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*Stanisław Nawrat *, Natalia Schmidt *, Sebastian Napieraj **

SELECTED ISSUES CONCERNING PROTECTION OF ROAD TUNNEL STRUCTURES AND VENTILATION SYSTEMS IN RELATION TO FIRE HAZARD

1. Introduction

The continuous development of the economy results in the demand for a high quality road and railway transport infrastructure. In many countries, topographic conditions and overcrowded communication tracts in the growing conurbations show that the one of the most efficient solutions, as far as the economy and infrastructure are concerned, are communication tunnels.

In the European Union White Paper titled "European transport policy for 2010 — time to decide" [7] we can read, among the other: "Everyone should enjoy a transport system that meets their needs and expectations, but the price we pay in Europe for mobility is too high. Out of all transport systems, road transport is the most dangerous and cost consuming, as far as human life in concerned". Awareness of this fact forced actions to be taken, to carry out an analyses and research of works concerning the safety, also in the road tunnels.

The issues of safety in road tunnels can be examined in several areas concerning the stages of construction and operation of the tunnels: among other things, in the scope of tunnel equipment, safety of the structure, and also the fire safety are a major issue.

This article presents some of the issues concerning the construction and ventilation of road tunnels in relation to fire hazard in road tunnels.

2. Fire hazard in road tunnels

Recently, both in Poland and in the world at large, we can observe the dynamic development of road infrastructure, which in some ways becomes the driving force for the progress

* AGH University of Science and Technology, Faculty of Mining and Geoengineering, Krakow

of civilization. Projects which are more and more daring and modern force routes through such areas, where building the tunnels is a must. Road tunnels substantially relieve congestion of the communication network in crowded towns, reduce travelling time and make it possible to overcome obstacle.

It is not difficult to imagine, that one of the most considerable hazards during operation of the tunnel is the outbreak of a fire. Fire in the tunnel leads to the accumulation of the thermal decomposition and combustion of products and cause smoke just under its ceiling. Development of the fire can be described by parameters which are variable in time, such as the temperature of the gas in a compartment, heat flux, the volume of thermal and combustion decomposition products, their flow rate as well as gas and smoke concentrations. The greatest hazard is smoke which develops and spreads in the tunnel during a fire which, makes it difficult and sometimes impossible to evacuate people from the tunnel and is the cause of intoxication and death.

Vehicle collisions resulting from the drivers inattention or lacking caution are the most frequent causes of fires breaking out in road tunnels.

The extent of the fire hazard in road tunnels is decided by:

— traffic volume in the tunnel — the higher it is the higher is the probability of the fire occurrence,
— number of trucks — the higher the number, the more probable in the occurrence of a high-power fire,
— type of traffic in the tunnel (two-way traffic with separated roadways or a two-way road) and its fluidity (hindered traffic or occurrence of traffic congestions) influence the assessment of evacuation and rescue possibilities as well as a selection for the appropriate system of ventilation,
— gradient of the tunnel line, which has influence on the spreading of smoke, the higher it is, the higher is the dynamics of the fire gases and higher the spreading velocity of smoke.

The consequence of accidents in communication tunnels in Europe, which have taken place in the recent years, including among the other: the accident in Eurotunnel (1996), in the tunnel under Mont Blanc (1999), Tauern (1999), Kaprun (2000), St. Gotthard (2001), April 29th, 2004, the European Parliament issued the Directive 2004/54/EC on the minimum requirements for tunnels in the trans-European road network. This document included among the others, tighter regulations concerning all elements linked to structures of that kind, starting from the toxic effect of exhaust gases which are the by-products of the motor vehicle operation, up to requirements concerning fire protection and industrial safety. Rules of law also regulate design requirements for the tunnel equipment, technical means for outfitting the tunnels as well as road signs, obligatory in the tunnels, that make a part of the TEN (Trans European Network).

Despite the large number of fires in road tunnels around the world over, the last dozen years, interest concerning studies on the course of such fires is relatively low. The reasons can be mainly attributed to the high financial costs of the research, but also result from the conviction, that the knowledge obtained and current experience are sufficient to understand the specificity of these issues. In Poland, experience of tunnel fire research is small, due to the low number of such accidents when compared to other European countries. There is a demand for acquiring such knowledge by conducting experimental research in the real scale, laboratory research and numerical modeling.

