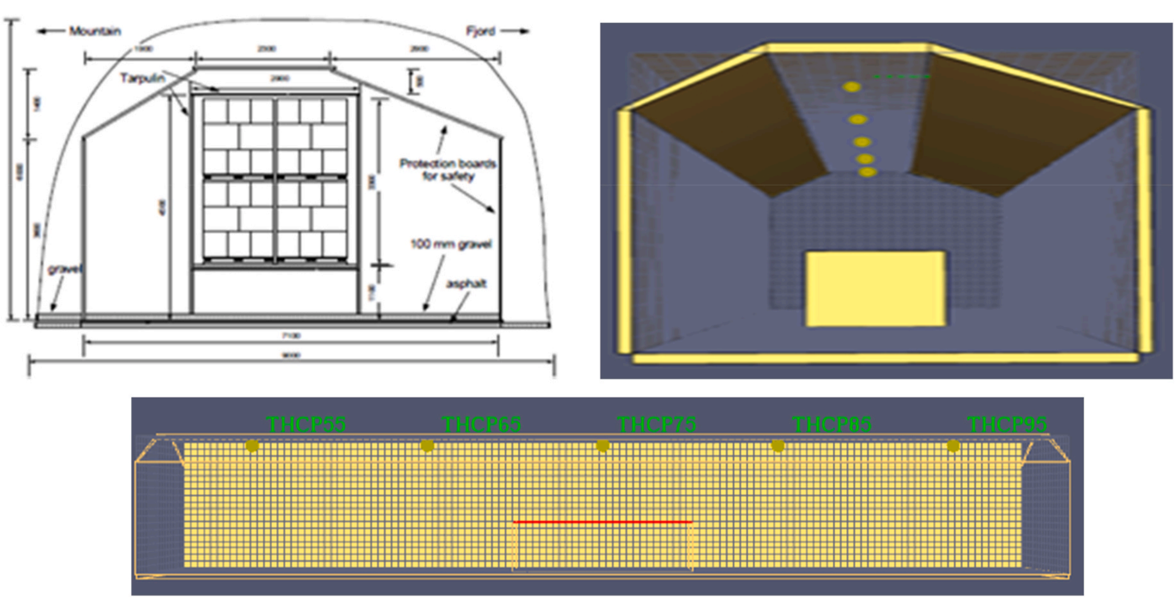
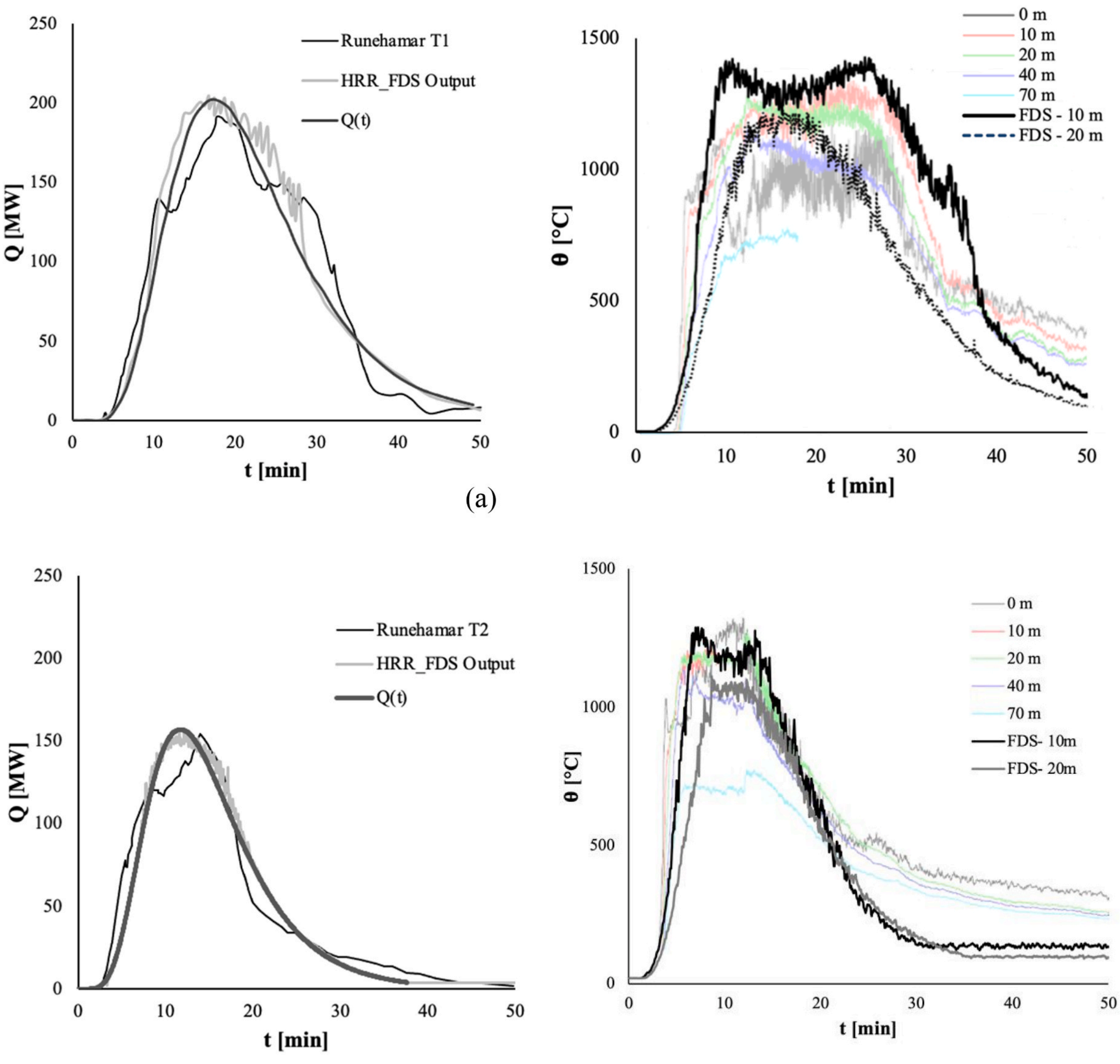


Fig. 5. FDS Runehamar test model.



