Structural Fire Protection For Road Tunnels

ITA Working Group 6
Maintenance and Repair

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1.1 BACKGROUND

Fire resistance of tunnel structures is an important issue. If it is not properly addressed, fire in a tunnel can result in loss of life to both tunnel users and the fire and rescue services. Resulting economic losses for both the tunnel owner/operator and to the local economy and environment can be catastrophic.

This document is produced by Working Group 6 *Repair and Maintenance of Underground Structures* and has been solely developed by the members of that Working Group. The purpose of this effort is to develop recommendations for fire protection for concrete road tunnel structures. However, many of the issues addressed in these guidelines are relevant to rail tunnels and this will be referenced as part of this document at a later date.

Full scale fire tests carried out as part of the EC Funded Research Project "UPTUN" and privately funded Runehamar Fire Tests [1.1] have shown that fires in tunnels can be much more severe than previously assumed (even with non-hazardous goods). For this reason, this document makes reference to the time - temperature curves developed in these tests. It also references the relative heat release curves (RHR) developed from these full-scale fire tests as separate graphs.

1.2 SCOPE

As an addition to PIARC guidelines, the scope of this ITA document is to provide recommendations for techniques and materials to answer these structural requirements and make tunnels and their ancillary structures more resistant to fire damage. These recommendations take into consideration the time - temperature curves as recommended by others and develop suitable means and methods for the protection of the structures. The aim or focus of the protection may vary from preventing minor damage to preventing a total collapse both during the fire event and during the rescue operation.

This document is intended to be a guideline and is to be used for road tunnels only and not for rail, mass transit, or pedestrian tunnels. However the basic principles for the protection of tunnels and underground structures may be applied to other types of structures; in such cases special consideration must be given to the particular application and its own unique operational and other site-specific elements.

This document is for informational purposes only and applicable codes, standards and local regulations must be consulted for compliance to specific structural and life safety requirements of the locale in which the structure is located.

1.3 REASON FOR DEVELOPING GUIDELINES

Between 1990 and 2010, there have been a number of serious underground fires in road tunnels. These fires have caused extensive loss of life and severe collateral loss to the infrastructure. Aside from the tragic loss of life, the long-term financial effects to the local infrastructure, the loss of public confidence in the safe use of tunnels have necessitated the development of safety recommendations. This document is intended for use to identify the categorisation of road tunnels and propose methods for the protection of the structural elements. The behaviour of structures is a key factor to allow users to evacuate and rescue personnel to enter the scene and effectively perform their required duties and to limit damage to the tunnel. Improved specifications for tunnel fire resistance are required in order to mitigate the consequences of a serious fire, which could result in structural failure or complete collapse.

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2.1 INTRODUCTION

The design of tunnels to be resistant to damage as a result of vehicle fire is an important issue for the construction of new tunnels and the rehabilitation of existing underground facilities. The objectives of tunnel structural fire resistance associated to safety equipment and smoke control systems are to allow for users to evacuate safely in the event of a tunnel fire, rescue operations to be performed under safe conditions, and tunnel suffers minimal damage.

The tunnel system must be protected from collapse during a specified time period. The potential for collapse is particularly important for submerged tunnels (Immersed Tube Tunnels), and tunnels in urban environment that are located under other buildings or structures. The second focus of this document is to ensure appropriate protection of property, which also involves indirect costs associated with the disruption to business, the local economy and the restoration of the facility to normal operation.

The World Road Association (PIARC) has issued several reports related to tunnel fires. These reports have been prepared by PIARC Working Group 6 *Fire and Smoke Control* and edited by the PIARC *Technical Committee on Road Tunnels* (now Technical Committee on Road Tunnel Operation – D5) :

- The report *Fire and Smoke Control in Road Tunnels* [2.1] published in 1999: This document is the results of the review of numerous fire scenarios and actual case histories. The report has identified typical scenarios for heat generation caused by a fire event.
- The report *Systems and Equipment for Fire and Smoke Control in Road Tunnels* [2.2] published in 2004: It includes a final recommendation on the question of design criteria for resistance to fire for road tunnel structures.
- The report *Road tunnels: Operational strategies for emergency ventilation* [2.3] published in 2011;
- And the new report *Fixed fire fighting systems in road tunnels: current practices and recommendations* [2.4] published in 2016 (update of the 2008 version).

2.2 DATA ON TUNNEL FIRES

Section II.4.1 of the PIARC report of 1999 [2.1] indicates the heat release from vehicle fires is dependent on many variable factors such as:

- Number of vehicles involved in a fire
- Type of vehicles (passenger cars, coaches, heavy goods vehicles, petrol tankers)
- The type and quantity of flammable material available
- Rate and method of extinguishing the fire
- Cross section of tunnel structure

The temperature is highest on exposed surfaces and particularly at the higher elevations of the tunnel structure. This is illustrated in Figure 2.1

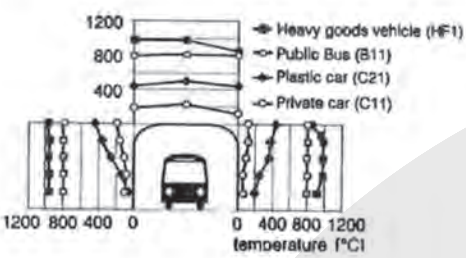


Figure 2.1 : PIARC Maximum Temperatures within Tunnel Cross Section [2.1]

PIARC has also established from tests the limits of the areas affected by a typical tunnel fire. These limits were based on a single fire event occurring in a tunnel. This information is useful structurally in the determination of areas to be inspected for damage. However, since the location of a fire within a tunnel is random and may occur at any location, the entire tunnel must be designed to resist fire. Figure 2.2 documents the maximum ceiling temperature in relation to the fire location for various scenarios as found in the Eureka tests.

Figure 2.1 indicates the temperature distribution within the test tunnel. There seems to be little difference between the temperature distributions at the ceiling and near the road surface, when the cause of the fire is Heavy Goods Vehicles (HGV) and public buses. In the cases of plastic cars and private cars, the temperature is relatively low at the road surface when compared with that at the ceiling.

The reason for this is that HGV and buses have a relatively large cross-sectional area, or in other words the ratio between projected area of the vehicle and tunnel cross-section (blockage ratio), which is relatively high. The blockage ratios between vehicle and cross sectional area of actual road tunnels are relatively lower than those for the fire tests. This means that the measured values in Figure 2.1 include some allowance of safety for the correspondence to tunnel safety planning. Even if the conditions pertaining to fire source in the tunnel are similar, temperature distribution is influenced by the tunnel configuration. The main reason for this is the effects of heat radiation from the vehicles as measured by thermocouples, which measure gas temperatures.

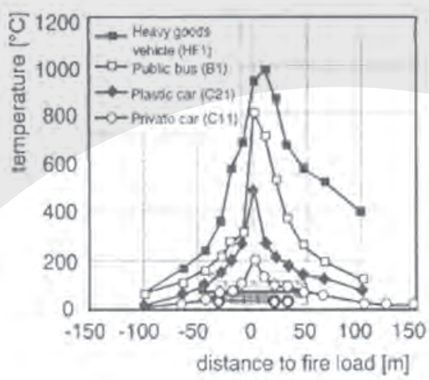


Figure 2.2 : PIARC Maximum temperatures in the ceiling area of the tunnel [2.1]

In addition to the maximum gas temperature and limits of various fire scenarios, the report also present temperature vs. time duration plots for the various types of fires encountered in the Eureka Tests as shown in Figure 2.3 and the full scale fire tests carried out in the Runehamar Tunnel in Norway in September 2003 in figures 2.4 and 2.5. Temperatures estimated in actual tunnel fires such as the Mont Blanc and St. Gotthard should also be considered.

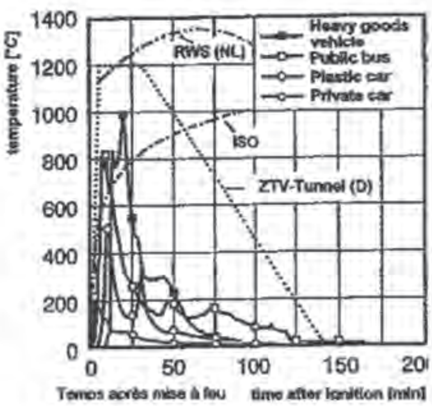


Figure 2.3 :Time Dependence Temperature Data from Eureka Test Program [2.1]

With all the data available measured from real large scale fire tests with real vehicles it is possible to identify the maximum ceiling gas temperatures that can be obtained for different types of vehicles.

A simplified model was developed by Ingason and Li [2.5]. To illustrate this model, two tables are presented below. For further details on the model, see also Appendix 2.