The dynamics of smoke propagation in a tunnel is decided among others, by the intensity of the fire (quantities and types of burning materials and fuels), the ventilation system and the air flow rate in the tunnel. For example, the heat release rate for a burning passenger car, according to, e.g., PIARC 2007 (PIARC Technical Committee on Road Tunnel Operation: Systems and Equipment for Fire and Smoke Control in Road Tunnels) is assessed to ca. 5 MW, while heat release rate for a truck is ca. 20–30 MW. Table 1 presents the calculating ratings of the fires in the tunnel according to the different design guidelines.

TABLE 1

Calculating heat release rate according to the French design guidelines depending on the burning vehicle

	PIARC 2007
1 small passenger car	2,5 MW
1 big passenger car	5 MW
2-3 cars	8 MW
Van	15 MW
Coach	20 MW
Truck	20–30 MW
Tanker with fuel	100 MW

During a real fire, the maximum heat release rate can be much higher, as seen the tunnel under Mont Blanc, where the rating was as high as ca. 180 MW, in Tauern tunnel ca. 120 MW, while in St. Gotthard tunnel 120–200 MW.

Fires in the tunnels usually achieve very high temperatures, due to the burning fuels and vehicles, reaching even 1350°C. Peak temperatures for fires with the same fire loading appear faster in the tunnels, in comparison with fires in buildings, mainly due to the presence of hydrocarbons in petrol and fuel oil, but also because of the limited space.

Experimental research allows one to elaborate the fire curves showing the increase of the temperature in relation to time and the fire guidelines (Fig. 1).

Due to the great hazard connected with a possibility of the fire breaking out, appropriate prevention should already be anticipated at the design stage. Experimental models as well as mathematical models using computerized techniques allow one to select systems ensuring safe conditions.

Typical fires and their effects are presented in table 2.

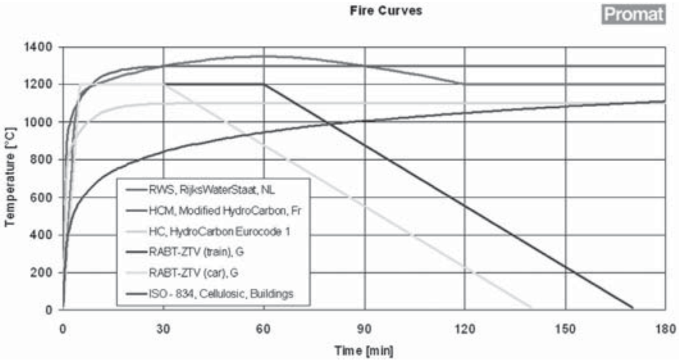

Fig. 1. Design fire curves [6]

TABLE 2
Typical fires and their presented effects [9]

Fire in the Tunnel						**Consequences**		
Year	**Tunnel length m**	**Country**	**Vehicle in which the fire was noticed**	**Probable cau-se of the fire**	**Duration of the fire**	**Consequences in people**	**Destroyed vehicles**	**Tunnel tubing and installations**
1994	Huguenot 3 914 m	South Africa	Coach with 45 passengers	Short circuit in electrical installation and the fire	1h	1 fatality 28 injured	1 coach	Serious tun-nel damage
March 24th, 1999	Mont Blanc 11 600 m	France–Italy	Truck with liquid margarine	Oil spill from the engine and the fire	—	39 fatalities	23 trucks 10 passen-ger cars 1 motorcycles 2 fire fighting vehicles	Serious da-mage Tunnel reopened 22.12.2001
November 18th, 2000	Euro–tunnel	Great Britain–France	Truck	Oil spill from the engine and the fire	7h	—	10 vehic-les, Tunnel damage	Interruption of traffic for 7 hours
October 24th, 2001	St. Got-thard 16 918 m	A2 Swit-zerland	Truck	Head-on collision of two trucks and the fire	2 days	11 fatalities	13 trucks 4 vans 6 pas-senger cars	Serious damage. Tunnel clo-sed for two months

3. Fire protection of the tunnel structure

In analyzing the tragic effects of fires in European tunnels we should also think about the damage caused to the tunnel structure, which may both indirectly and directly cause a serious hazard to the users of the object.