(a)

(b)

Fig. 6. FDS Runehamar test results: (a) test 1, (b) test 2 [22].

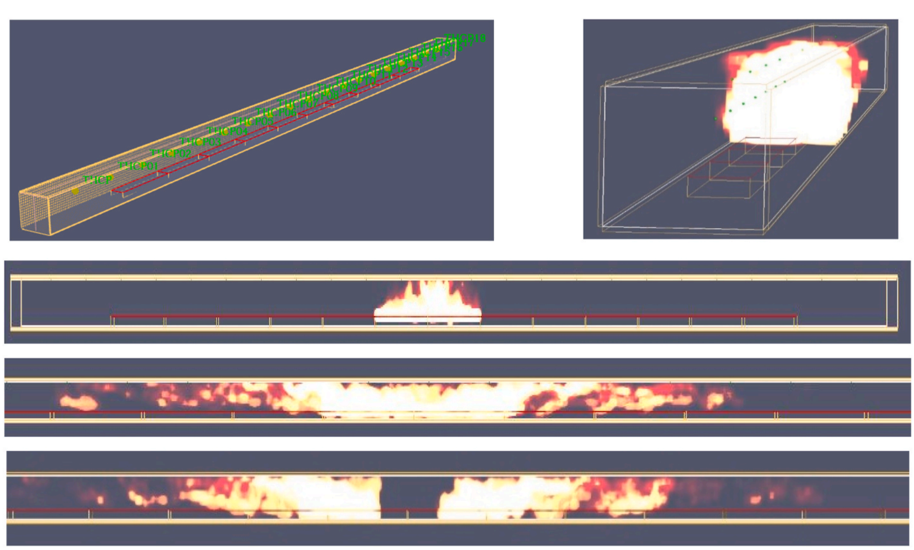


Fig. 7. Channel fire FDS simulations.

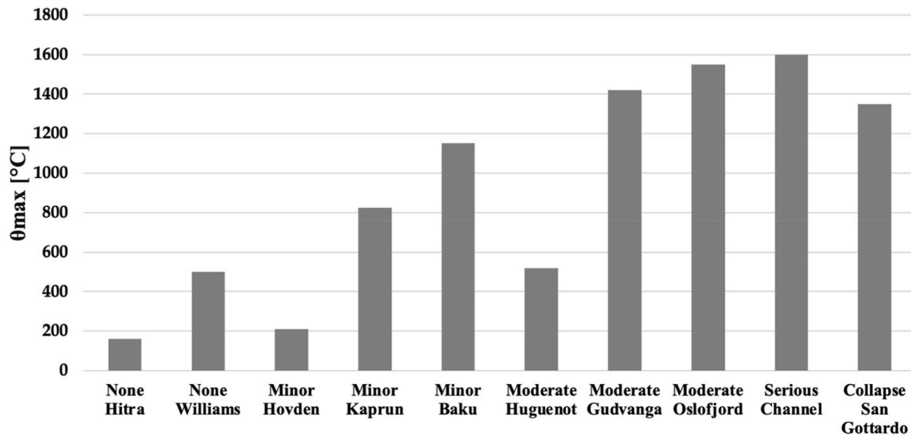


Fig. 8. Maximum temperatures reached during each analysed fire [27].

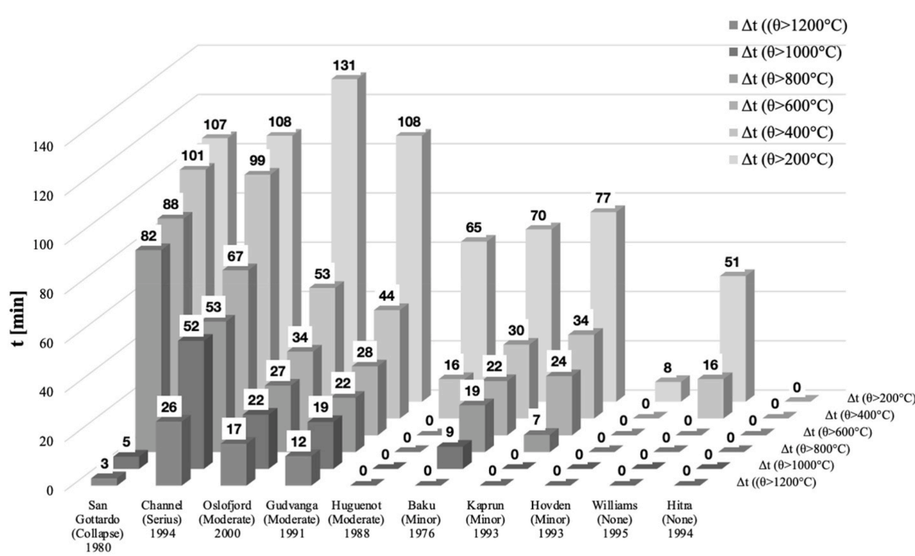


Fig. 9. Duration of each temperature threshold.

- there is a link between the observed structural damages and the construction year, indeed the tunnel built after the 1990 year seems to have better fire performance. This observation can be due both to the state of preservation of the tunnel and to a possible more modern construction technique.

The Baku and Huguenot cases seem to disagree with the level of damage that has been attributed. However, in the case of Baku tunnel, even if the gas temperature reached 800–1000 °C for short period of time, the observed structural damage is minor; from the literature we learn that the fire was confined by the outer casing of the train, preserving the structural lining from high temperatures.

Based on the results described in the previous section, a summary of the procedure for the assessment of concrete lining fire resistance is presented in the following flow chart (Fig. 10). In particular, the procedure can be used both for the design and assessment starting from evaluation of the real fire temperatures and for reconstructing the real fire, starting from the structural damage on site observation.