- Table 2-1 concerns pool-fires, assuming a tunnel height of 5,5 m;
- Table 2-2 concerns vehicle fires, with a tunnel height 4,5 m.

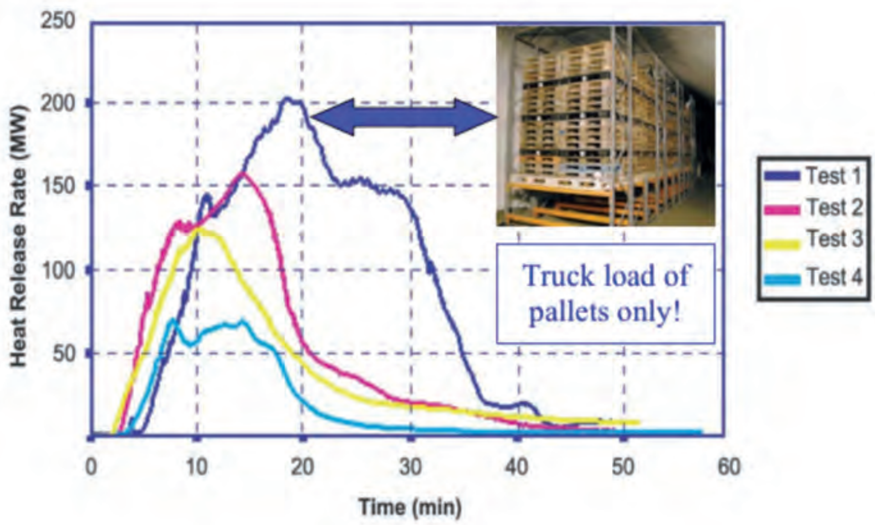


Figure 2.4 : Heat Release from Runehamar tunnel test

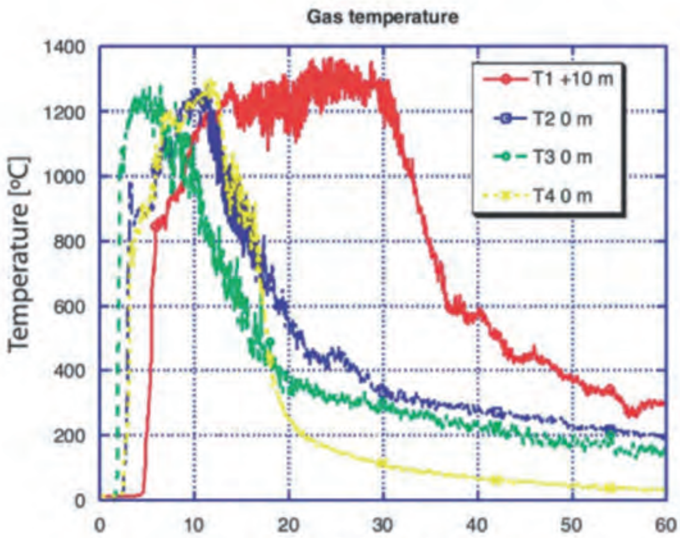


Figure 2.5 : Temperature recordings from the Runehamar tunnel Tests

HEIGHT OF TUNNEL (m)	ELEVATION OF FUEL-LOAD (m)	AREA OF FIRE (m²), ASSUMING A MAXIMUM HRR OF 1,5 MW/m²	HRR (MW)	MAXIMUM TEMPERATURE (C)
5,5	0	33,3	50,0	634*
5,5	0	50,0	75,0	880*
5,5	0	66,7	100,0	1113*
5,5	0	83,3	125,0	1337*
5,5	0	100,0	150,0	1350
5,5	0	133,3	200,0	1350

Table 2 1: Pool fires

HEIGHT OF TUNNEL (m)	ELEVATION OF FUEL-LOAD (m)	AREA OF FIRE (m^2)	HRR (MW)	MAXIMUM TEMPERATURE (C)	COMMENTS: RELATED TO AREA OF FIRE, AND HRR
4,5	1	7,2	5,0	206*	1 car: Fire area = 1,6*4,5 m^2
4,5	1	9,0	15,0	558*	Minivan: 1,8*5 m^2
4,5	1	38,3	35,0	1006*	Bus: 2,55*15 ("small"/old)
4,5	1	38,3	50,0	1350	Bus: 2,55*15 (new/ski)
4,5	1	38,3	50,0	1350	LGV: 2,55*15
4,5	1	38,3	100,0	1350	HGV: 2,55*15

Table 2.2 : vehicle fires

* Higher if flames touch the wall

2.3 DESIGN CRITERIA ESTABLISHED BY PIARC

After the publication of its 1999 report, the PIARC *Working Group 6 Fire and Smoke Control* continued its work on resistance to fire of road tunnel structures. This paragraph presents its final recommendation on the question of design criteria for resistance to fire for road tunnel structures, which has been included in the 2004 PIARC report System and Equipment for Fire and Smoke Control in Road Tunnels [2.2], and subsequent updates in 2007.

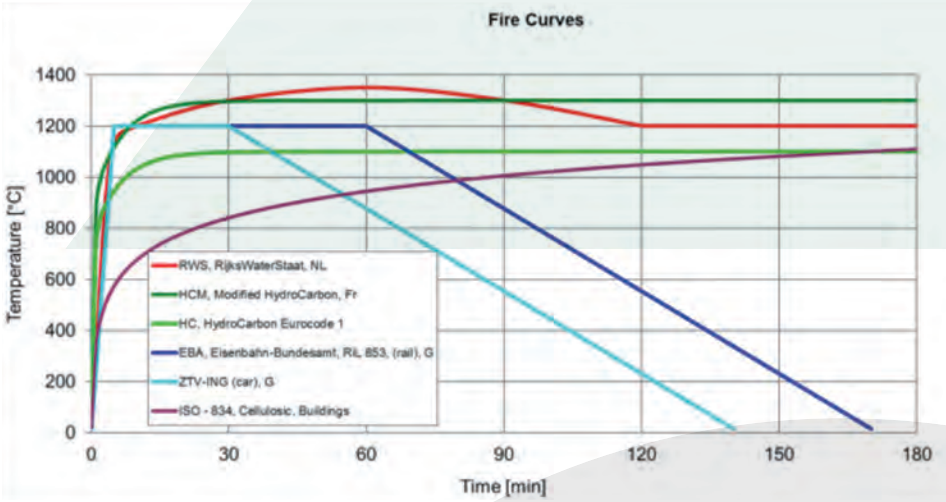


Figure 2.6 : Recommended Temperature versus Time Curves for ZTV, RWS, HC_{inc}, and ISO Standards [2.6]

2.3.1 PIARC RECOMMENDATIONS

A preliminary and basic criterion to be met by any tunnel structure is that there should not be any risk of progressive collapse: the local failure of any element should not lead to an increased load on other parts of the structure which may cause their failure.

There are several time-temperature curves proposed to the date. Figure 2.6 sketches the ISO 834, RWS, RABT (former ZTV) and a modified Hydrocarbon (HC) curve, HC_{inc}, in which the temperature are multiplied by a factor of 1300/1100 from the basic HC curve of Eurocode 1 Part 2-2.

Recommendations for design of the structure should consider the aforementioned time-temperature curves, and any local applicable time temperature curves, with regard to the possible events within the tunnel. Hence the early stages of the fire development, following the first part of the curve, will require a consideration of escape and the time conceived for evacuation. There should be no collapse during this period that can affect the zones where there may be users or rescuers.

Spalling of the structure can occur in the early stages of a fire but no incidents have been reported where it has had major consequences for firemen, although it may indicate a rapid deterioration of the structure. The main concern at the time of fire service intervention would be the collapse of items, such as jet fans, signs or lights from the tunnel ceiling or walls. This question of fire resistance has been addressed in the PIARC 1999 and 2007 reports in section [2.1], which states:*"In all cases, the minimum requirement is that heavy equipment should not fall down when evacuating users or rescue personnel are in the tunnel. This means no heavy item must fall under exposure to temperatures of 400-450°C during the time necessary to fight fire (in a tunnel, such temperatures can produce a radiation level of about 5 kW/m², which is the maximum tolerable value for firemen)."*

Shelters should only be provided in a tunnel if there is an escape way for rescuers to reach the users waiting in the shelter and assist them to the outside. If such shelters are available, then a resistance of about two hours would be needed for protection prior to rescue.

The overall duration defined by the curve will need to be considered. For instance, in France current thinking is 2 hours for the fire brigade intervention; after 2 hours it would be considered to be unsafe. If the tunnel is under a building and in other cases where protection of property is an important issue, then a longer time may be considered.

