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Fire Safety Checking of Tunnels based on Probabilistic Analysis

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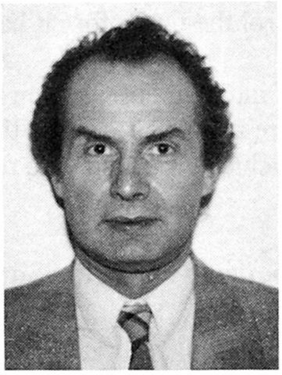

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Summary

The fire safety regulations, standards and codes of practice, traditionally based on descriptive requirements deriving from experience of authorities and experts, are more and more including performance requirements expressed independently of the building solutions.
The probabilistic fire analysis is a new step forward to represent more closely the global fire safety really obtained : any possible cause of failure (accidental actions, fire scenarios, structural defect, human error, ...) is considered and its probability of occurence is assessed by methods based on available statistical data about real fires.
The feasibility of standards and regulations based on probabilistic analysis is discussed and practical problems raised by this approach for tunnels are detailed.

1. General objectives of fire safety

The general objectives of fire safety in tunnels are usually :

The safety of persons : *occupants :* passengers, drivers, train personnel, ...
rescue teams : fire fighters, medical assistance, ...

The protection of goods : *properties :* vehicles, loads, structure of the tunnel
environment : smoke, surface and underground pollutants

2. General performance requirements

From these objectives of fire safety, general performance requirements are usually derived, such as those defined by the European Commission for the construction products (1) :

2.1 Fire prevention strategy

To minimize the risk of an outbreak of fire.

2.2 Loadbearing capacity of the tunnel

In case of fire, to guard against collapse and to provide for the safety of occupants and rescue team.

2.3 Limitation of generation and spread of fire and smoke within the tunnel

To enable occupants near and remote from the origin of fire to have sufficient time to escape and to enable the fire brigade rescue teams to control the fire before it has grown too large.

This requirement includes the prevention of initial ignition within the technical installations, the limitation of the generation and spread of fire and smoke within the vehicles circulating in the tunnel (trucks, railways, cars, ...) and beyond the vehicle of origin (fire resistant compartmentation, control of hot gases and smoke between zones).

2.4 Limitation of spread of fire to neighbouring construction works.

To ensure safety of occupants in other construction works nearby and remote from the tunnel.

2.5 Safety of evacuation of occupants, by provision of means of escape and of access for rescue teams :

- to allow occupants anywhere within the tunnel to be able to evacuate to a place of safety
- to allow rescue teams to have access to, search, and get out of the tunnel safely

The required safety measures concern the design and layout of escape routes, their separation from the surroundings, the control of smoke and other equipments (lighting, signs, ...).

2.6 Safety of rescue team, by additional provisions :

- to ensure possibility for rescue operations to be carried out
- to allow fire fighting to be carried out effectively
- to enable rescue teams and fire fighters to operate with a reasonable level of safety and leave the site safely.

The additional safety measures include extinguishing installations and equipments, emergency communication installations, control of utilities and safety systems, fire protective systems, marking and signs to assist fire fighters, ...

3. Traditional prescriptive approach

These general performance requirements are traditionally expressed in the fire safety regulations, standards and codes of practice by prescriptive requirements based on a conventional fire development, usually the temperature growth over time defined by the international standard ISO 834 (2), and on specific design solutions which have proved to be satisfactory by experience.

This traditional approach doesn't take into account the variability of fire developments and imposes design concepts which are often limiting artificially the freedom of search for design solutions.

4. The natural fire safety concept

One step forward to a more realistic fire assessment is to consider the various possible developments of real fires which may occur, associated with their probability of occurence, based i.a. on statistics of real fires.

This approach needs to identify the different fire origins and their possible scenarios, in order to check the fire safety against the most unfavourable developments of temperature over time. These temperature developments over time are calculated in each case of fire from a combustion model which takes into account the oxygen available to adapt the curve of Rate of Heat Release over time obtained from full scale tests (3).

From the total development of the temperature over time in the tunnel (temperature increase and decrease), the temperature evolution within the tunnel walls and its consequences on the properties of the materials and the stability to fire of the structure of the tunnel may be assessed.

