NUMERICAL EVALUATION OF THE FIRE BEHAVIOUR OF A CONCRETE TUNNEL INTEGRATING THE EFFECTS OF SPALLING

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Abstract: Massive concrete structures submitted to fire usually exhibit a satisfactory behaviour. However, in some cases, spalling phenomenon's may cause a fast and significant decrease of the resistance of the affected elements.
Tunnels are often exposed to heavy fire loads and may lose some concrete layers on their heated faces. The disappearance of the cover makes the reinforcement bars unprotected.
In this paper, it is shown how the code SAFIR may be used to perform a risk analysis by integrating acceptable values of spalling. This concept will be illustrated by examining a particular application.

1. INTRODUCTION

Several European tunnels were recently concerned by accidents leading to fires. Mont-Blanc Tunnel (France/Italy, 1999), Eurotunnel (France/England, 1996), Tauern Tunnel (Austria, 1999), Saint-Gothard Tunnel (Switzerland, 2001) and more recently Fréjus Tunnel (France, 2005) are worth mentioning. These disasters have led authorities to focus on this problem for which few studies have been performed up to now. Some European projects are in progress on this matter (DARTS, FIT, UPTUN).

There are two forms of spalling: progressive spalling and explosive spalling. In both cases, they occur when concrete is submitted to high temperatures. The consequences on the stability of tunnels may be considerable because the loss of the first concrete layers implies a weakening of the structure and an increase of the heat transfer speed.

This paper includes the definition of a fire scenario for a particular case, the determination of the temperature field in the tunnel and the fire resistance calculation of that construction, with and without consideration of spalling of concrete.

2. DESCRIPTION OF THE TUNNEL EXAMINED

Located in the south-west of Belgium, the structure studied is a cut and cover rectangular-shape reinforced concrete tunnel (Figure 1). Its short length (100 meters) is a particular feature compared to the very long tunnels mentioned above, especially for safety reasons (evacuation conditions, fire control). However, information such as temperature distribution and structural damage generated must here also be examined carefully in order to perform a risk assessment.

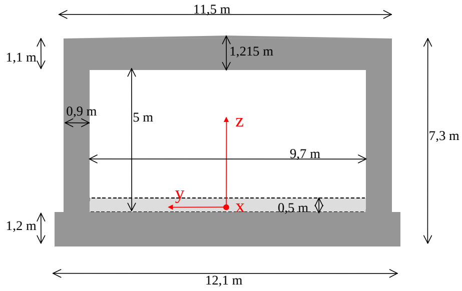

Figure 1 : Dimensions of the tunnel cross-section

3. FIRE SCENARIO

Each tunnel is unique concerning the development of the fire scenario and many parameters have to be considered. In order to take into consideration the heavy fire conditions that may occur in tunnels, the temperature-time curve selected is the Majorated Hydrocarbon Curve. That curve, established in French standards, is similar to the Hydrocarbon Curve defined in Eurocode 1 [1], but its maximal value is 1300°C instead of 1100°C.

The ceiling and the two lateral walls of the tunnel were submitted to the fire, whereas the floor of the section was not because of the presence of a non structural concrete layer forming the pavement.

According to CETU recommendations [2], the most powerful fires are produced by tank trucks conflagrations containing 20 tons of fuel and reach 200 MW. In the SFPE Handbook [3], the power per square meter released by petrol is estimated between 1700 and 2000 kW/m². That gives approximately an area of 100 m² (10.6 m*9.7 m). The SFPE Handbook proposes a method to evaluate the longitudinal distribution of temperature in function of the flux and geometrical values (Figure 2).

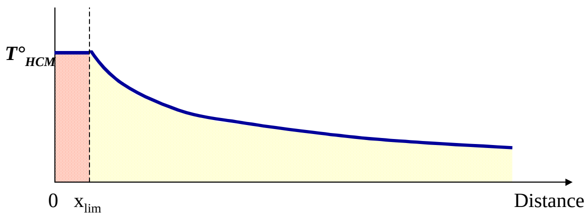

Figure 2 : Longitudinal distribution of temperature

The fire scenario chosen is caused by a tank truck during a limitless period of time. This scenario is unrealistic because the fire intensity should decrease after the combustion of the fuel and the short length of the tunnel allows a quick action of fire fighters. Anyway, the question being asked here was "how long could the fire last before failure of the structure?".