Proposed Guidelines by PIARC

The proposed guidelines for design criteria are presented in Table 2.3. This table makes a distinction according to the type of traffic (consequently the possible fire load) and the consequences of a structural failure due to a fire (when the consequences are unacceptable, a protection against a very severe fire is required – e.g. submerged tunnel or in unstable ground; when the consequences are limited, no protection is needed – e.g. tunnel in stable ground).
Table 2.3 uses the ISO curve and either the RWS or the HC_{inc} curve to define design criteria for different circumstances. The Working Group believes that the RWS and HC_{inc} curves correspond to very similar levels of fire resistance, and only one of the two should be used. ISO TC92/SC2 also believes that which one you use has no impact, but considers that the HC_{inc} curve is a more natural, better choice, should one only be kept. Currently the Working Group proposes that any of these curves can be used, with very similar results.

	MAIN STRUCTURE				SECONDARY STRUCTURES[4]			
Traffic Type	Immersed or under/inside superstructure	Tunnel in unstable ground	Tunnel in stable ground	Cut & Cover	Air Ducts[5]	Emergency exits to open air	Emergency exits to other tube	Shelters[6]
Cars/Vans	ISO 60 min	ISO 60 min	2	2	ISO 60 min	ISO 30 min	ISO 60 min	ISO 60 min
Trucks/Tankers	RWS/ HC_{inc} 120 min[1]	RWS/ HC_{inc} 120 min[1]	3	3	ISO 120 min	ISO 30 min	RWS/ HC_{inc} 120 min	RWS/ HC_{inc} 120 min[7]

Table 2.3 : PIARC Recommendations

Notes :

[1] 180 min maybe required for very heavy traffic of trucks carrying combustible goods

[2] Safety is not a criteria and does not require any fire resistance (other than avoiding progressive collapse). Taking into account other objectives may lead to the following requirements:
- ISO 60 min in most cases
- No protection at all if structural protection would be too expensive compared to cost and inconvenience of repair works after a fire (e.g. light cover for noise protection)

[3] Safety is not a criteria and does not require any fire resistance (other than avoiding progressive collapse). Taking into account other objectives may lead to the following requirements:
- RWS/HC_{inc} 120 min if strong protection is required because of property (e.g. tunnel under a building) or large influence on road network
- ISO 120 min in most cases, when this provides a reasonably cheap protection to limit damage to property
- No protection at all if structural protection would be too expensive compared to cost and inconvenience of repair works after a fire (e.g. light cover for noise protection)

[4] Other secondary structures should be defined on a project basis

[5] In case of transverse ventilation

[6] Shelters should be connected to the open air

[7] A longer time may be used if there is a very heavy traffic of trucks carrying combustible goods and the evacuation from the shelters is not possible within 120 min

2.3.2 PENDING QUESTIONS

Introduction of Tunnel Fire Curves into European and International Standards

PIARC has contacted the European Committee for Standardisation, in particular CEN/TC250 (*"Structural Eurocodes"*) and proposed that a temperature-time curve representative of very severe tunnel fires (either RWS or HC_{inc}) be introduced into the relevant European standard.

In 2015, revision work on the Eurocodes has started, among which the relevant parts for fire assessment. Recently also through national input in CEN TC127, attention was raised to (the Horizontal Group Fire of) CEN/TC250, to address the lacking tunnel fire curve in structural Eurocodes. The process to adopt tunnel fire curves has started, but the final implementation in the CEN standards, may take a number of years. At the same time, the introduction of the supporting calculation rules should be considered for inclusion in the "material" dependent Eurocodes, especially EN 1992-1-2 for concrete.

Recently, renewed attention has been raised in ISO TC92Mid 2017, a decision will be taken to install a taskgroup, which should investigate if and how ISO TC92 should start activities on tunnels, and if so, how it should organise these activities in its SC's. Anticipating on a positive decision as well as on the taskgroup's findings, it appears likely that all 4 SC's (SC1 "fire initiation and growth", SC2 "fire containment", SC3 "Fire threat to people and environment", and SC4 "Fire safety engineering") are involved in the activities. The taskgroup should report and advise by the end of 2017.

Fire Safety Engineering

The important FSE standardisation committees and tunnel fire committees, including CEN TC127/WG8, ISO/TC92/SC2 and SC4, PIARC D5 and ITA WG6, believe that every tunnel is unique as concerns the development of a fire scenario and numerous parameters are of importance:

- The type and density of traffic, and consequently the fire load and its distribution (area), as well as the possible fire spread
- The cross-section configuration, the length and inclination of the tunnel
- The ventilation design and ventilation capacity of the tunnel
- The possible use of active measures such as sprinklers or water mist
- The roughness of the tunnel surface and changes in cross-section
- The thermal inertia of the tunnel boundaries, etc.

These comments open the field to fire safety engineering and performance-based approach namely new approaches for the assessment of the safety level.

2.4 ITA CLASSIFICATION

Based on the information developed in Guidelines for Structural Fire resistance for Road Tunnels (ITA 2004) it has been determined that the temperature vs. time curves should reflect the typical use of road tunnels and a more general classification of tunnel fires. Consideration was given to the types of tunnel structure, cross section, materials and experience of tunnel operators and designers. The modified ITA time/temperature plot also classifies the fires based upon the use and does not consider the fire suppression system or methodology. For ease in design, road tunnel categories are presented in the following Table 2.4 :

CLASSIFICATION	TYPE OF VEHICLE
Category 1	Cars only (no HGV)
Category 2	Heavy Lorries (HGV)
Category 3	Petrol Tankers

Figure 2.4 : Road tunnel Categories

The general classification of tunnels as determined by vehicle type and fire time duration is further expanded by the tunnel type and potential risk of collapse.

CATEGORY	NUMBER VEHICLES INVOLVED	IMMERSED TUNNEL	TUNNEL IN UNSTABLE GROUND	TUN-NEL IN STABLE GROUND	CUT & COVER	AIR DUCTS	EXIT TO OPEN	EXIT TO OTHER TUBE	SHELTER
1	1-2	ISO 60 min	ISO 60 min	(ii)	(ii)	ISO 60 min	ISO 30 min	ISO 60 min	ISO 60 min
1	≥ 3	ISO 60 min	ISO 60 min	(ii)	(ii)	ISO 60 min	ISO 30 min	ISO 60 min	ISO 60 min
2 , 3	1-2	RWS/ HC_{inc} 2 hrs.	RWS/ HC_{inc} 2 hrs.	(iii)	(iii)	ISO 2 hrs.	ISO 30 min	RWS/ HC_{inc} 2 hrs.	RWS/ HC_{inc} 2 hrs.
2 , 3	≥ 3	RWS/ HC_{inc} 3 hrs.	RWS/ HC_{inc} 3 hrs.	(iii)	(iii)	ISO 2 hrs.	ISO 30 min	RWS/ HC_{inc} 2 hrs.	RWS/ HC_{inc} 2 hrs.

Table 2 5 : Design criteria for different circumstances

Notes :

(i) : The elongation of the design time temperature curve from 2 hours to 3 hours may be considered by tunnel owners who aim to protect the asset, reduce repair costs and limit the closure time of the tunnel, limiting economical costs of closure and environmental impact of diverted traffic. These longer fire scenarios correspond to a fire with important propagation to multiple vehicles.

(ii) Personnel Safety is not a criteria and does not require any fire resistance (other than avoiding progressive collapse). Taking into account other objectives (asset protection, limited costs in case of fire…) may lead to the following requirements:

- ISO 60 min in most cases
- No protection at all if structural protection would be too expensive compared to cost and inconvenience of repair (e.g. light cover for noise protection)

(iii) Safety is not a criteria and does not require any fire resistance (other than avoiding progressive collapse). Taking into account other objectives may lead to the following requirements:

- RWS//HC_{inc} 120 min if strong protection is required because of property (e.g. tunnel under a building) or large influence on road network
- ISO 120 min in most cases, when this provides a reasonably cheap protection to limit damage to property
- No protection at all if structural protection would be too expensive compared to cost and inconvenience of repair works after a fire (e.g. light cover for noise protection)

2.5 TIME-TEMPERATURE CURVE VERSUS MEGAWATTS

2.5.1 Issues with conversion

In the fire specifications of tunnel projects, the performance of the fire protective lining and other passive fire protection measures, is described.

Passive fire protection systems are first of all based on a design fire curve in terms of temperature development over time as the thermal attack to the system. On the other hand there are the thermal failure criteria of the structure or system that requires protection, described as maximum exposure temperatures to certain elements of the structure. The required thermal protection can be selected using these parameters.