Imposed and constrained expansions and deformations caused by temperature changes shall be considered not only within the members exposed to fire but also in any other member and part which may be affected.

5. The global fire safety concept

5.1 General principles

The next step forward is to express and assess directly and quantitatively the performance requirements, independently of the building solutions, in order to give more freedom to the designers and to allow a better optimization of the combinations of safety measures.

5.2 Loadbearing capacities

5.2.1. Probabilistic approach

As suggested by J.B. SCHLEICH and his European research team (4), the probabilistic approach described in EUROCODE 1 (5) (6) may be used in order to quantify the influence of safety measures. The safety condition to be checked is that the failure probability of the structure Pf_S is lower than a target failure probability Pt :

$$Pf_S \leq Pt$$

where $Pt = 10^{-6}$/year or 10^{-4} over a working life of 100 years
is the level of structural safety standardized by EUROCODE 1

$Pf_S = Pfi \cdot Pacc$
Pfi = failure probability in case of fire
Pacc = probability of fire

The probability of a fire in a tunnel may be derived from statistical analysis of real fires having occured.
For railway tunnels, an order of magnitude of Pacc is 6.10^{-4}/year per km of tunnel (7).
For roadways, an order of magnitude of Pacc for one civil engineering structure (tunnel or bridge)

has been established for example for France (8) :
- any fire : $1{,}5.10^{-3}$/year
- fire from trucks : 4.10^{-4}/year

A target value of the failure probability in case of fire Pt,fi may then be obtained :

$$Pt{,}fi = \frac{Pt}{Pacc}$$

The analysis may be further developped if alternative fire scenarios may lead to failure; in this case, the failure probability of the structure will be obtained by the addition of the probability of occurence of each alternative fire scenario multiplied by the failure probability in case of this fire scenario :

$$Pf_S = \sum_j Pfi{,}j . Pacc{,}j$$

The probability of occurence of each fire scenario Pacc, j may be derived from statistics of real fires.

The failure probability in case of one specific fire scenario Pfi, j is depending on the safety factors applied in the checking of the design against the effects of this fire, considered as an accidental action.

When a part of the failure probability is allocated to each fire scenario, a target value of the failure probability in case of each fire scenario may be established and safety factors may be derived as described in EUROCODE 1.

5.2.2. Safety factors

If the resistance R and the stress or sollicitation S in a structural section are represented by their statistical distributions defined by their standard deviation σ and mean value m, the failure occurs when S > R and the failure probability Pf is given by the hatched area under the probability density function of the variable z = R - S for which z < 0 (figure 1).