Great catastrophes, as in case of the Eurotunnel (1996), helped to make the public aware of the tragic consequences of fires in tunnels, and emphasized defects in the building materials and the structural solutions applied [11]. The majority of the Eurotunnel structure consisted of reinforced concrete elements 40 cm thick. The heat of the fire was the cause of chipping of the tunnel tubing as deep as 5 to 20 cm which occurred in many places, leaving the reinforcing steel visible (Fig. 2). The greatest damage was noted at a distance of 50 meters, where in many places the thickness of the concrete left was only 2 cm.

Fig. 2. Damaged structure after the fire in Eurotunnel in 1996 [2]

The concrete, as well as the rock body have been damaged.

Damage to a tunnel structure can entail very expensive repairs as well as the loss of the service continuity, which may have a negative impact on the economy or tourist business in the region.

Pursuant to the Ordinance of the Minister of Transport and Maritime Economy of May 30th, 2000 on technical conditions road engineering objects should comply with their location (Journal of Laws No 63 of August 3rd, 2000, item 735) and the tunnel structure should be made of non-combustible materials and should have fire resistance time not shorter than 240 minutes.

It is not practically possible to construct the tunnel tubing totally resistant to the fire, however, there are a number of technical methods allowing for the passive and active protection of the tunnel. Today in Europe, the active and passive systems applied in combination, are perceived as the necessity for the new tunnels in the future.

3.1. Passive systems of the structure protection

Reaction of the structure to the tunnel fire depends mainly on:

— power of the fire, where key feature is the temperature,

— thermal conduction of the tubing and the rock body, e.g., temperature rate of increase, which impacts development of the temperature, humidity and pressure gradient in the concrete pores;
— maximum temperature level, which impacts the nature of the physical chemistry relations in the material, and through it, on its properties;
— duration time of the fire, which impacts the temperature development in the structure,
— cooling of the tunnel tubing by means of air and gases flowing through,
— method of the fire extinguishing (e.g., water cooling will have different impact on the material and temperature distribution than the "natural" cooling) [4].

Dependence of the original strength drop in the tunnel tubing on the temperature and type of material is shown in Figure 3.

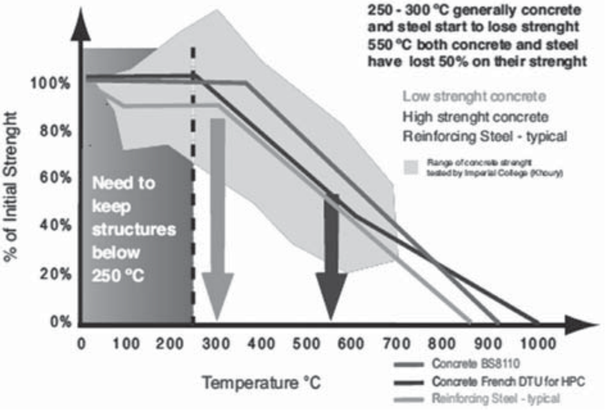

Fig. 3. Loss of resistance and structural capacity [5]

In order to determine the properties of the fire protection system to be applied for constructions, first of all, the type of the fire should be anticipated, to which the structure could be exposed. When the concrete tubing of the tunnel is endangered by the fire, the following structural issues should be taken into account:

— concrete is usually chipping off and this situation lasts as long as it chips off totally, or by the time the fire is reduced,
— concrete is heated up to high temperature the result of which is the structure loss of strength,
— if the structure contains steel reinforcement, then due to the action of high temperatures its tensile strength decreases,
— due to the gradient of temperature and different expansion rates of the concrete components, various cracks, deformations and furrows appear in the concrete [5].

At maximum temperatures the heat release rate is of key importance, because it has a great impact on the mechanism of chipping: the higher the heat release rate, the higher the production of the water steam pressure and heat increase in the tubing and the rock body.

The chipping off effect causes a violent separation of the structure fragments, and consequently, lowering of the tubing section, i.e., it leads to a reduction of the strength (the barrier thermal resistance) and load capacity of the structure. Many research activities have been devoted to the creation of facing materials in order to minimize the effects of the concrete surfaces chipping off in contact with serious fire [8]. There is clear proof, that adding polypropylene fibre to the concrete mix is an effective solution, and makes a concrete that is „breathing" in fire situations, which in result causes the probability of reduced chipping off of the material [11].