It is therefore imperative to prescribe the selected design fire curve in the fire specifications of the tunnel project, along with the thermal failure criteria. The thermal failure criteria can sometimes be derived from fire testing procedures and standards.

In some cases only the Heat Release Rate (HRR), along with the fire duration, is mentioned in the project requirements, without any guidance as to the time – temperature development. This brings up the question of how to convert a HRR figure to a design fire curve. For example, which fire curve represents 100 MW for 4 hours?

In fact there is no direct physical relation between HRR and time-Temperature, so to answer the question, the following issues need to be addressed:

Tunnel Height and Width

A fire in a high tunnel will build up less heat as opposed to a fire in a tunnel with a small cross sectional area. In a large tunnel, the air volume that needs to be heated is larger and also the surface area of the walls and ceilings is larger, and is therefore able to absorb more heat.

Ventilation speed

Ventilation systems in tunnels are an important part of the holistic fire safety concept. Full scale fire tests have shown that an increased ventilation speed in the tunnel tube will most likely increase the fire size and can potentially induce fire spread from one vehicle to the other. The maximum heat release rate for solid materials can increase by a factor of 1.4 – 1.7 compared with a fuel burning outside a tunnel. The fire growth rate may increase much faster, or by factor of 6 or more. By increasing the ventilation speed additional oxygen is fed to the fire source and thereby tilting the flames so the risk for fire spread between vehicles increase. A slower ventilation speed reduces the fire size and fire growth rate but the duration of the fire will be prolonged.

Ventilation speed also influences the gas temperature in the tunnel. For a given fire size and fire duration increasing the ventilation speed will either increase or decrease the gas temperature. In this case the overall effect of increasing the ventilation speed may be a lower thermal attack to the system. Therefore it is not clear, whether mechanical ventilation will increase or decrease the thermal attack.

Location of the fire in the tunnel

If the fire is located near the entrance or exit of the tunnel tube, the heat can escape from the tunnel and can dissipate into the surrounding atmosphere. Should the fire be located in the centre of the tunnel, the heat is trapped and will start to heat up the walls and ceiling, which in return will radiate the heat back into the tunnel.
This is also related to the length of the tunnel. In a short tunnel the heat can quickly find its way to one of the exits, decreasing the temperature in the tunnel.

Gradient

The gradient or slope of the tunnel influences the so called chimney-effect. If the tunnel has no gradient the heat and smoke will spread through the tunnel in the same direction as the ventilation direction. In case of a low ventilation speed the heat will build up at the location of the fire, leading to an increase in temperature.
With a gradient of say 5% the heat and smoke will climb upwards. If in that case the ventilation goes into the same direction, the heat will be taken from the fire location even quicker, reducing the temperature development at the fire location.

Time/duration of the fire

Depending on the amount and type of combustible materials being involved in the fire, the fire duration will be influenced, along with the temperature rise in the first minutes.

2.5.2 Concerns about megawatt output of bus fires

There is a growing concern about the rather low MW predictions of bus fires which are listed in several national and international standards and guidelines. Very little research has been undertaken so far to substantiate these figures whereas bus fires in practice have indicated to have larger MW outputs. The authors therefore have little information to analyse in this document but felt that this concern at this stage has to be shared with the industry.
On top of that, buses are increasingly propelled using new (more environmental friendly) energy carriers, such as CNG. This comes with additional risks, such as jet fires [2.7].

2.5.3 Recent research and modelling

If all the above parameters would be known, an advanced Computational Fluid Dynamics (CFD) calculation would have to be made in order to come to an understanding of the temperature development in a certain fire scenario. The complexity of CFD calculations, especially when aimed at accurate predictions of temperatures, makes them not always the first choice when doing performance based design. Using tables and predetermined time-temperature curves is the most simple and robust method. There may however be situations or projects, where more efforts are needed, and then a CFD may be an option. This can be the case if one wants to investigate a specific type of scenario involving multiple vehicles under a very critical infrastructure. The interest may be in analysing the effects on the construction, not in the point where the fire started, but further downstream if the fire spread to other vehicles. Here CFD is a possible option. There are also other intermediate solution available, namely engineering models that correlate the heat release rate to the ceiling gas temperature. These engineering models can be used in pure performance type of design, and it should be encouraged that designer starts to use such approaches. An example of such model is given below.

Recent research has however revealed the possibility to calculate the maximum ceiling temperature, based on some of parameters as outlined under 2.5.1 thus enabling the designers to convert their conceptual tunnel design (based on the Heat Release Rate curve and other data) to a maximum expected temperature at the ceiling of the tunnel. The tables presented in par. 2.3 above, are based on the simplified model.

Such models can be both very useful but also very susceptible to user error. Amongst other reasons, the user has to understand to which maximum ceiling temperature the model is limited.
Very often the fire load in the models, including the more advanced CFD modelling is posi-tioned in middle of the tunnel (no flame impingement on wall), which in almost all fire scenarios is not typical.

Another subject that the user needs to be aware of is to which extent fire spread to other vehicles is accounted for in the model.

The example of the model developed by Li and Ingason [2.8, 2.9] is presented in appendix 2.

3.1 CONCRETE

In the following is briefly described the behaviour of the lining material during heating from a fire. The behaviour associated with the heating itself and the associated loss of strength and stiffness is discussed separately. The context of the structural behaviour is dealt with in section 5.

In the normal load cases the thermal properties of concrete are of limited importance to the design. However in case of a fire the thermal properties are important for the transfer of heat into the structures, the increase in temperature, which subsequently influences the mechanical properties and the load-bearing capacity.

3.1.1 Heating

The heat inside the tunnel will be transferred to the lining with a rate depending on the tunnel material. This process of heat transfer involves terms of convection as well as radiation.

Heat transfer by means of convection under fire conditions can reasonably accurately be correlated linearly to the temperature levels of the fire gases, whereas heat transfer by means of radiation is related to the temperature to the power 4. With a view to assess the tunnel lining behaviour, in most practical tunnel fire situations, the heat transfer by radiation therefore governs. [3.1, 3.2 and 3.3].

Knowing the temperature-time curve and through that the heat transfer to the tunnel lining, further assessment of the conduction of heat inside the tunnel lining is possible. However, given the rather high temperature levels to be considered, the behaviour of the tunnel lining appears specifically complex:

- The thermal material properties vary (significantly, and non-linearly) with temperature (such as thermal conductivity, and the specific heat);
- Also the thermo-mechanical material properties show a significant non-linearity at elevated temperatures (expansion coefficient, and strength and stiffness parameters);
- In addition to that, within porous lining materials (concrete, and also passive protective materials), mass transport takes place under influence of the heating (moisture and above 100°C also water-vapour).

Accurate assessment would therefore require advanced computer simulations of the physical phenomena involved, and results in rather complex coupled models to capture chemical (phase) changes, thermal-hygral and thermo-mechanical physics.

3.1.2 Thermal properties

The information required for the determination of heating of the lining is:

- Thermal conductivity (depending on aggregates, temperature and humidity)
- Specific heat /heat capacity (depending on aggregates and temperature)
- Density (depending on concrete mix)
- Convection coefficient (depending on temperature and boundary conditions)
- Emissivity coefficient (depending on surface and shape)
- Thermal properties for surrounding ground and other thermal boundaries.
- Decomposing reactions (dependent on material mix and water content)

The properties will depend on the type of concrete (especially the aggregate, either normal weight (granite, limestone…) or light weight). It is noted that aerated concrete may have a rather low thermal conductivity, but these types are of little use to normal tunnel construction. Also the cement aggregate ratio and the moisture content may influence the (apparent) thermal conductivity. In addition the thermal conductivity appears to decrease with increasing temperatures. In normal cases the conductivity is simplified by a double linear curve with values between 2 and 0.5 W/mK.

The specific heat capacity for the dry concrete will be in the magnitude of 0.5 to 1.5 kJ/kgK increasing with temperature and depending on the aggregates. Concrete with limestone aggregates tends to have higher capacity than concrete with siliceous aggregates. Taking into account also the moisture content the specific heat capacity is in the magnitude of 0.8 - 1.2 kJ/kgK, with a peak at about 100°C dependent on the moisture content. For a water-content of 3% the peak value is in the magnitude of 2 kJ/kgK. Alternatively a coefficient indicating the capacity multiplied with the density can be indicated. The coefficient is for concrete in the magnitude 2.3 MJ/m3K, (EC value). The 100°C peak is in the magnitude of 4.5 MJ/m3K for a water-content of 3%. In the Eurocode there is a list of temperature depend correlations for heat conduction, enthalpy and heat of capacity for different concretes. Both upper and lower limits are given. It is recommended to use the values given there, if the exact knowledge for the concrete is not known.

