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FIRE RESISTANCE OF CONCRETE LINING IN ROAD TUNNELS

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Abstract

Fire is an incidental load on structures. Experience has shown that in the event of a fire, extremely high temperatures are developed, as a result of which very often a colapse of the tunnel bearing structure happens, usually caused by spalling of concrete.
Road tunnel fires are usually caused by vehicles using the tunnel, but can also be caused by exidants, technical breakdowns in tunnel equipment or improper tunnel maintenance. The intensity and frequency of fires in the tunnels are function of several factors such as: length and geometry of the tunnel, density and type of traffic, vehicle speed, slope, availability of ventilation equipment and so on. All of these factors define the fire risk. Based on the defined fire risk, known fire load and location of the fire, it is possible to define the fire curve that defines the temperature in the tunnel versus time. Several fire curves, usually used in EU countries, will be described in this paper, the fire curves characteristics will be defined and the most proper fire curve for typical tunnel, as case study, will be recomended.
In the framework of this paper, a methodology for fire resistance analysis of road tunnels, based on the performance, is elaborated. A numerical procedure for defining the behavior of the tunnel lining in case of nominal fire curve (standard fire) is described and applied on one case study. The impact of the fire on the stress-strain state of the concrete structure of a tunnel is analyzed and measures for proper tunnel design in terms of increasing the fire resistance is proposed.

Keywords: tunnel, fire risk, fire curve, thermal analysis, stress-strain analysis

1 Introduction

Fires in road tunnels are usually result of ignition of vehicles using the tunnel and are mainly caused by: electrical defects (most common cars); overheating of breaks (about 60 % to 70 % of fires caused by trucks) and other defects leading to self-ignition of the vehicle [1-3].
Other reasons, which are very rare, but still exist, are: car exidants; technical defects (self-ignition) of equipment in tunnels and improper performance of maintenance work.
Theoretically, the frequency of tunnel fires is related to factors such as: the length of the tunnel, traffic density, speed control and slope. These factors should be taken into account when comparing different tunnels. Therefore, to include the effects of tunnel length and traffic density, the frequency of fires is estimated not only by the number of fires per tunnel, but also by the number of vehicles per kilometer. All these factors define the fire risk.
The safety of the tunnels in case of fire depends on the applied cladding system and the appropriate design procedures for taking into acount the fire as incidental load on the tunnel structure. The “design fire”, defined in terms of its increacing rate and duration, provides the basis for determining the necessary protection systems and influence on the operational

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measures that have to be set. In case of new tunnels, this may affect the choice of tunnel configuration, or the use of additional mitigation systems.
In general, according to the options given in Eurocodes, a nominal approach for designing fire-safe tunnels has been adopted. Normally, in the past, the rate of increase of fire was adopted in the range up to a maximum value of 30 MW. However, the experience of real large tunnel fires and the tests performed in real dimensions indicated that there could be much larger fires. For this reason, different fire models have been adopted in different countries, ranging from 20 to 300 MW.
Given the large range of fires with a varying intensity, it is evident that the choice of fire intensity for a particular tunnel cannot be precisely defined without including all relevant factors. Several factors need to be considered, such as the type of traffic, the ventilation system, the geometry of the tunnel and the fire-fighting system. Even in the nominal approach, when the fire is defined by a prescribed temperature-time curve, such considerations are taken into account.
In order to provide more guidelines for the selection process, a methodology for a performance-based approach has been developed in this paper and a numerical analysis of the tunnel lining behavior in the case of nominal (standard) fire has been conducted. The influence of the design fire on the stress-strain state of the tunnel was analyzed. Tunnels with and without reinforcement of the secondary lining and with different lining thickness were analyzed. Based on the obtained results, measures for appropriate design of tunnels from the aspect of increasing their fire resistance are proposed.