Thermal barriers prevent the mechanisms of chipping off and loss of strength in the structure exposed to temperatures as a result of fire. Maintaining structural concrete below 300°C (e.g., through limitation of the maximum temperature in the massif/rock body) in the case of a fire of hydrocarbons or cellulose, prevents the occurrence of negative structural problems. In the case of a fire in a tunnel, non-flammable and nontoxic pavement will definitely contribute to the level of safety for persons in vehicles and life saving services. The concrete meets these requirements, because it is inflammable, is does not pass into a plastic state, does not increase fire loading, and also does not emit harmful gases when in contact with fire, regardless of how extreme the conditions [11]. Apart from using concrete alone or the concrete with thermal insulation as a tubing, it seems it would be good to use it as a pavement, especially that it can replace asphalt. Some European countries, such as Slovakia, Austria, Spain and others have implemented an obligation to apply concrete pavements in the newly built tunnels. The high strength of concrete became the absolute condition to maintain the life of the structure.

3.2. Active methods to protect the tunnel structures

In increasing tunnel fire resistance can be also be achieved by using an active systems of fire protection, which can include systems using water, mist and foam sprinkling and other. These systems act directly on the fire; in theory, they can reduce the fire before it gets out of control. Yet, the most effective, as far as the protection of the tunnel structure is concerned, are the passive systems of fire protection.

4. Requirements concerning ventilation

Due to the tightening of regulations relating to safety in tunnels, caused, among the other, by the increasing lengths of tunnels and the intensity of the traffic, and with regard to the environmental protection, the higher and higher the demands which are being required from the ventilation systems in communication tunnels. Correct ventilation is the basis for the safe operation of communication tunnels and first of all should ensure:

- the replacement of air in a degree allowing for the reduction of concentrations of harmful gas, dust and smoke pollution in the air in tunnels to the level permitted by respective regulations or other requirements, e.g., medical,
- good visibility,

— favourable climatic conditions in tunnels achieved, through, the control of the air flow rate and temperature,
— the possibility of the efficient evacuation of users from tunnels in the case of fire occurrence,
— efficient extinguishing of the fires [9].

4.1. Systems of the road tunnel ventilation

Ventilation systems for communication tunnels are designed for two modes of action: normal and emergency. In normal conditions, the number of working fans and parameters of ventilation depend on the concentrations of carbon oxides and the level of air transparency in the tunnel. Taking into account the level of technology and the requirements of the regulations, we can distinguish the following tunnel ventilation systems:
— longitudinal (natural ventilation, natural ventilation with a shaft, natural ventilation with fans, mechanical ventilation, Saccardo Nozzle system),
— transverse (semitransverse mechanical ventilation, reverse semitransverse mechanical ventilation, full reverse transverse mechanical ventilation),
— mixed,
— special [9].

4.2. Ventilation at the time of fire

The main purpose of the ventilation system ion the case of fire in a tunnel is to provide appropriate air flow, to carry formed smokes and gases away in order to make vehicle and passenger evacuation possible, and to allow for the intervention of emergency services. For users of the tunnel are the first minutes of the fire, the most important, where visibility and the concentration of toxic gases still allow for efficient evacuation. As time passes the heat release rate and temperature will be increasing dynamically. It is essential in the stages of the fire, to keep the toxic gases and fire smoke close to the ceiling of the tunnel. We should remember, that the air flow rate, caused by ventilation system operation has a great impact on the course of the fire. If the velocity of the air will cause is too high it the heat release rate to increase, and consequently an increase in the volume of fire smoke and gases.

In the case of a fire in a tunnel with the longitudinal ventilation for the removal of fire gases and smoke according to the air flow direction, which will also cause heating of the tunnel structure in this section. A correctly calculated air flow rate in the tunnel should prevent the smoke from backlayering (critical velocity). In order to intensify and ensure the direction of the smoke flow, stream fans are usually used which are placed along the tunnel every 60–120 m from each other. According to the Ordinance of the Minister of Transport and Maritime Economy of May 30th 2000 regarding technical conditions relating to road engineering objects, states that they should comply with their location, therefore the fans at the tunnel ceiling, operating in a longitudinal ventilation system, should be adapted for smoke removal in case of the fire.

In unidirectional tunnels, without congestion, systems of longitudinal ventilation allows for vehicles moving in the direction opposite to the seat fire to leave the tunnel safely (Fig. 4.). Vehicles stopped before the seat of fire can be protected by the one-way removal of smoke in the direction of the traffic. In case of the traffic congestions on such a road, and also on the two-way roadway, vehicles can be trapped on both sides of the fire, from which they would not be able to leave the tunnel (Fig. 5.).