For calculations of the temperatures in a tunnel it may be necessary to model also the thermal properties of the surrounding ground, in which case the thermal properties of the ground will have to be modelled.

In principle it may be possible by use of CFD to determine the temperature in the tunnel and in the lining at the same time. This will ensure the modelling of the interaction between the lining and the gas temperature. However, it makes the CFD model even more complex and makes an extreme detailing necessary. So in most cases it is practical to separate (un-couple) the two calculations.

Note that the heating is in most practical cases sufficiently accurately described with a thermal model only, implicitly accounting for mass transport (hygral, i.e. moisture and vapour).

A final, but important remark is made with respect to the fact that due to the migration of the heat front through the tunnel linings, maximum temperatures may be reached at a point in time after the fire has reached its maximum temperature, and a decay phase of the fire has started. This lagging effect may extend to as long as 30-60 minutes, and it suggests that critical structural behaviour may become apparent long after the fire has died out, or has been extinguished.

3.1.3 MECHANICAL PROPERTIES

Concrete

During the fire, thermal gradients will develop in the concrete lining, which over a depth of no more than a couple of cm, may range up to more than 1000 C. Also large thermal gradients may develop over the length of the tunnel, with associated complex effects of (restraint) to thermal expansion. Particularly for a tunnel lining which will be heated from one side the temperature and the constitution of the concrete on the inside will be very different from the conditions at the outside. The mechanical properties of each part of the section will be affected according to the depth and the heating of this particular point. The loading of the individual points of the section is dependent on the thermal expansion, different creep/ transient strain phenomena and influenced by the surrounding stress state. Overall the boundary conditions of strain compatibility and static equilibrium will govern.

Expansion and shrinkage

Similar to other materials concrete will expand when heated. In the most simplified form the expansion is described by a coefficient giving a linear relationship between the increase in temperature and the expansion. However, for the calculations of concrete structures subjected to fire it is relevant to define the expansion by curves giving the relationship between the strain and the temperature. This curve will depend on the type of aggregate, the aggregate cement ratio and the water cement ratio. For siliceous concrete the thermal elongation will be about 0.5 % at 400°C and 1.4% over 700°C. Simplified linear or double linear relationships can be found from codes or handbooks.

In addition to the thermal expansion also transient strain, creep strain and strain from external forces contribute to the deformation of the concrete. The transient strain depends on the temperature change and the level of load whereas the creep will be dependent on the matrix and aggregates, the temperature, time and the load level. The strain from external forces depends on the reduced stiffness and the strain compatibility.

The deformation of the cross sections, the segments and the tunnel structure in general shall be investigated in order to find the degree of confinement. Often the deformations are able to redistribute the loads and relieve confinement stresses.

When the thermal expansion is confined it will produce a mechanical stress. The stress is determined by multiplication of the confined expansion with the stiffness at the particular point. It should be noted that the stiffness will be significantly reduced at the points of the highest increase of temperature. The thermal strain is an expansion of the concrete, however, the total deformation may in some cases be a compression.

In contrast with the expansion of the aggregates in fire conditions, the cement paste will dehydrate and therefore shrink. The adverse behaviour of these two components of concrete causes internal stresses and will introduce (micro) cracks at temperatures as low as 150°C.

Reduction of strength and stiffness

The concrete is weakened in compressive strength and in stiffness due to the heating, i.e. thermal decohesion and thermal damage of the concrete. The reduction of strength and stiffness is normally expressed in curves indicating fc respectively E relative to the value at 20°C for temperatures up to 800°C - 1000°C. Values can be found in handbooks or codes, e.g. Eurocodes, national codes and e.g. CEB. The curves found in codes are in many cases a reasonably good estimate for the remaining strength and stiffness. It should be noted however, that the curves depend on the concrete mix: in Eurocode curves are indicated for siliceous aggregates respectively calcareous aggregates. In the work of Prof. Glerum, a number of curves for different aggregates are indicated [3.4]. Furthermore test results reveal a variation of strength reductions [3.5].

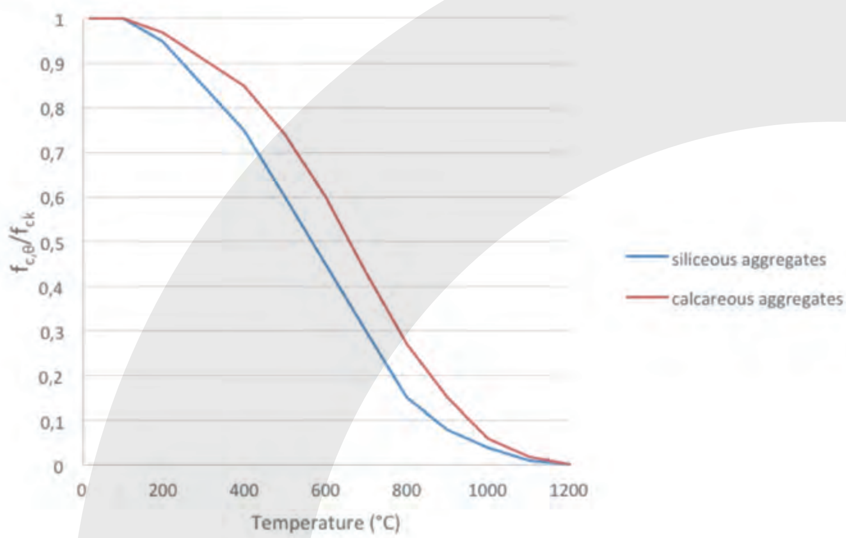


Figure 3.1 : Reduction of compressive strength of concrete at elevated temperatures according to Eurocode 2 (EN1992-1.2) [3.2]

Generally in structural design, permissible stress in structural members is assumed to be within the range of 30% 50% of the compressive strength of concrete by the suitable scale of fire with comprehensive risk assessment.

The temperature at which concrete spalling may occur will vary between the condition of the temperature which entire concrete structure receives, the concrete strength, cement water ratio , the quality of aggregate and the mechanical loading. The relationship between temperature and strength, showed in Figure 3.1, would not have any strength reduction up to 200°C.

Figure 3.1 shows the effect of temperature on the strength of concrete. The strength of concrete is still 100 % at a temperature of approximate 200°C and ends at 750°C. The effect of temperature on high tensile steel is worse than on reinforced steel. Before 1992 only one safety coefficient to calculate the safety of concrete structures built in the Netherlands, and this was 1.7. This means that if the strength of the concrete is reduced to 100% / 1.7 i.e. 59%, the safety of a structure is 1.0, in the other words it is no longer a safe structure (very simplified). The graph shows that the temperature of concrete can rise to approximately 450°C before a structure might fail.

According to Figure 3.1, it can be thought that hair crack or spalling already exists over the concrete surface, which has already been affected by high temperature, in the area of temperature where initial strength gets lower (decreases). Therefore, if the requirement is to avoid any resistance loss, it is necessary to limit the temperature that the concrete is subjected to a range within 350°C 400°C. In any of these cases, if the temperature concrete is subjected to in a fire is between 1,000ºC and 1,350ºC (RWS standards), set at planning or design stages, it is required to take into account the resistance reduction and eventually provide materials that shield an approximate maximum temperature of 1,350ºC (see below).

To go further, we can distinguish 2 cases:

a/ if no temporary damage of the concrete structure is allowed

This is the case for example when the requirement is to reopen the tunnel very quickly after a fire with all the guarantees that the structure characteristics remain fully intact. Based on experience, the accepted maximum temperature of 380°C[(1)] is to be applied to concrete and 250°C to reinforcement steel for the following reasons :

Concrete :

- Both concrete and lining have a high thermal capacity. They hold the heat and even after the fire has been extinguished, the temperature within the concrete continues to rise;
- To minimise the concrete damage, a maximum temperature of 380°C is defined; it provides a certain safety compared with the limit of 450°C discussed before
- Large shear forces are concentrated near the supports (walls), at places where there is no shear reinforcement, which occurs especially in the older tunnels.

Steel :

- It is true that the strength of steel is not reduced at 250°C, but deflections occur. Due to the permanent load on the roof of the tunnel, the chance is high that the deflections will be permanent.