2 Fire risk and protection measures for tunnels

As a result of more intensive road traffic and the need of fast underground communications, the probability of accidents in tunnels caused by fire has increased. Additional factors that increase the fire risk are:
- the increased length of modern tunnels;
- increased vehicle speed;
- transport of dangerous goods;
- two-way traffic with physically undivided carriageways;
- increased fire load as a result of increased vehicle volume and increased transport capacity;
- mechanical defects in motor vehicles.

There are three reasons for taking protection measures against fire in a tunnel. The first and most important reason is the safety of the passengers. To fulfill this condition, on time evacuation is required, and it depends not only on the stability of the structure, but also on the functionality of the ventilation system, the accessibility of the evacuation exits, etc. The second reason is to enable the tunnel to function and the traffic to run smoothly. Very often, fires in tunnels cause explosive spalling of concrete and collapse of parts of the structure. The third reason are the economic losses caused not only by the structural damages, but much more by the non-functionality of the tunnel and the interruption of the traffic during the rehabilitation period, which is certainly a long period of time.
In order to ensure adequate fire safety of tunnels, it is necessary to pay attention to the following aspects: fire resistance of the load-bearing structure; air supply system; ventilation and smoke extraction system; construction of evacuation pats protected from smoke and flames; active and passive fire detection systems; fire extinguishing systems; fire doors and alarm systems.

3 Fire models for road tunnels

A special feature that makes tunnel fires different from other fires (for example, those that occur in buildings) is the sudden rise in air temperature under the vault, which can reach over 1000 ° C in just a few minutes. This phenomenon negatively affects both the fire extinguishing process (rapid extinguishing is almost impossible) and the structural system.
In order to be able to perform appropriate thermal and static analysis of the tunnel structure and to define its fire resistance, it is first necessary to define the temperature of the fluid (air) inside the tunnel. This is possible by implementing a numerical procedure that solves the differential equations of heat release and transfer based on the laws of fluid dynamics (CFD). The temperature inside the tunnel is influenced by: the length and geometry of the tunnel, the fire load, the burning time of the primary ignited vehicle, the materials that are built into the structure, etc. The ventilation has an effect on the HRR of the burning items and should be considered when designing the type of fire curve and the period of required fire protection.
Eurocode 1-1-2 [4], which treats fire as an incidental load for the structure, defines the fire load due to the increase in temperature in the fire sector in time. Nominal curves "temperature - time" are defined, but they are valid only for indoor fires (buildings). The European countries, in their national regulations for design of tunnels, define curves "time-temperature" for a nominal fire in a tunnel [1, 2]. They are defined on the basis of results from conducted fire risk analyses, laboratory tests and experiences of fires in tunnels.
The most characteristic and often used "time-temperature" curves are presented in Figure 1. The cellulose or ISO 834 fire curve is typical for fires in buildings. The Hydrocarbon curve is applicable where small petroleum type fires might occur, e.g. car fuel tanks, petrol or oil tankers, certain chemical tankers. The temperature rise in case of Hydrocarbon curve is far more rapid than in case of ISO 834 fire curve, but after the initial 30 min. the temperature follows an almost horizontal line. The RABT-ZTV curve was developed in Germany as a result of a series of tunnel fire tests, such as Eureka project. In RABT curve the temperature rise is very rapid, up to 1200°C within 5 minutes. The duration of this temperature is shorter than for other fire curves and drops after 30 minutes in case of road tunnel, and after 60 minutes in case of railway tunnels.
The RSW curve was developed in Netherlands. This fire curve is based on the assumption that in a worst case scenario, a fuel oil or petrol tanker with a fire load of 300 MW lasting up to 120 minutes could occur. This curve is usable for enclosed area, such as tunnel, where there is little or no chance of heat dissipating into the surrounding atmosphere. The RWS curve simulates the initial rapid growth of a fire in case of petroleum tanker source, and gradual drop in temperatures when the fuel burnt off.
In the Netherlands, this curve lasts 120 minutes, as it is estimated that by then the temperature will have dropped to a level that will allow firefighters to approach the vehicle and put out the fire. This curve is also used in Switzerland and Austria, but the time is 180 minutes as the tunnels under the mountain massifs are significantly longer. When this curve is applied, the criterion for failure of the structure is taken to be the moment when the temperature of the surface of the primary tunnel lining, which is protected by concrete secondary tunnel lining or by installing insulation materials, reaches 380 °C, and the temperature in the reinforcement does not exceed 250 °C. If high-strength concrete is used, which is more sensitive to explosive spalling, the surface temperature is limited to 250 °C.