Fig. 4. System of the longitudinal ventilation in the one-way tunnel [1]

Fig. 5. Fire in the two-way tunnel with the longitudinal ventilation [1]

This system can create a hazard for the users, who may find themselves in the smoky section of the tunnel (especially in case of long tunnels).

Because of this, and on the basis of theoretical considerations and experience, EU Directives and national regulations require the need to apply transverse ventilation in a tunnel more than 1000 m long. In such a system, the removal of smoke is performed by open ceiling flaps located in the direct neighbourhood of the fire (Fig. 6), under the influence of the negative pressure created by the fans situated by the portals, or by the ventilating shafts. Fresh air is usually supplied through the channels located under the pavement. Such a system restricts the possibility of a larger area of the tunnel filling with smoke and creates better conditions for the evacuation of users, and also the facilitates the fire extinguishing. The execution of such a system of ventilation requires additional constructions in the tunnel, mainly a section of the ceiling and floor channels in the tunnel.

According to Ordinance of the Minister of Transport and Maritime Economy of May 30th, 2000 regarding technical conditions, regarding road engineering objects, states that they should comply with their location, in tunnels with transverse ventilation, and the fresh air and used air channels should be separated by barriers made of non-combustible materials with a fire resistance time not shorter than 120 minutes. Exhaust fans in all ventilation systems should be adapted for operation in the raised temperature or should be cooled.

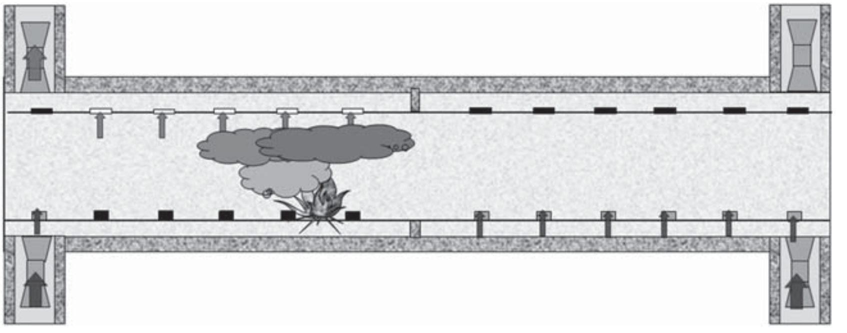

Fig. 6. System of full transverse ventilation at the time of the fire [1]

5. Summary

1) Fires in tunnels create not only a hazard for their users, but they can also contribute to the damage of the construction of the tunnel structure (tubing), which can cause significant economical losses, due to the stopping of traffic as in the case of the (e.g., Mont Blanc tunnel – which was closed for a period of more than 2 years).
2) Due to the important role of tunnels in the communication system, it is necessary to ensure adequate structural requirements for tunnel tubings (among the other, fire resistance of the structure) and ventilation systems (longitudinal and transverse ventilations), which should ensure the safe evacuation of users and effective fire extinguishing.
3) Specially designed tubings should be used in tunnels, to maintain a fire resistance time of at least 240 minutes.
4) An important issue is to select concrete and steel reinforcements, expansion joints, etc., of the appropriate class, and pavement that provides a high degree of thermal resistance. It is recommended to resign from using a bituminous mix for the roadway, and to apply concrete pavement instead.
5) Appropriate ventilation systems for tunnels to ensure not only efficient retreat of the tunnel users from the fire zone, but also add to the protection of the tunnel structure.
6) In case of the longitudinal ventilation, it is necessary to apply appropriate reinforcements in the tunnel structure, in order to locate (suspend) stream fans, that allow for the adjustment of the air and gas stream flow in the tunnel.
7) In the case of transverse ventilation, there is a need for separate ceiling and floor ventilating channels in the tunnel, in order to evacuate the fire gases and smoke through the appropriate fire flaps, and channels usually placed under the pavement, to supply fresh air into the tunnel. The separation of a ceiling ventilation channel can be executed by making the appropriate concrete construction or by applying the suspended metal ceiling.
8) Aiming to avoid catastrophes which are connected with the outbreak of fire, the appropriate systems of fire protection should already be applied at the tunnel designing stage. This provides the possibility to ensure an adequate level of safety for persons using the tunnels.

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