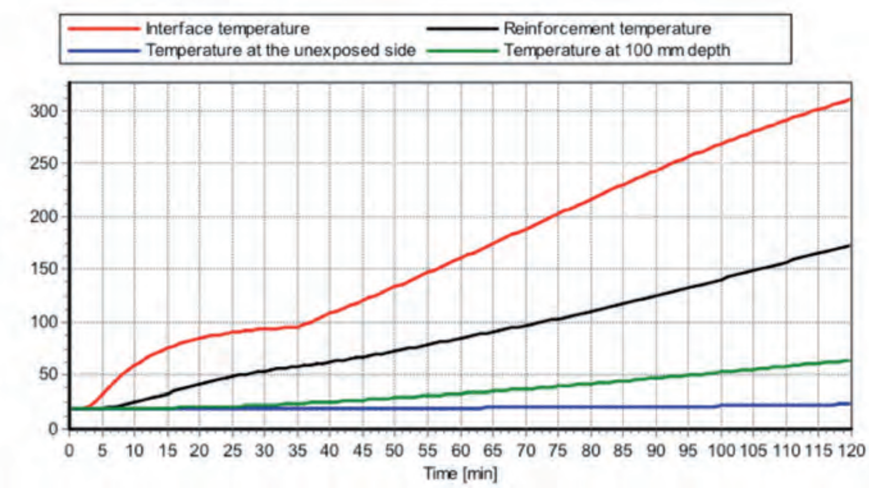


Figure 3.2 : An arbitrary example of a temperature development throughout the structure of concrete with fire protection material

Figure 3.2 illustrates a concrete tunnel liner with 25 mm of fire protection material on exposed surface, cover on reinforcing steel is 25 mm and slab thickness is assumed to be 250 mm. Fire exposure is 120 minutes Rijkswaterstaat (RWS). This graph is indicative only and cannot be used for specific projects.

Note that the below concrete related parameters do have a significant influence on the temperature development in a concrete structure:

- Type of aggregate being used (calcareous or siliceous)
- The density of the concrete
- The moisture content of the concrete

[(1)]These values are related to the retained strength and durability of (ordinary cast in-situ) concrete. Espe-cially for higher grade concretes, lower values (180-220 °C) may apply.

b/ if temporary damage of the concrete structure is allowed

Concrete tunnel structures may be fire resistant without the use of fire passive protection. In this case, the effects of high temperature on the materials and the structures (resistance and stiffness reductions, thermal dilatation…) have to be carefully taken into account in the design.

It is important to keep in mind that even unprotected, a tunnel may be able to guarantee the required level of safety during a fire. The main drawback is that the concrete will be damaged by heating and require more extensive repair works. In such a case, the tunnel owner should be aware that, after a fire, the tunnel may be closed for a longer period. Especially for immersed tunnels, fire induced cracking at the unexposed side might occur, which initially may be acceptable, but due to durability issues over time lead to unacceptable situations.

3.1.4 SPALLING

Whereas the reduction of strength and stiffness is relatively well described, the spalling is an area for which the mechanisms are still discussed. A practical engineering model for determining the risk of spalling and the possible thickness of spalling does not exist yet.

On the other hand the topic of spalling is important to take into account. There is not much point in discussing the reduction of the strength and stiffness if it is not known whether 50, 100 or 150 mm or more may spall during the fire.

There are two basic mechanisms, which internationally are considered now as equally relevant to consider, but depending on specific cases one mechanism may govern the spalling phenomena, or initiate it: the water vapour pressure clog consideration and the (restraint to) thermal expansion.

Some of key observations concerning spalling are listed below :

- Dense, impermeable concrete is more susceptible than low quality concrete.
- Hence, the concrete mix and production conditions are important parameters.
- Spalling can occur both for high strength concrete and classical concrete.
- The diffusion of water and the water content are important.
- The aggregates influence the spalling (calcareous aggregates are reported to give more spalling than siliceous aggregates).
- The arrangement of reinforcement influences the spalling especially in normal strength concrete but it does not prevent the spalling (contrary to indication in some codes).
- Spalling of unprotected concrete exposed to rapid increase of temperature (RWS, HC_{inc}) commences within minutes.
- Fires with rapid increase of temperature (RWS, HC_{inc}) are worse than fires with gradual increase of temperature.
- Mechanical pressure (compression) on the structure is reported to make the spalling worse.
- The geometrical shape of the element influences the spalling pattern.
- The occurrence and course of the spalling is a random process if studying the individual fragments.
- Self Compacting Concrete is reported to suffer more from spalling compared to regular concrete.
- The thermal gradient that the interface will be exposed to impacts on the spalling behaviour.
- Concrete structures which are protected against fire, but using insufficient insulating capacity (material type improper or material thickness insufficient), can suffer from more (explosive) spalling.

A realistic practical engineering estimation of the spalling is not common practice and may not be possible with analytical tools.

The question is then what can be done to take into account the extent of spalling in the estimation of fire resistance. Some ideas are given:

1. The spalling characteristics can be determined experimentally. This estimation has the disadvantage that it is performed in a relatively advanced stage of the construction. Due to the size effect, and the production conditions, a full size sample should be taken from the production and the sample should have a reasonable age, as the spalling is dependent on the water content. A new development is mobile furnace which can be installed in an existing tunnel or at a yard nearby the construction location of the tunnel, for a segmented tunnel for example. The mobile furnace aims to define the spalling sensitivity of the concrete, providing interface temperature limits at time intervals during the fire exposure period.

2. The spalling can be assumed. It has earlier been indicated in codes etc. that spalling could (in case it is taken into account) be assumed to be limited to the cover, i.e. 30 - 50 mm. This has in case of especially the Channel Tunnel shown to be too little. However, in place of other design basis one can assume a certain spalling e.g. 50, 100 or 150 mm and test the structure towards this spalling damage. The spalling can in turn be confirmed or updated by experimental testing.

3. It can be aimed to prevent or limit the spalling. A classical idea for existing structures is fire protection, in form of boards or sprayed-on material. Especially pre-mounted material has disadvantages in connection with segmental lining, as it may be damaged during erection or will hinder the erection rate. In any case also fire protected concrete may under circumstances spall, so the fire protection must have a suitable thickness (see [3.6]). For new tunnels, other fire protection measures like admixture of polypropylene and steel fibres can be applied. These measures are not discussed in this document. Reference is made to relevant research [3.7].

3.2 REINFORCEMENT

Thermal

The thermal behaviour of the reinforcement can be described by the conductivity, the heat capacity, etc. similar to the parameters indicated for the concrete.

The detailed description of the heating and heat flow in the reinforcement can be important for the analysis of details around the reinforcement or for heavily reinforced parts of the tunnel.

For less reinforced parts of the tunnel, the calculation of the heating of the reinforced concrete may often be simplified as a homogeneous material.

Mechanical

Similar to the concrete the strength and stiffness of the reinforcement is reduced due to the heating. For many types of structures the load bearing capacity during a fire is directly dependent on the moment capacity and thereby on the remaining capacity of the reinforcement. For tunnels the capacity is often determined by a combination of bending and normal force (see section 5).

The reduction of the strength and stiffness is dependent on the type of reinforcement: cold deformed reinforcement will lose more strength at high temperatures than hot rolled reinforcement.
Examples of the yield strength reduction are indicated in figures 3.3 and 3.4. The stiffness and the stress-strain relationship of the reinforcement in general will be affected by the heating. As for the concrete, the stiffness of the reinforcement is reduced at a higher rate as illustrated in figure 3.5.

Simplifications of the strength reduction curves are indicated in different handbooks and codes (the curves of figures 3.3 to 3.6 are taken from Eurocode 2 Part 1-2). These indications will in most cases be sufficient; if more information is necessary the producer of the reinforcement may have test results. Otherwise particular tests will have to be made.

The reinforcement will to some extend regain its strength after cooling. The hot rolled reinforcement will regain most of its yield strength and ultimate strength. The cold deformed reinforcement will regain most of its strength up to a heating of 300°C, for heating up to 600°C about 60% of the yield strength and ultimate strength will be remaining.