4. SPALLING PHENOMENON

4.1. Progressive spalling - When a dry concrete is heated during a long period of time, the chemical bonds existing between water molecules in concrete are broken, destroying the links between the various constituents. As water molecules disappear, concrete loses cohesion and its surface disintegrates**.**

4.2. Explosive spalling - This phenomenon is characterised by the sudden loss of rather massive elements at the concrete surface. According to recent research studies, two types of stresses cause explosive spalling:

- Because of the low porosity of concrete, the free water situated in the external layers only can escape from the structural element. In other layers, water pressure increases and this induces stresses perpendicular to the exposed surface [4]. This pressure is maximum at a critical thickness and drops to zero at the external surface;

- The prevented thermal dilatations induce restraint stresses parallel to the heated surface. Compression appears close to the surface and tension further inside the element.

According to Khoury [6], spalling is due to the superposition of both types of stresses (Figure 3).

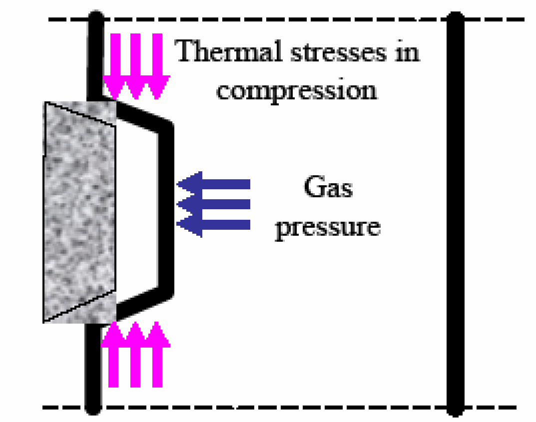

Figure 3 : Stresses causing concrete spalling according to Khoury

Many parameters have an impact on the spalling depth and speed: concrete resistance, density, type of aggregate, fire loading, water content, size of the structure, cover, reinforcement density, restraints,…. As a consequence of these numerous factors, concrete spalling is difficult to predict and quantify.

Figure 4 shows and compares some experimental spalling values for different concrete classes. It can be observed that spalling phenomenon is important during the first 30 minutes. The most resistant concretes are strongly affected, due to the low permeability and the slow evacuation of water vapour. It is important to mention that these results come from several independent articles [7],[8],[9],[10] and that other parameters may have an influence on the results.

In the numerical simulations, two different assessments were realised in order to analyse the tunnel behaviour under a realistic spalling scenario (3 mm/min during the first 30 minutes) and an unfavourable spalling scenario (7 mm/min during the first 30 minutes).