6. Application of the proposed methodology to a real tunnel

The proposed methodology is applied to a real concrete tunnel, in order to assess the potential damage level under fire, using the natural fire curves obtained from advanced thermo-fluid dynamic analyses. In particular, the expected damage level of the underground structure is identified, trough the temperatures reached in the ambient during the fires and then it is demonstrated through advanced thermo-mechanical analyses.

The main steps for applying the proposed methodology are:

- to obtain the natural fire curves through CFD analyses considering several fire scenarios;
- to perform the cross section thermal analyses;
- to carry out the thermo-mechanical structural analyses.

From the first step, knowing the gas temperatures, the first classification of the expected damage level is possible and in the last two steps it is confirmed by assessing thermo-mechanical analysis results.

6.1. Case study description

The analysed structure is the “UR15” tunnel, which is part of an infrastructure created for the European Organization for Nuclear Research (CERN) "*High Luminosity LHC*" project (see Fig. 11a). This tunnel has a length of about 300 m, a depth of 70 m and some services, including transformers, ducts and electrical and fiber-optic cables [34].

The analysed section is the one highlighted in light blue in Fig. 11b. Regarding the structure geometry, in the following analyses the final

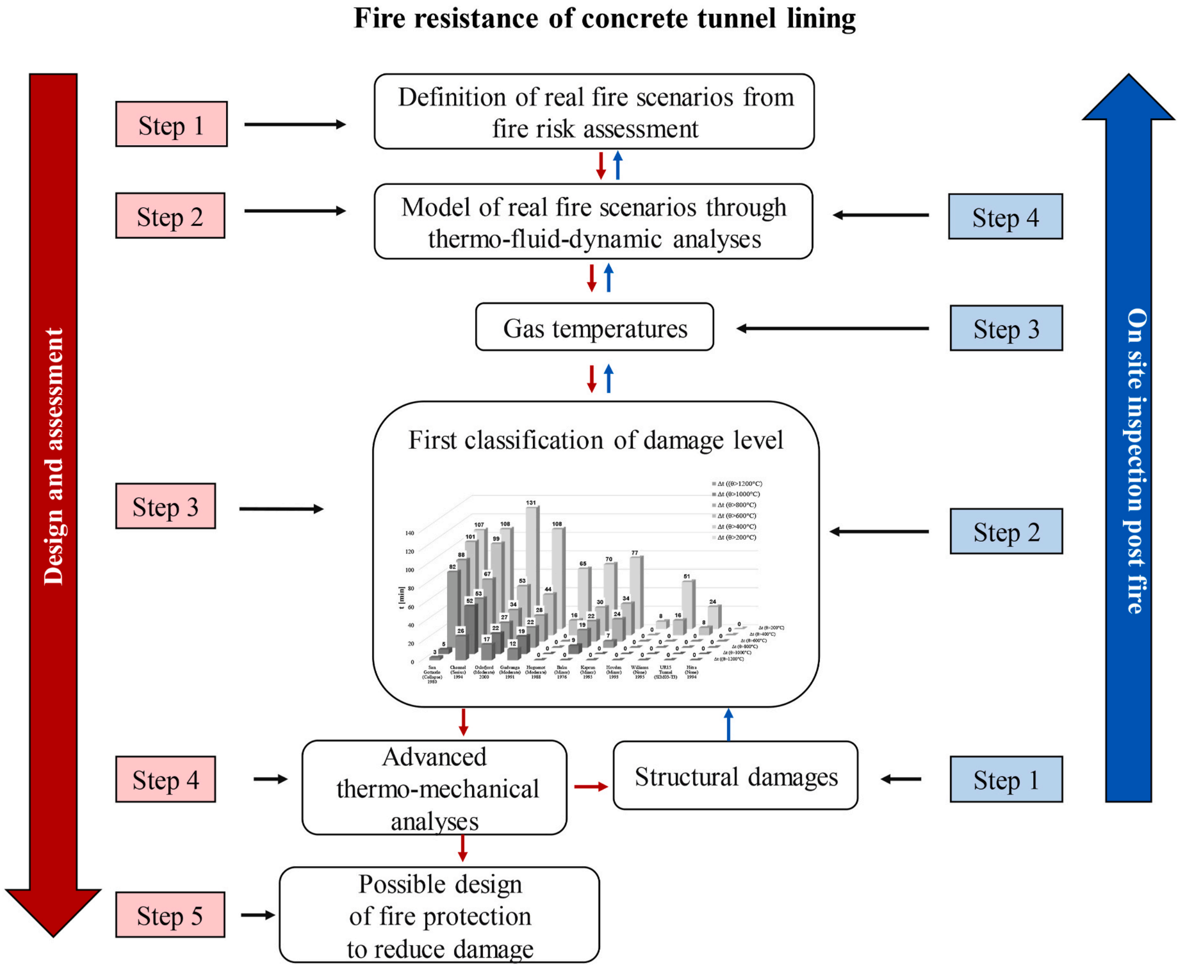


Fig. 10. Procedure for the application of the proposed methodology.