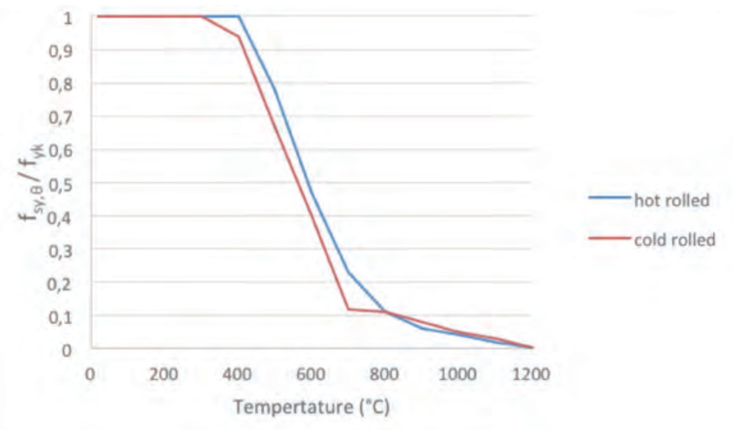


Figure 3.3 : Relative strength of class N reinforcing steel at elevated temperatures according to Eurocode 2 [3.2]

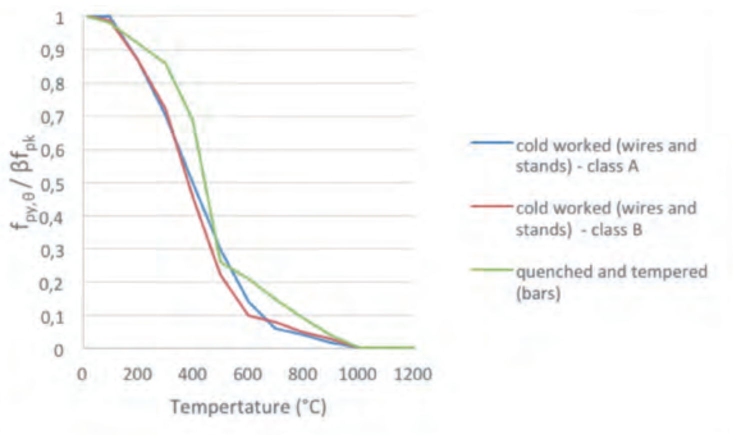


Figure 3.4 : Relative strength of prestressing steel at elevated temperatures according to Eurocode 2 [3.2]

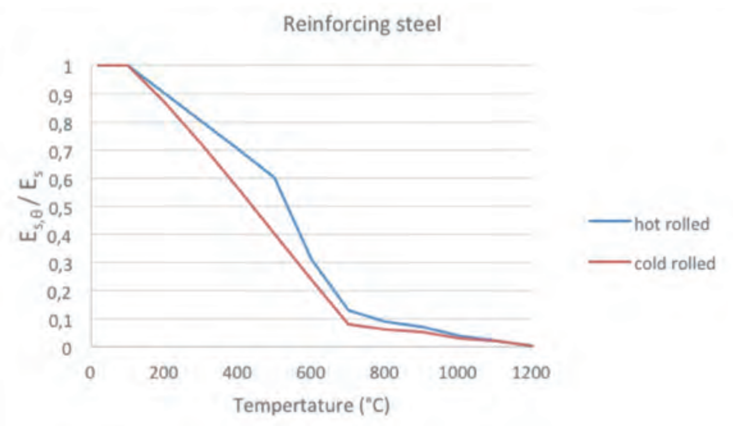


Figure 3.5 : Relative modulus of elasticity of reinforcing steel at elevated temperatures according to Eurocode 2 [3.2]

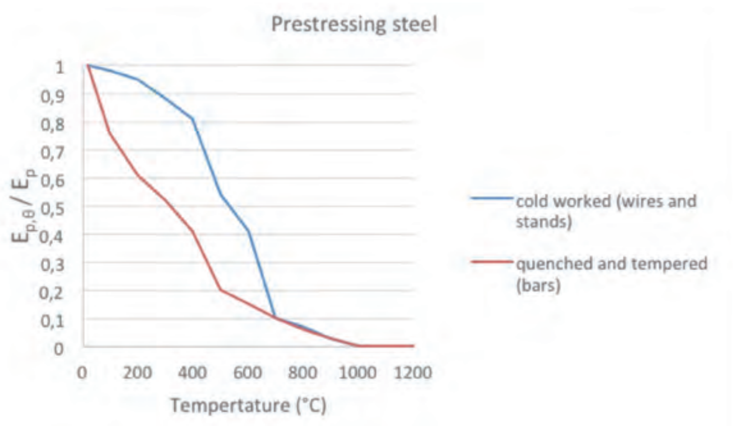


Figure 3.6 : Relative modulus of elasticity of prestressing steel at elevated temperatures according to Eurocode 2 [3.2]

When subjected to very high temperatures the steel may melt or decompose.
Details should be particularly observed: welds will also lose strength and corrosion protection by paint or similar may influence the behaviour of the structure during the fire.

Thermal expansion

The thermal expansion of the reinforcement is in most cases modelled by a linear or double linear temperature- strain relationship. The expansion coefficients are moderately influenced by the type of reinforcement. The coefficient is higher for pre-stressing cables than for reinforcement bars. The coefficient for reinforcement is in the same magnitude as the initial thermal expansion coefficient for the concrete.

Bond of reinforcement

Due to the heating, the reinforcement will gradually lose its bond. The reason is mainly cracking in the concrete and the reduction of the strength of the surrounding concrete. Curves indicating the relationship between the bond and the temperature are given in the literature, but the exact models are still disputed. It has been observed that ribbed steel remains more of its bond up to temperatures of 400°C - 500°C compared to smooth steel. At temperatures over 600°C, no or very little bond will be left.

If possible structures should be designed so that the reinforcement is bonded at the side of the structure that is less subjected to fire.

For the design and analyses of details such as joints and fixations a closer study of the bond of the reinforcement might be relevant. For larger structural elements it may not be necessary to study the bond in detail.

3.3 PROTECTIVE MEASURES

3.3.1 Commonly used product types

The industry of passive fire protection materials offers a range of suitably tested and certified products which can withstand design fire curves which can withstand fires that range between ISO and RWS. For each tunnel project the suitability of the use of the intended product and system needs to be checked against the project requirements.

The common products are:

- Calcium Silicate boards
- Calcium Silicate Aluminate boards
- Vermiculite / cement spray on systems
- Perlite / cement spray on systems
- Composite panels

Reference is made to special studies and product information in section 5 [3.4, 3.8]. Fire protection materials are discussed in sections 5.12 and 5.13.

By means of passive fire protection the heating can be reduced. The types of fire protections vary from organic to inorganic materials, sprayed-on material and boards.

3.3.2 Non-suitable fire protection for use in tunnels

3.3.2.1 Paint products and systems

Fire isolating paints also exist but these are not suitable for use in tunnels. These Inorganic Coatings, also known as Intumescent Coatings can be either Solvent based or Water based and rely on the ability of the product to react under fire conditions and swell to create an insulating char. These products would be unable to react in a timely manner to keep pace with the rapid temperature development associated with tunnel fires. Therefore the use of such coatings is not recommended.

In addition:

I) Solvent based products are combustible and health and safety hazard during application needs to be considered

II) Water based products most typically cannot cope with heavily laden moisture conditions often present within a tunnel requiring the additional application of a water protective topcoat (Solvent Based) They are known to produce toxic fumes and dense smoke under fire conditions, which make them unsuitable for use in tunnels where life safety is an important consideration.

3.3.2.2 Magnesium Oxy-Chloride based materials

In the general building industry, the use of Magnesium Oxy-Chloride based board materials is rather common. Several of the manufacturers of fire protective board materials in the market, either produce such boards or have access to this technology. Magnesium Oxy-Chloride materials are also known as “Fibre reinforced magnesium” and “Magnesium oxide, silicates and other additives” which all contain Chloride.

However, for technical and life safety reasons mentioned below, it has to be noted that Magnesium Oxy-Chloride boards are not suitable for application in a tunnel environment.

a/ Corrosive effects of leaching Chloride ions

Magnesium Oxy-Chloride present within the board matrix will have a detrimental corrosive effect on the anchors, steel components in the tunnel and steel reinforcement in the concrete, especially in high humidity environments negatively impacting on the long term durability of the completed tunnel facility. This is associated with the leaching of Chloride ions when the Magnesium Oxy-Chloride material is exposed to moisture, high humidity levels or water. Reinforcement steel, steel brackets, anchors, jet fans, cable trays etc. will be exposed to Chloride concentrations to the extent that corrosion and/or premature failure is inevitable.

Reports have been available in the public domain in this regard for years and most recently a further critical report has emerged from an expert consultant in Australia on this very topic [3.9, 3.10, 3.11].

Such detrimental effects on the durability of the tunnel are a concern with owners, engineers and contractors.

b/ Impact of Hydrochloric acid (HCl) on tenable environment

During fire conditions, Chloride is being released from the board, exposing tunnel users, who are trying to escape from the fire scene, and emergency response teams, to Hydrochloric acid (HCl).
Such detrimental effects on the tenable environment and life safety of tunnel users cause serious concerns with owners, engineers, and emergency response teams.

c/ Independent research conclusions

The Technical University of Denmark and Bunch Building Physics ApS from Denmark have issued a paper which is attached in annex [3.9]. Their recent (August 2016) research concludes as follows:

"The experiments described in the paper seem to indicate a relative humidity level of 84% RH as a limit above which the MgO-boards that have been tested begin to absorb excessive amounts of moisture from the surrounding air. Since this and higher values of relative humidity are typical in locations where exterior sheathing is to be used, it can be stated that MgO-boards cannot be a suitable product for this use. This is supported by the numerous examples of failures, which have been seen in recent years, where such boards leak salty water that cause damage on adjacent construction members of wood or metal, and which even over time lead to disintegration of the MgO-board itself."