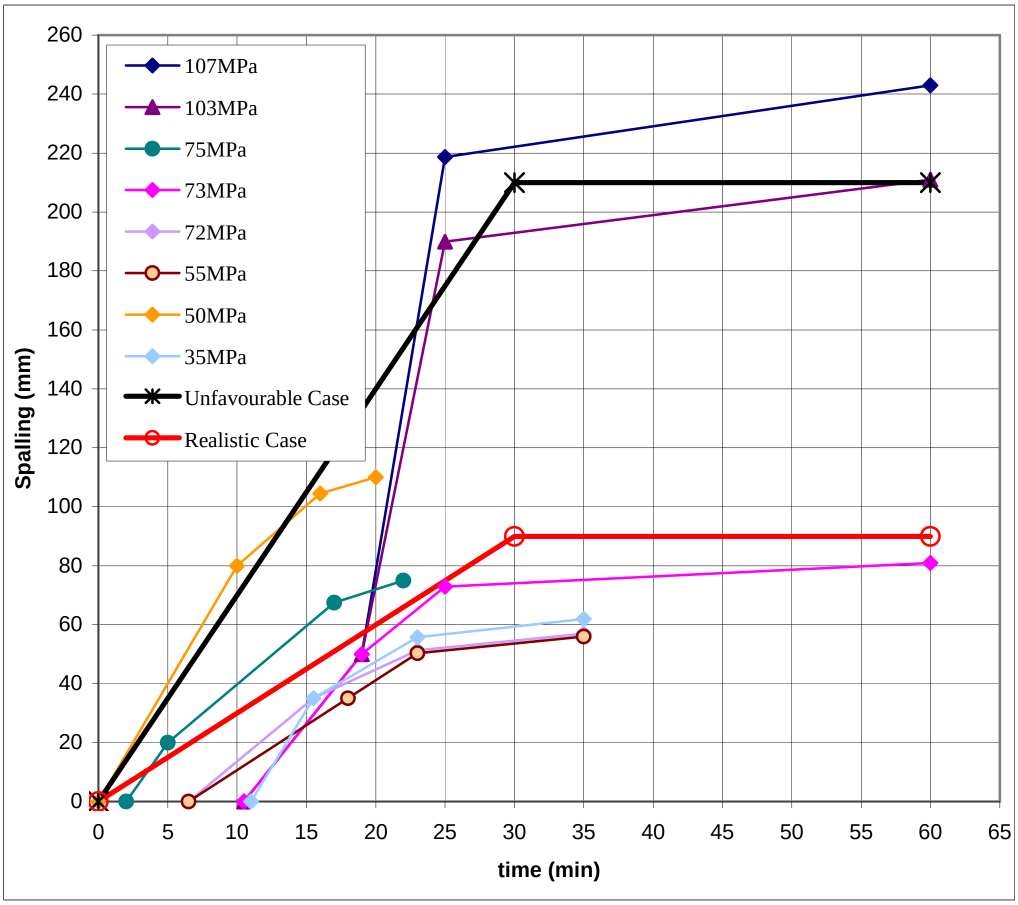

Figure 4 : Concrete spalling thicknesses in function of time

5. FIRE RESISTANCE CALCULATION OF THE TUNNEL

The structure analysed is loaded by its self-weight, soil weight, lateral soil pressure and traffic loading. The soil behaviour is simulated by linearly elastic-perfectly plastic springs, the limits of which correspond to the Rankine limit states. The analysis is made with non linear 2D Bernoulli type beam finite elements (software SAFIR [11]).

5.1. Fire resistance without considering spalling – When submitted to the Majorated Hydrocarbon Curve, the structure resists to the mechanical and thermal loads during 4h10min. Plastic hinges form at mid-span of the ceiling because tensile reinforcing bars are exposed to fire and lose their resistance, and in the upper corners where the bending moment increases significantly due to the thermal deformations of the ceiling that are restrained by the increase of lateral pressure in the soil (Figure 5). These three hinges lead to a mechanism (Figure 6).