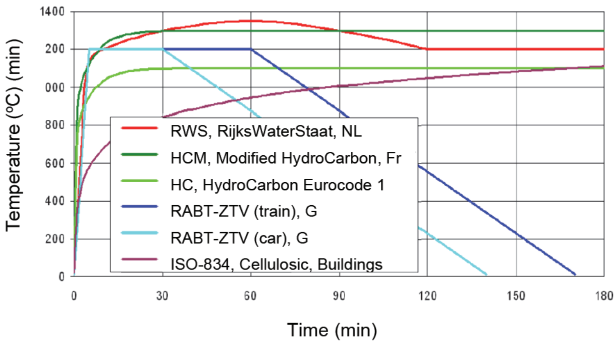

Figure 1 Standard temperature-time curves used to simulate a fire in a tunnel

Figure 2 compares these curves with the results of the experimental study, Eureka project [1]. The fire was caused by wooden and plastic pallets and 240 GJ of heat was released. The temperature was measured 10 m from the energy source. It is obvious that the RWS curve is closest to the real development of the temperature when this type of fire will happen.

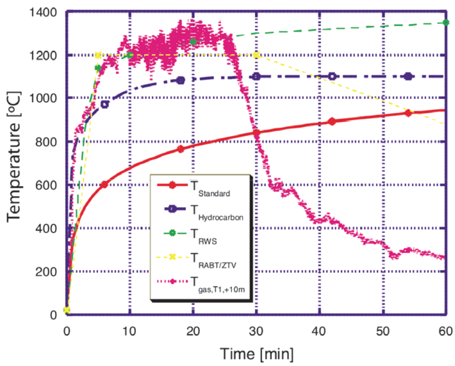

Figure 2 Comparison of Standard “temperature-time” fire curves and measured temperatures in a real fire in a tunnel - EUREKA project

4 Fire resistance analysis of concrete lining of road tunnel

As it was already mentioned, one of the factors that influence the fire safety of tunnels is the stability of the tunnel structure which is exposed to extremely high temperatures. This problem connects two parallel analyses: thermal analysis for defining the temperature distribution in the cross section of the tunnel linings and the stress-strain analysis for defining the structural response.

This paper presents the analysis results for a road tunnel exposed to RSW fire curve. For the analyses the program FIRE [5], based on Finite Element Method, was used. The tunnel length is about 900 m and belongs to the group of short tunnels. The road width is 3 x 3.50 m, the height of the tunnel is 4.70 m, with a slope of 2.5 % to 4.0 %.

On one part, the secondary tunnel lining is made of plain concrete, and on the other part as reinforced concrete arch structure. Concrete grade MB30 is applied. The minimum thickness at the top of the dome for section type 1 (plain concrete lining) is d = 30 cm, and for section type 2 (reinforced concrete lining) is d = 45 cm. The two cross-sections are shown in Figure 3.

The calculation of the fire resistance of the tunnel was performed in accordance with Austrian regulations. According to the characteristics of the traffic, the fire load is defined by the nominal fire curve RWS for 3 hours (180 min). The criterion for fire resistance is taken to be the

moment when the temperature of the surface of the primary tunnel lining, which is protected by concrete secondary tunnel lining, reaches 380 °C, and the temperature in the reinforcement does not exceed 250 °C (the lower value is adopted).
The failure time of the secondary concrete lining is defined as a third condition. Failure occurs as a result of temperature-induced stresses and in case of failure the primary lining is directly exposed to fire, so the surface temperature of the concrete is almost equal to the air temperature inside the tunnel.