ill. 1

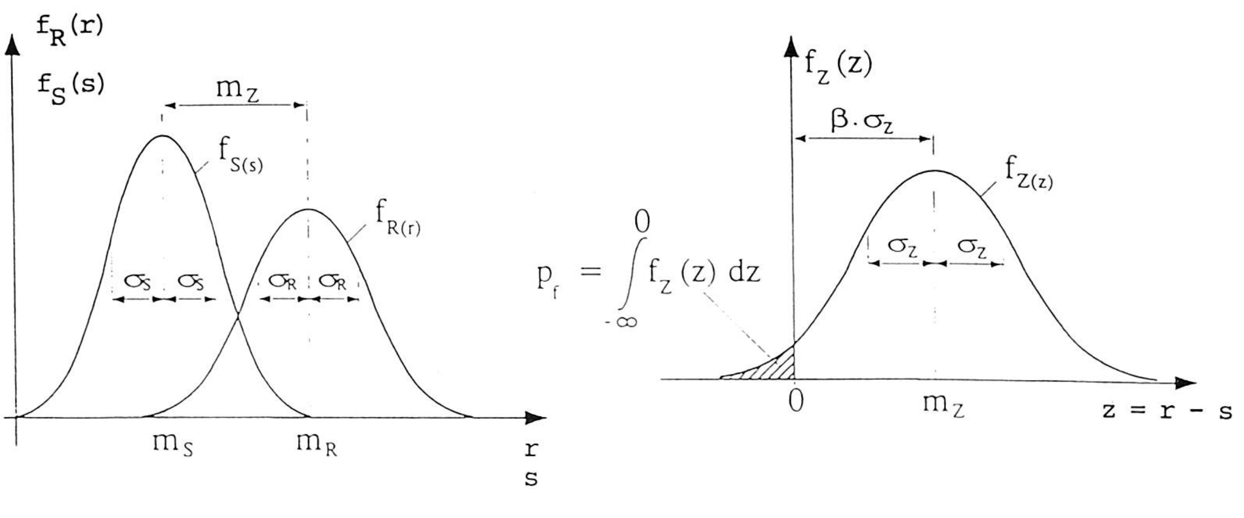

Figure 1

In order to simplify the verification, EUROCODE 1 has adopted a semi-probabilistic approach, the FORM (First Order Reliability Method), based on the following assumptions :

ASSUMPTION 1 :
The two variables R and S may be represented by equivalent normal distributions, so that z = R - S is also a normal variable defined by its mean value $m_Z = m_R - m_S$ and its standard deviation

$$\sigma_z = \sqrt{\sigma_R^2 + \sigma_S^2}$$

The value z having a probability P of not being exceeded is given by $z = m_Z - \beta \sigma_Z$ where β is the value of the standard normal variable ($m_\beta = 0$, $\sigma_\beta = 1$) having the same probability of not being exceeded.
For z = 0, $\beta = m_Z/\sigma_Z$ and the probability of failure $Pf = \phi(\beta)$ can be read from standard normal distribution tables (Table 1). Conversely starting from a value of Pf, the corresponding value of β, called the safety index, may be obtained.

ill. 2

Pf	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
β	1,3	2,3	3,1	3,7	4,2	4,7	5,2

Table 1

ASSUMPTION 2 :
The failure condition may be written : $R_d < S_d$
where $R_d = m_R + \alpha_R \beta \sigma_R$ = design value of resistance
$S_d = m_S + \alpha_S \beta \sigma_S$ = design value of stress or sollicitation
and $\alpha_R = \sigma_R/\sigma_Z = 0,8$
$\alpha_S = \sigma_S/\sigma_Z = - 0,7$

By considering constant (simplified) values for the weighting factors α_R and α_S, the design values R_d and S_d may be defined independantly of each other : each design value depends only on the safety index β and on the statistical distribution of the variable represented.

As a consequence, it is possible to define safety factors γ_R = Rd/Rk and γ_S = Sd/Sk where Rk and Sk are the standardized characteristic values of the variables R and S.
The safety factors γ_R and γ_S depend on the nature of each variable and the safety index corresponding to the target value of the failure probability.

5.3 Limitation of generation and spread of fire and smoke

For each possible fire scenario, the ability of the tunnel ventilation systems to control air flows has to be checked in order to provide for the safety of occupants along their escape routes for the time needed to evacuate, and for the safety of rescue teams along their access routes to the fire area.

The performance requirements to be checked may be expressed in terms of air toxicity, temperature and obscuration, and will depend from the concept for evacuation of occupants and for access of rescue team.

5.4 Safety of evacuation of occupants

This requirement may be expressed by a maximum evacuation time to be assessed by calculation models, and by additional performance requirements regarding functional geometry of escape routes, emergency lighting, guidance signs, etc ...

5.5 Safety of rescue teams

This requirement may also be expressed by a maximum access time for fire fighters, medical teams, etc ... together with additional performance requirements.

5.6 Global probability of casualties

One could think ultimately to look for a safety objective expressed as a global probability of casualties not to be exceeded, which would include the influence of all the above mentionned causes. To achieve this objective, a quantitative risk analysis has to be performed, which balances the consideration of an accident's consequences with an estimation of its frequency.

This approach mixes together technical factors, which may be quantified, and human factors, which are much more difficult to evaluate.

A fire prevention strategy with regard to training, inspection, maintenance, testing, fire fighting exercices, etc ... is required to minimize the risks but it would not be wise to rely on it completely for fire safety assessment of civil engineering design. Therefore, we would recommend to maintain two criteria : a target value for the structural failure probability and a target value for the global probability of casualties.

6. References

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