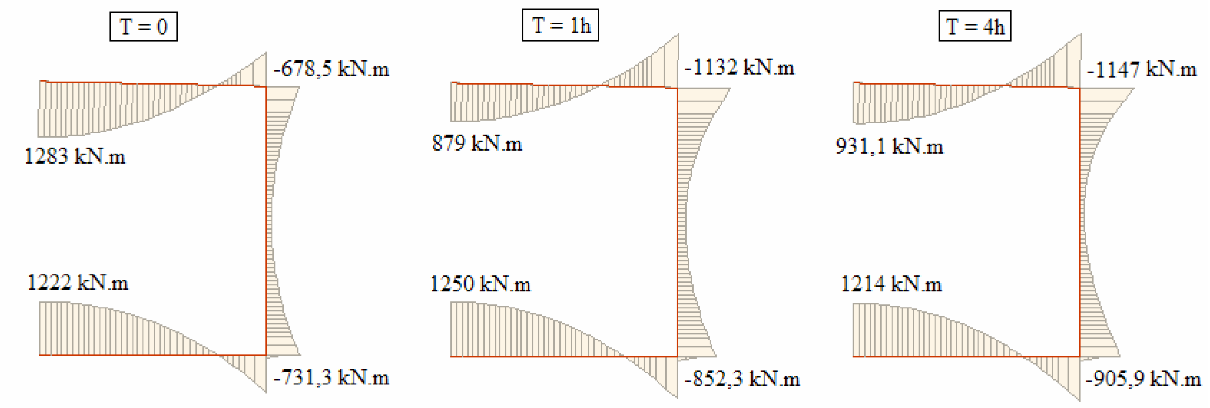

Figure 5 : Bending moment diagram during fire

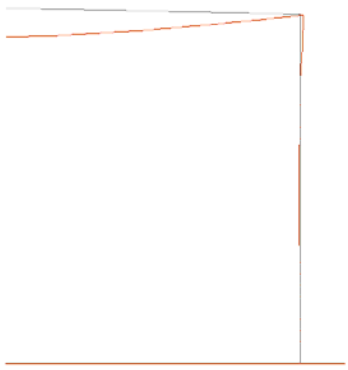

Figure 6 : Tunnel deformation at failure (amplification factor = 3)

5.2. Fire resistance taking spalling into consideration - As mentioned before, concrete spalling is modelled by removing successive layers of concrete at a constant rate. The rate is 3 mm/min in the « realistic case » or 7 mm/min in the « unfavourable case ». Steel reinforcing bars elements are removed together with concrete elements in the same layer. This can be explained by the fact that exposed steel will reach rapidly 1200°C because of the HCM curve severity. Furthermore steel bars may fall down if they are not sufficiently fixed in concrete.

In addition to the reduction and disappearance of concrete and steel elements resistance, spalling also causes an increase of the temperature rise in the section. Figure 7 shows the temperature evolution in the bars located near the internal side of the walls. For the two curves corresponding to spalling phenomenon's, there is a sudden temperature increase after a short period of time, while the increase is moderate when there is no spalling. For the bars located near the external side of the walls, heating is very slow even when spalling occurs, since the remaining concrete thickness constitutes a very good thermal protection.

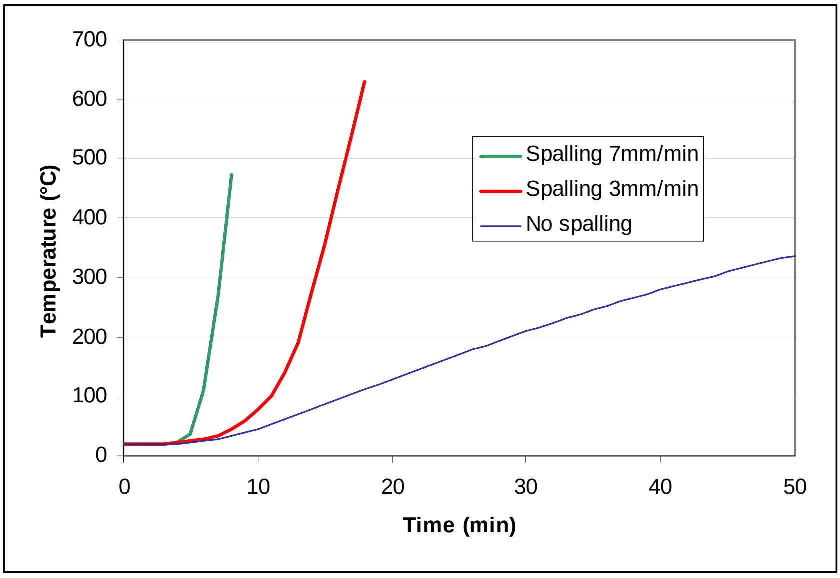

Figure 7 : Temperature evolution in the reinforcement bars (internal side of the walls)

Numerically, the modification of the number of elements due to spalling is not easy to manage. When performing a numerical simulation in SAFIR with 2D beam finite elements, two steps are considered.

- A thermal analysis of the cross-sections with all the thermal information stored for each cross-section ;
- A mechanical analysis of the structure that takes into account the thermal loading and the stiffness and strength reductions.

In the thermal analysis of a cross-section submitted to spalling, it is necessary to generate a new file each time a row of elements disappears. The resulting file necessary to run the mechanical analysis is created by assembling the thermal information contained in each thermal file related to this cross-section. As the number of fibres in a beam finite element has to be constant during a mechanical analysis in SAFIR, the elements that have disappeared are replaced by fictitious elements at 1200°C. This process could advantageously be made automatic, should this type of calculation be performed regulatly.