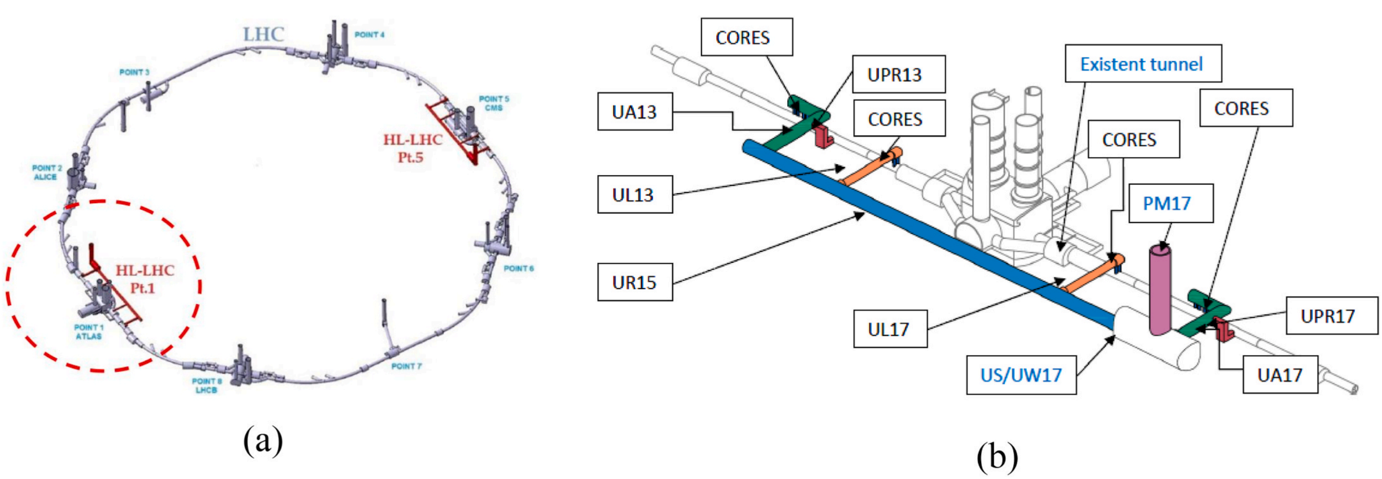


Fig. 11. (a)Description of LHC tunnel, (b)Position of the Hi-Lumi tunnel UR15, from file [36].

lining is considered, because it is directly heated during the fire. The following Fig. 12a shows the geometry of UR15 tunnel cross section. Along the entire tunnel, the invert is a precast concrete element and the lining thickness is 50 cm in all the rest of the tunnel section. The section is made by C35/45 concrete and B500b steel for reinforcement bars. The crown and the wall side sections are 50 cm high and 100 cm wide, with φ14 reinforcement bars positioned every 15 cm, for a total of 7 φ14 both on the lower and upper edges with a concrete cover of 5 cm (see Fig. 12b).

The lithology, where the tunnel is built, is characterized by several sub-horizontally layers of sedimentary rocks called molasses. Six categories of rock masses have been defined: 3 types of marl and 3 types of sandstone. The analysed sections are in zone made by “hard sandstone” in the lower part and “medium marls” in the upper part, with the following geo-mechanical properties (see Table 5):

The UR15 tunnel is divided by a fire door in two compartments A and

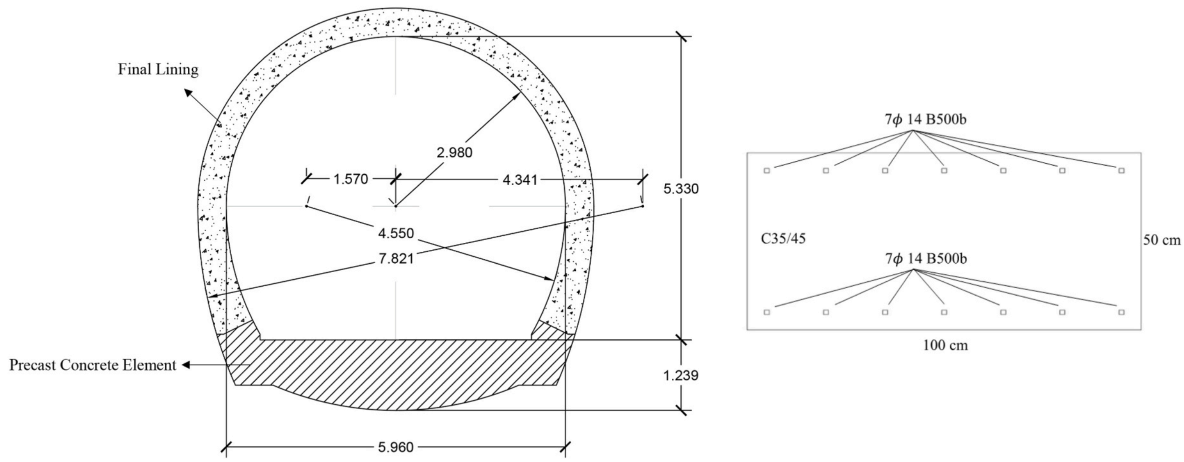


Fig. 12. a) Geometry of cross section layout for UR15 – typical section; b) R.C. Tunnel Sections.

Table 5
Geomechanical properties.

Ground type	γ [kN/m^3]	E [MPa]	K0 [-]
Medium Marls	25	3500	1.5–2.2
Hard Sandstone	25	5000	1.5–2.2

B. There is also a ventilation system and smoke extractors, as indicated in Fig. 13. The analyses described in this paper concerns the A3 sector, where the maximum temperature was found through fluid dynamic analyses; all the details are explained in the following.

6.2. Advanced fire analyses

The first step of the proposed procedure consists in the definition of the natural fire curves to which the structure could be subjected. Computational fluid dynamics (CFD) modelling provides a feasible approach to obtain both temporal and spatial fire temperatures distributions within the tunnel. A series of fire scenarios are modelled using again FDS, to find the zones of the tunnel in which the highest temperature is reached [34].

For performing CFD analyses, the heat release rate curve (HRR) has to be defined; in this case, the chosen design fire was the ignition and combustion of an electrical cabinet due to electrical fault. The selected fire design to be used is based on literature review of scientific publications looking at HRR of electrical cabinets fires and their capacity to spread towards adjacent racks. So, the fire design was based on electrical cabinet failure that propagates over time. To characterize the HRR, the methodology described in Ref. [35], was followed. In particular, the total HRR with the 5 individual burners was represented in Fig. 14a, where each burner last for 60min and as they are ignited in a 10min delay time, the total fire last 110 min until complete burnout.

The selected scenarios assume the fire spreads symmetrically along five electrical cabinets located together. The electrical cabinets are assumed to contain 50 kg of combustible material each, and to be placed adjacently with doors closed. In this case, five burners with a maximum HRR per unit area of 1000 kW/m^2 are used to reproduce this curve. They are sequentially turned on every 600 s. This fire is an illustration of a realistic representative scenario of industrial facilities housing electrical equipment. It is worth noting that inputting a given HRR to the simulation does not mean that this is the actual HRR that will be simulated. In a partially confined compartment, the oxygen available will limit this HRR.