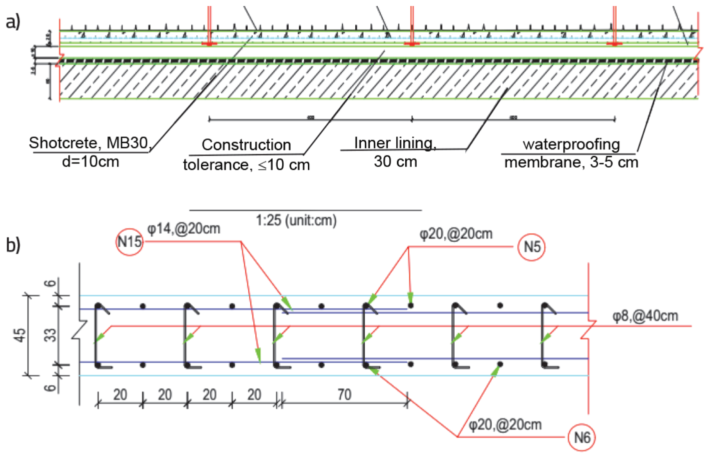

Figure 3 Secondary tunnel lining: a) plain concrete d=30 cm, b) RC lining d=45 cm

The thermal analysis was performed for a 1,00 m width strip of the arch structure. Due to the axial symmetry, only one half of the arch structure was analysed. In the thermal analysis, in addition to the concrete lining, the waterproofing layer with a thickness of d = 3 cm, the free air space d = 10 cm and the primary reinforced concrete lining with a thickness of d = 10 cm were included. The discretization of the cross section was performed with 994 finite elements with 4 nodes, of which 680 were used for the secondary lining. The time step was Δt = 0.01 hours = 0.6 minutes = 36 seconds.
The temperature inside the tunnel was defined by the fire curve RWS, Figure 1, as the most appropriate fire load. When discretizing the secondary tunnel lining, the symmetry of the tunnel cross-section and the loads was used. 11 elements with a width of 1 m were used and were placed in such a way to follow the curvature of the tunnel lining (Figure 4a). The first element was fixed in the terrain, while the rotation and the horizontal displacement at the end point of the last element (highest point of the tunnel) were restricted and only vertical displacement was free.
Temperature-dependent physical and mechanical characteristics of concrete and steel (coefficient of thermal conductivity, specific heat capacity, density, compressive strength and tensile strength of concrete, tensile strength of steel and modulus of elasticity) were adopted in accordance with the recommendations given in EN1992-1-2 [4], while the thermal properties for the waterproofing and the air in the cavity were taken in accordance with the data given in the literature. Isotherms in the cross section of the tunnel structure after 180 minutes of fire action are presented in Figure 4b, only for the case of tunnel lining type 1 (secondary lining d = 30 cm).
The non uniform temperature field in the initial moments of fire action (only the surface layers of the inner part of the lining are heated to more than 1000 °C, while the layers on the opposite side are at 20 °C) and the inability the thermal dilatation of the cross section to be freely realized, leads to additional bending moments.

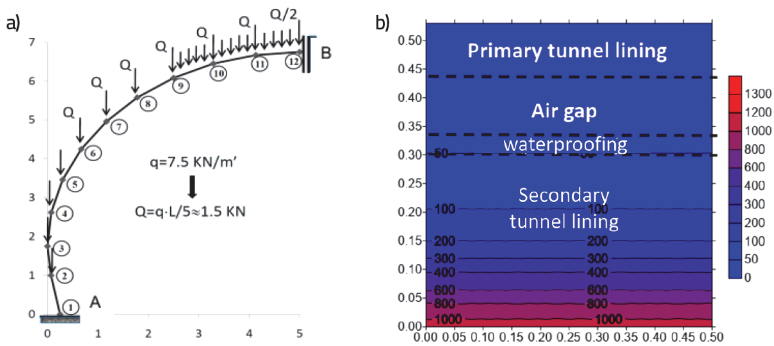

Figure 4 a) Discretization of the tunnel structure; b) Isotherms in the cross section of tunnel structure in case of lining d=30 cm, after 180 min of fire exposure

According to Figure 4b, it could be concluded that the criterion for fire resistance concerning the temperature at the surface of the primary tunnel lining is not reached after 180 minutes of fire exposure, as the temperature is lower than 380 °C. The temperature in the reinforcement in the primary lining does not exceed 250 °C, too. It is even better for concrete lining type 2 (d = 45 cm).