The fire resistance of the structure is equal to 20 minutes for a spalling rate of 3 mm/min and 11 minutes for a spalling rate of 7 mm/min. The big difference between the fire resistance with spalling (11 or 20 min) and without spalling (4h10min) is due to the rapid loss of the strength of the internal reinforcement in critical sections. The failure mode is the same in both hypotheses, with or without spalling.

5.3. Fire resistance with thermal insulation - The use of insulation on the internal surface of the tunnel produces a strong reduction of the heating in concrete and should help avoiding spalling phenomenons. In this case, the fire resistance time should be much more than 4h10min.
The tunnel has been analysed for four thicknesses of a generic insulation product (10 mm, 15 mm, 20 mm, 25 mm). The properties of that product are :

- Coefficient of thermal conductivity λ_p : 0.175 W/m.K
- Specific heat c_p : 1000 J/kg.K
- Volumic mass : ρ_p : 870 kg/m³
- Water content w_p : 0%

The assumption of a water content equal to 0% corresponds to ignoring the positive effect of water in the insulation product; in fact, the water heating and evaporation contribute to slow down the temperature rise in the protected element.

The calculations are made considering the following assumptions:

- The behaviour of the insulation product is not modified during the fire ;
- The possible joints between adjacent boards of insulation product have a negligible impact ;
- Spalling of concrete is prevented due to the presence of the insulation.

The fire resistance of the tunnel protected by a 10mm-thick insulation is given in Table 1. This value of 11 hours is of course somehow optimistic. A more accurate calculation should take into account the behaviour of the insulation and fixation system at high temperatures. The values corresponding to thicker insulation layers are even higher.

Table 1 : Fire resistance of the thermally protected tunnel (no spalling)

	0 mm	10 mm
RF	4h10	11h40

5.4. Fire Resistance outside the fire source - The previous paragraphs are dedicated to the structural analysis of the tunnel in the zone of the fire source. These bi-dimensional calculations do not give any indication about the tunnel length that would be affected in case failure would occur.

Some dilatation joints divide the tunnel longitudinally in five 20 meters long independent parts. The width of the fire source is 10.5 meters. The elevation of temperature in concrete is less severe outside the fire source than above the fire source. In order to assess the failure length, the tunnel cross-section has been studied at different distances from the fire source by varying the temperature-time curve, see Figure 2. It can be observed that the fire resistance time increases significantly as soon as the fire severity decreases (Table 2). It can be concluded that failure might concern a limited part of the tunnel only.

Table 2 : Fire resistance of the tunnel outside the fire source

Distance from fire source :	0 m	1 m
Fire resistance :	11h40	14h45

The effects of longitudinal stresses and of possible longitudinal load redistribution have not been considered here because of the presence of several dilation joints that cut the continuity and because of the short length of the tunnel. Also, the most critical section in the tunnel is rather near one end of the tunnel. These effects should perhaps be taken into account in longer and continuous structures but, of course, this would increase the required numerical efforts tremendously.

5.5. Partial protection of the tunnel - The failure mode of the tunnel is characterized by the formation of three plastic hinges in the tunnel ceiling. A way of avoiding this mechanism without protecting completely the internal faces consists in covering with insulation the plastic hinges zone only.

The tunnel has been studied with different protection configurations and the same spalling speeds as previously for the unprotected zones. The insulation thickness is 10 mm.

Simulations show that it is necessary to protect the complete ceiling width to increase significantly the tunnel fire resistance. In the case, when only the ceiling is protected, the fire resistance reaches 6h35min (3 mm/min) and 5h30min (7 mm/min).

6. CONCLUSIONS

The impact of the consideration of spalling on the fire resistance calculation of concrete structures is important. The main difficulty of this problem is the large amount of parameters that influence the spalling phenomenon. It is possible to obtain an evaluation of the effects of spalling on the structural stability if an hypothesis can be made on the spalling rate.

Providing insulation plates sufficiently anchored has a very positive influence on the structural behaviour if, in addition to reduce the heating rate of the section, it has the effect to prevent the occurrence of spalling.

The presence of additional reinforcing bars in the ceiling-walls junctions would postpone the formation of plastic hinges in that section and delay the tunnel failure, as has been demonstrated by additional calculations not presented in this paper.

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