Six CFD simulations (see Table 6) were carried out by changing the position of the fire and the activation of the protection systems with the aim to create different fire scenarios and to provide the corresponding natural fire curves which last 60 min. In the tunnel cross-section, seven thermocouples (see Fig. 15) were inserted in the model, every 15 m, for a total of 20 reading stations. All the performed simulations are listed in Table 6. In the SIM03, SIM04, SIM05 and SIM06 simulations, normal ventilation is blocked on the Detection Time (DT) and smoke extractors are activated on DT. In the SIM03 and SIM04 simulations, the fire door is closed at DT while it remains open in the two other simulations (SIM05 and SIM06). In addition, two other SIM03 analyses are carried out with fire position at the end of the A3 section:

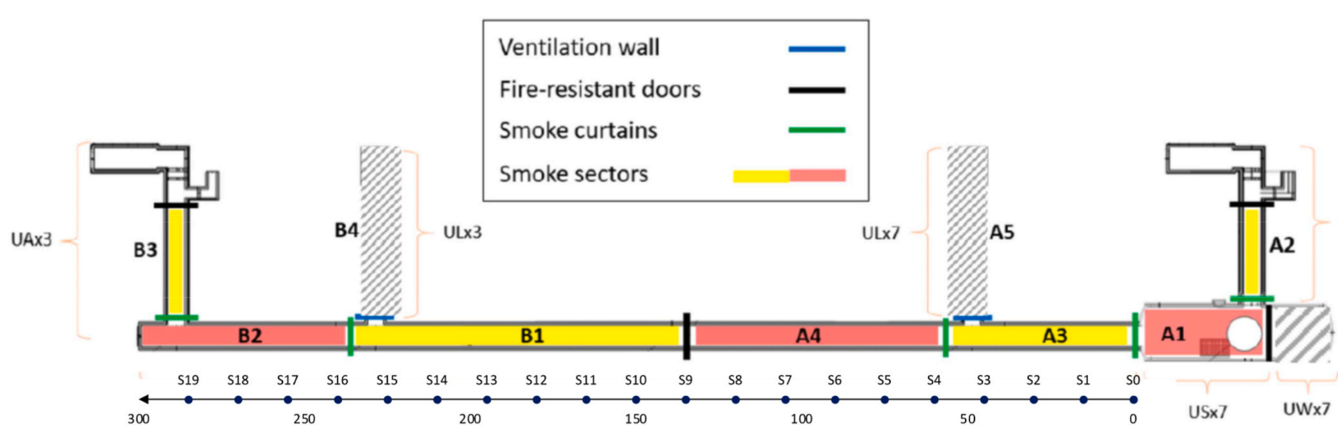
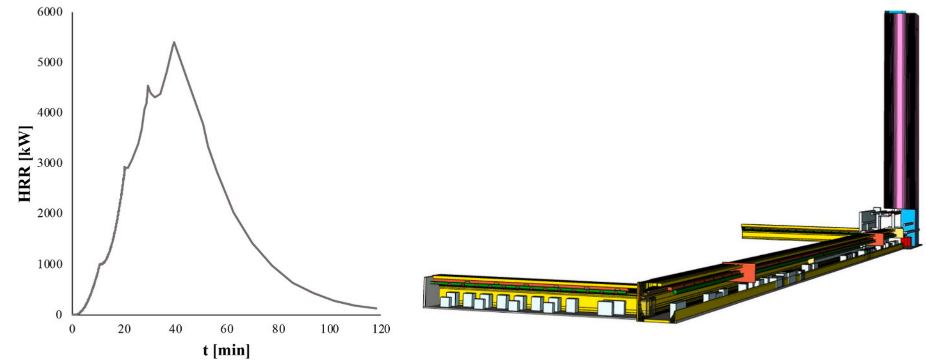


Fig. 13. Identification of fire compartment and smoke sectors.



(a) (b)

Fig. 14. (a) HRR used in the FDS simulations, (b) FDS model.

Table 6
Fluid-dynamic simulations.

SIM ID	FIRE POSITION	NORMAL VENTILATION	SMOKE VENTILATION	FIRE DOOR
SIM03	END A3	STOP on DT	ON on DT	CLOSED (at DT)
SIM03 NO DET	END A3	ON	ON on DT	CLOSED (at DT)
SIM03 NVENT FAIL	END A3	ON	OFF	IS KEPT OPEN
SIM04	MIDDLE A4	STOP on DT	ON on DT	CLOSED (at DT)
SIM05	END B1	STOP on DT	ON on DT	IS KEPT OPEN
SIM06	END B2	STOP on DT	ON on DT	IS KEPT OPEN

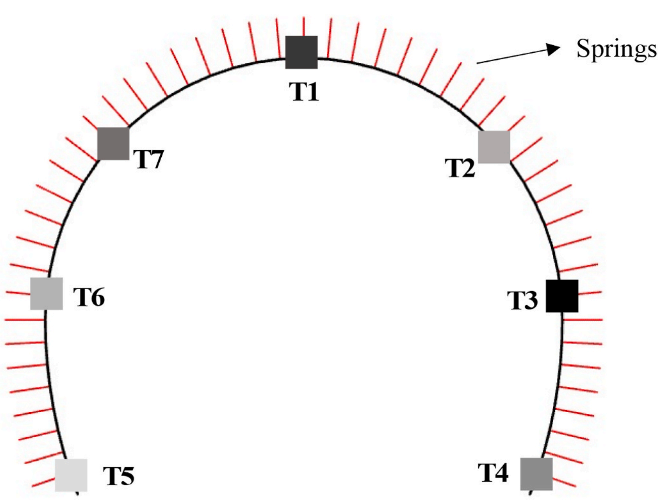


Fig. 15. Position of the seven AST in the tunnel cross-section.

- SIM03-NODET: where the fire is not detected. Therefore, the fire door is not closed, and the smoke extraction system is not activated, and normal ventilation does not stop;
- SIM03-NVENT FAIL: where the fire is detected. So, in this case the fire door is closed, and the smoke extractors are active, but the normal ventilation does not stop.