Additionally, the third criterion concerning the collapse of the secondary lining is controlled. If free thermal expansion of the secondary lining is possible, no axial compressive forces will occur and the bending moments caused by temperature difference will result in compression at the hot side of the cross section and tension at the opposite and cold side. In case when the concrete lining is not reinforced, there is no option for accepting the tensile forces and cracks will appear on the cold side of the lining. At the same time, in the hot inner zone, the compressive stresses reach up to 90 % of the concrete strength for the respective temperature. When the cracked zone expands to more than 80 % of the lining cross-section, the balance of the internal forces cannot be achieved and the cross-section will fail due to crushing of the "hot" concrete. In this case the failure occurs only after t = 0.3 hours = 18 minutes.

In order to solve the problem with the bearing capacity of the secondary lining in the initial moments of fire exposure, there are two solutions: to prevent free dilatation by anchoring the secondary lining to the primary lining, or to install a minimum percentage of reinforcement at the inner cold side of the lining, for accepting the tensile forces. In both cases, the secondary lining achieves fire resistance for more than 6 hours.

Figure 5 presents the time dependent stresses at the top and the bottom edge of the secondary concrete lining, in case of minimal reinforcement ($\mu = 0.1$ %) placed in the tensioned (upper) zone of the cross section, expressed as a percentage of the bearing capacity of the concrete for the actual temperature ($\sigma_c/f_c(T)$). Due to the large temperature differences in the concrete (hot lower and cold upper part of the cross section) and the impossibility of free thermal expansion, after only 15 minutes of fire action the compression stresses in the lower zone increase significantly, while in the upper zone tensile stress occurs. Over time, as the temperature difference decreases (the temperature penetrates deeper into the cross section), the compressive stresses in the lower zone slowly decrease. The tensile stresses in the upper zone have to be accepted by the reinforcement, which, even minimal, ensures the balance of the internal forces in the cross section.

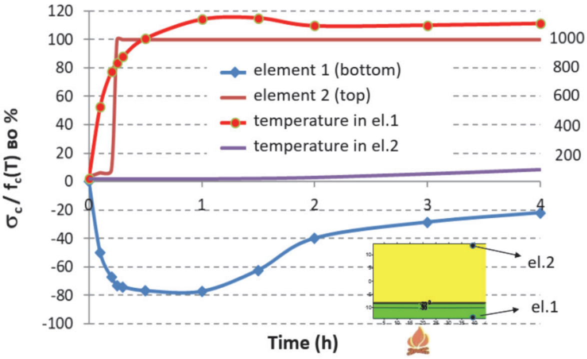

Figure 5 Time dependent stresses at the top and bottom edge of the secondary concrete lining, in case of minimal reinforcement, as a percent of the bearing capacity of concrete for current temperature ($\sigma_c / f_c(T)$)

5 Conclusions

Based on the numerical analysis, it was determined that in order to ensure stability of the tunnel structure in case of fire, a reinforced concrete secondary lining has to be constructed. Due to the tensile stresses on the cold side of the lining, if there is no reinforcement, the secondary lining will collapse in the first twenty minutes of fire exposure and will not be able to protect the primary tunnel lining during the required period of fire resistance. Reinforcement of the secondary lining, even with a minimum percentage, will delay the moment of failure and will additionally reduce the risk of explosive spalling of concrete, which is a special problem in tunnels and occurs not only in high-strength concrete, but also in normal concrete.

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