The tunnel gas temperature, during each fire scenario, is measured thought Adiabatic Surface Temperature (AST) sensors. This kind of device is ideal for performing the subsequent thermo-mechanical analyses, since it measures a temperature on an imaginary adiabatic surface, geometrically identical to the real one on the structural model and exposed to the same fire scenario (see the suggestions given in Refs. [29,37]).

After the fluid-dynamic analyses, the structural fire behavior was assessed. In particular, thermo-mechanical analyses of the cross section of the tunnel were performed using the dedicated software SAFIR [38,39]. The structural fire performances are investigated, considering each tunnel section exposed to its own natural fire curve (see Fig. 15).

The tunnel lining was modelled using 50 beam elements, the ground-structure interaction was considered using compression-only springs by mean 49 truss elements and the tunnel base was modelled as fixed. The stiffness of the springs was calculated based on Eq. (1), as a function of tunnel radius R, modulus of elasticity E, and Poisson's ratio ν of the surrounding soil [4]. Considering a weighted average of the two soil layers, E and ν were taken as 4578 MPa and 0.3, respectively.

$$k_s = \frac{E}{1+\nu}\,\frac{1}{R} \tag{Eq. 1}$$

As for the material properties, at ambient temperature, the compressive strength of concrete was 35 MPa and the tensile strength was assumed to be zero. The temperature-dependent material properties from EN 1992-1-2 [26] were considered both for concrete and steel. The loads applied on the tunnel were calculated as a function of the vertical ground pressure and the horizontal one, based on Eq. (2):

$$p_v = \gamma(H - R\cos\varphi)$$

$$p_h = K_0\, p_v \tag{Eq. 2}$$

where H is the depth of the tunnel axis, R is the radius and φ is the angle between the vertical axis and the tunnel lining position (Fig. 16).

The radial component and the tangential one were calculated as following:

$$p_r = p_v \cos^2\varphi + p_h sen^2\varphi$$

$$p_t = \frac{1}{2}\,(p_v - p_h) sen\, 2\varphi \tag{Eq. 3}$$

6.3. CFD analysis results

The results of the CFD simulations give the temperature in function of the time and the space along the tunnel. Considering all the simulations, the highest temperature is reached at the station 3 in the SIM03 simulation. In particular, considering the seven thermocouples of each tunnel station, the one recorded the highest temperature was the thermocouple 3 (T3) (see Fig. 17). In the following this section with the

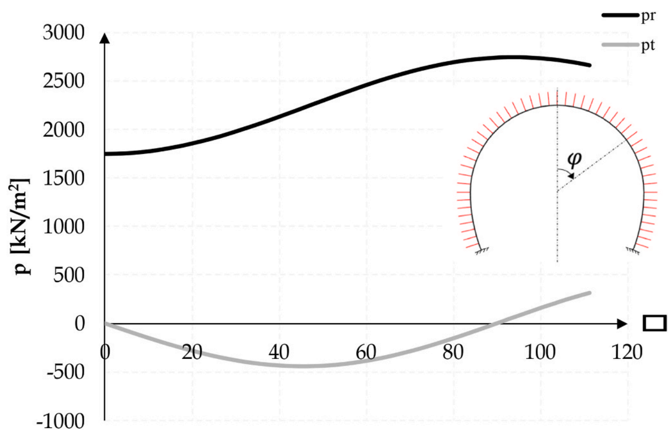


Fig. 16. Radial and tangential pressures by changing the angle.

highest temperatures will be considered.

The fire resistance assessment was conducted for 60 min of fire exposure because the temperature curves after 60 min reached almost the ambient temperature. In any case the temperatures are lower than 100 °C, temperature at which no reduction in material strength and stiffness occurs (Fig. 17a).

Fig. 17a shows that the maximum temperature reached during the SIM03, is about 450 °C and this peak lasts only 10 min. Therefore, these maximum temperature and duration cannot cause the collapse of reinforced concrete structures, for the reasons described above (see section 4.1). Furthermore, the analyses results show that the HRR curve are not fully developed (see Fig. 17b), so the combustion process is governed by ventilation, indeed the output HRR curves provided by FDS are shorter than the input one.

6.4. Damage level assessment

As described in the previous sections, after a tunnel fire, the structural lining can show various level of damages, even if the structure does not collapse. So the level of damage produced by the fire should also be quantified for reparability reasons. Consequently, the time duration, in which the gas temperature exceeds a certain threshold, is considered, because the maximum temperature reached during the fire is not sufficient to describe the consequences on the mechanical strength of concrete lining (see previous sections).

The expected damage level is assessed considering the tunnel exposed to the maximum temperature curve obtained by the CFD analyses described above (thermocouple T3- SIM03), which is about 500 °C. However, also the overcoming of the temperature thresholds defined in the methodology is considered in order to have a final estimation of the expected fire damage.

In particular, Fig. 18 shows that for the UR15 tunnel, the temperature is greater than 200 °C for 24 min and greater than 400 °C for only 8 min; in any case the temperatures are lower than 600 °C. Therefore, comparing the UR15 case study histogram with the ones obtained in the proposed methodology, the expected damage is “None”.

6.5. Thermo-mechanical analysis results

As described before, in order to confirm the absence of structural damages for the UR15 tunnel subjected to the natural fire curves, advanced thermomechanical analyses were carried out.

The results were assessed by analysing both temperatures and stresses evolutions inside the tunnel lining. The results were considered in three different sections: the fixed base section, the crown one and the one corresponding to T3 thermocouple.

Fig. 19 shows that, considering the lining section exposed to the maximum natural curve T3, the temperatures inside the concrete section are lower than 250 °C also in the directly exposed surface (see the solid grey line). Therefore, these temperature profiles do not cause any resistance loss of the section. This is also confirmed by observing the bending moment (M) – axial force (N) resistance domains that do not reduce for all the thermal transient (see Fig. 20). The resistance domains were evaluated using the bending moment- curvature method, explained in Refs. [40,41], considering the reduction of stiffness and strength of concrete exposed to fire in according to the Eurocode [26].

Furthermore, Fig. 20 shows that all the stress points by changing exposure time are inside the domains and so the resistance checks are all satisfied.

Fig. 21 shows that during the thermal transient, both the axial forces and the bending moments change due to the thermal curvature, linked to the gradients between the lining intrados and extrados. As the temperature increases, the tensile stress due to the bending moment, increases at the lining extrados, but this should not represent a real problem since this part of the lining is not directly exposed to fire. However, passing from 30 min to 60 min, the stresses decrease because after 30 min the cooling phase starts in the natural fire curve and the temperatures, also inside the lining, decrease.

So, all these results are consistent with the expected damage level based on the proposed methodology, according to which the lining does not collapse under the natural fire curves.

7. Conclusions

The paper shows a design and verification approach to the reinforced concrete linings of tunnels in fire. From the analyses the structural

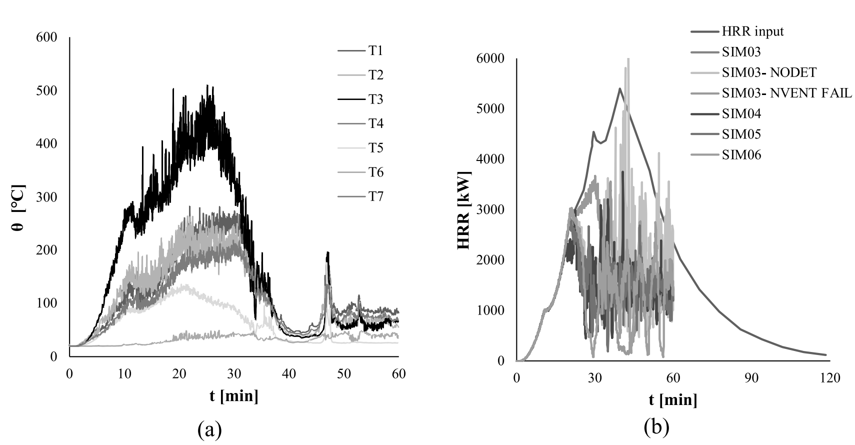


Fig. 17. (a) Natural fire curves read by thermocouples in S3 station during SIM03 simulation; (b) input and output HRR curves.

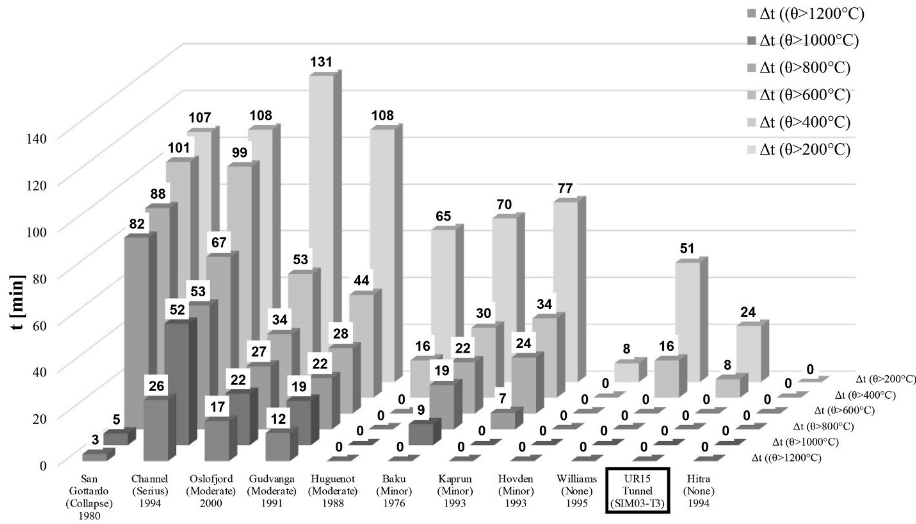


Fig. 18. UR15 case study damage state classification.

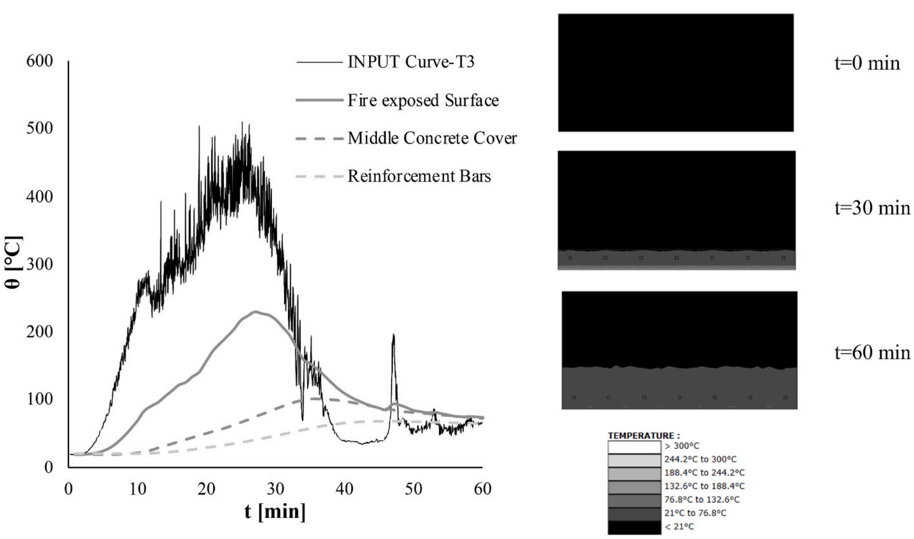


Fig. 19. Temperatures inside the concrete section subjected to T3 fire curve.

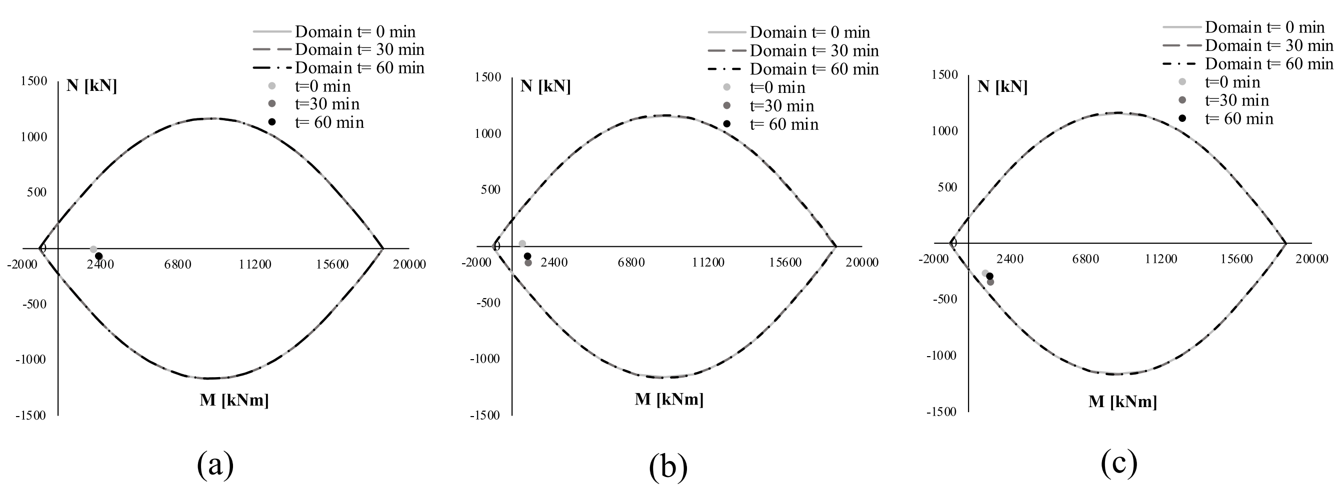


Fig. 20. M − N resistance domains under the natural fire curves in (a) crown section, (b) T3 section, (c) fixed base section.

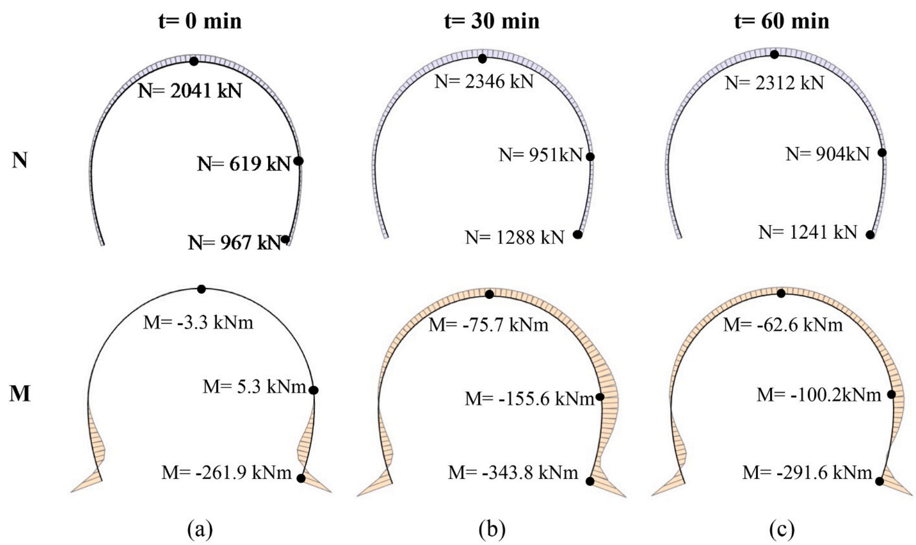


Fig. 21. Stresses evolution at different time exposure.

damage observed after sixty-six real tunnel fires and collected in literature, five damage states have been identified ranging between ds0 (no structural damage) and ds4 (lining collapse).

When the information provided in literature were enough to perform thermo fluid-dynamic analyses, the gas temperatures reached during the real cases have been simulated to link the structural damage with the temperature reached during fire. The analyses have been carried out with zone models (e.g., CFAST software) and computational fluid dynamics (CFD) models of fire-driven fluid flow (e.g. FDS software) in the case of high fire load (e.g. high HRR peak). Since the maximum temperature reached during the fire appeared not appropriate to describe the effect of fire on the concrete linings, the time lapse with temperature above specific thresholds has been correlated to the above mentioned damage states:

- fires with temperatures ranging around 1000 °C for a short time cause no damage or a minor damage;
- fires with temperature higher than 1000 °C cause greater damage as longer the duration of time when high temperature;
- in the case of the collapse, both temperatures and durations are high.

Moreover, a link between the observed structural damages and the construction year has been noted: indeed, the tunnel built after the 1990's seems to exploit better fire performance, probably due to both the state of preservation of the tunnel and the construction technique. More investigation is needed on this aspect.

Finally, the methodology has been applied to a real concrete tunnel in order to assess its potential damage level under fire. The damage level of the underground structure identified through the ambient temperatures reached during different real fire scenarios according to the methodology has been confirmed by analysing both the temperatures and the stresses of the structural lining, through advanced thermo-mechanical analyses.

In future the methodology could be applied to additional case studies and further validated.

Moreover, further studies will be carried out, to quantify damage levels and to correlate them to structural material mechanical parameters.

Authorship statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in the Fire Safety Journal.

Category 1

Conception and design of study: D.de Silva, M.Andreini, A.Bilotta, E. Nigro, S.La Mendola

acquisition of data: D.de Silva, G. De Rosa

analysis and/or interpretation of data: D.de Silva, M.Andreini, A. Bilotta, O.Rios;

Category 2

Drafting the manuscript: D.de Silva, G. De Rosa; revising the manuscript critically for important intellectual content: M.Andreini, A. Bilotta, E.Nigro;

Category 3

Approval of the version of the manuscript to be published: D. de Silva, M. Andreini, A.Bilotta, G. De Rosa, S. La Mendola, E. Nigro, O.Rios

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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