They continue to conclude :

"For this reason, it can be stated that MgO-boards are not suited as sheathing in exterior facades or any other application where the boards are in contact with a moist climate. At RH above approximately 84% RH the MgO-boards will form drops of salty water on the surfaces, and this water will be absorbed in wooden structures in connection with boards and water absorption will increase and can lead to mould growth on wood. The MgO-board itself is also sensitive to mould growth due to the content of organic material. Furthermore, the MgO board will itself also be disintegrated over time when it is exposed to high humidity due to the dissolution of the salts it consists of. If metal parts, such as galvanized steel, fasteners and flashings are in contact with MgO-boards, they will start to corrode within short time, leading to safety problems in the structure. Sheathing with MgO boards are now being replaced by other types of materials in a great number of buildings in Denmark."

Humidity levels in tunnels are often rather high, due to, for example:

- Water leaks of the tunnel structure
- In case of precipitation, moisture will be carried into the tunnel by vehicles
- Washing activities to clean the tunnel linings
- Meteorological circumstances.

4.1 GENERAL

Tunnels are classified in regard to the original design the type of construction and the physical properties of the tunnel in regard to the method of ventilation, egress and potential for collapse as a result of a fire event. Tunnels are generally classified as follows:

- External configuration (circular, box section, arch)
- Structural lining type
- Method of construction
- Type of environment for tunnel construction (stable, unstable ground)
- Ventilation configuration
- Location (under/near other structures, in water course)
- Types of emergency access (rescue tunnels, cross passages, emergency shafts)

External configuration of tunnels is divided up into the following subsets:

- Circular
- Box (Square or rectangle)
- Arch
- Twin Tube (Immersed Tube Tunnel), ITT)

The structural lining type is divided up into the following subsets:

- Cast-in-place concrete
- Shotcrete
- Precast concrete segmental
- Precast concrete
- Exposed cast iron/ steel segmental
- Concrete covered cast iron/steel segmental
- Dimension Stone (Asher stone)
- Masonry (brick)

The Medium or environment that the tunnel is constructed is divided up as follows:

- Stable ground
- Unstable ground
- Bedrock

The type of ventilation means of egress and proximity to other structures is a variable for each type of tunnel. These variables have been classified to illustrate each type of ventilation configuration and are best illustrated in the attached figures. The use of external rescue tunnels, emergency access shafts and cross passages and proximity to other structures are modifiers to each general type of tunnel illustrated.

4.2 TUNNEL CLASSIFICATION DESCRIPTION

The tunnel description is intended to simply classify tunnels into numerous classifications that will allow the tunnel type to be placed in a database for rapid retrieval and to standardise the de¬scription of tunnels. The most common types of tunnels are as follows:

Type 1 Circular; Exhaust above; supply air below roadway
Type 1A Circular; Supply & exhaust below the roadway
Type 1B Circular; Supply over the roadway, no exhaust
Type 1C Circular; Exhaust over the roadway, no supply
Type 1D Circular; Jet fans over roadway, no separate supply or exhaust
Type 1E Circular; Supply and exhaust over the roadway
Type 2 Arch; Exhaust over the roadway
Type 2A Arch; Supply air over the roadway
Type 2B Arch; Jet fans in arch, no separate supply or exhaust
Type 2C Arch; Supply air below the roadway
Type 2D Arch; Jet fans in arch, supply air below the roadway
Type 2E Arch; Supply and exhaust below the roadway
Type 2F Arch; Supply and exhaust above the roadway
Type 3 Box; Exhaust above the roadway, supply air under
Type 3A Box; Exhaust over the roadway, no separate supply air
Type 3B Box; Supply air over the roadway, no separate exhaust
Type 3C Box; Supply air below the roadway, no separate exhaust
Type 3D Box; Jet Fans in roof, no separate supply or exhaust
Type 3E Box; Supply and exhaust below the roadway
Type 3F Box; Supply and Exhaust above the roadway
Type 4 Immersed Tube; Exhaust above the roadway, supply air under
Type 4A Immersed Tube; Exhaust above the roadway, no separate supply air
Type 4B Immersed Tube; Supply air above the roadway, no separate exhaust
Type 4C Immersed Tube; Supply air below the roadway, no separate exhaust
Type 4D Immersed Tube; Jet fans above the roadway, no separate exhaust or supply Type
Type 4E Immersed Tube; Immersed tube tunnel with cross passages
Type 5 Tunnel with external egress tunnels (any type of construction)
Type 6 Urban tunnel with structure above tunnel (any type of construction)

4.3 TUNNEL CLASSIFICATION FOR RISK ANALYSIS

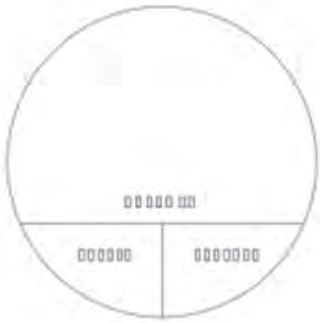
The classification of tunnels as shown here are intended to allow the owner/operator to easily evaluate the degree of sensitivity towards risk associated with a fire in the type of tunnel structure that one is evaluating. The key elements for protection are those that are to be protected from collapse or are necessary for the safe evacuation of the public and for protection of fire-fighters. Tunnels that are located in urban environments and/or are in soft unstable ground have the greatest potential for risk associated with collapse or the potential to effect other nearby structures (types 4,5,6), therefore more attention must be made to the protection of the structural elements from fire.

The information as to classification of tunnels is for informational purposes only and each tunnel type must be classified according to local codes and ordinances. The intent of this classification system is to standardise classifications to allow local codes and ordinance to adequately evaluate the potential risk and thereby develop appropriate guidelines for protection of the structural elements as described in Sections 5 and 6 of this document.

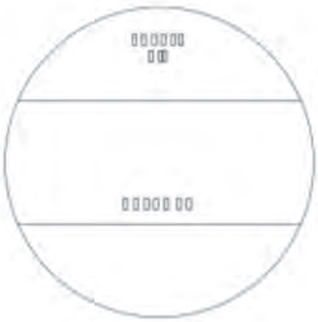
4.4 TUNNEL CLASSIFICATION SKETCHES

The following sketches are for informational purposes only and are representative of the classifications illustrated here. Variations in these configurations are common and are to be documented as discussed in Section 4.2

TYPE 1



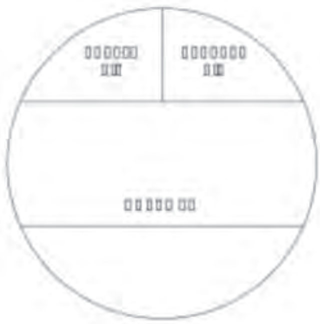
TYPE 1A



TYPE 1B

TYPE 1C

TYPE 1D



TYPE 1E

TYPE 2

TYPE 2A

TYPE 2B

TYPE 2C

TYPE 2D

TYPE 2E

TYPE 2F

STRUCTURAL FIRE PROTECTION FOR ROAD TUNNELS

TYPE 3

TYPE 3A

TYPE 3B

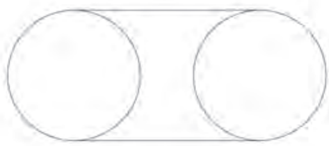
TYPE 3C

TYPE 3D

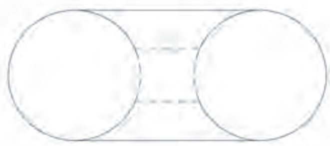
TYPE 3E

TYPE 3F

STRUCTURAL FIRE PROTECTION FOR ROAD TUNNELS

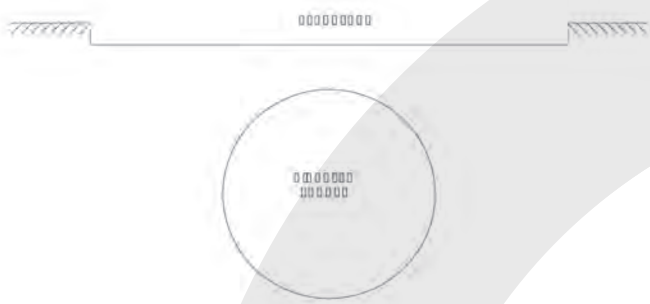


TYPE 4 (TYP)



TYPE 4
(Cross Passages)

Type 5 (typ)



Type 6 (typ)

4 >> Tunnel classification

The following table is provided to illustrate typical elements of a tunnel to be preferentially protected from rapid heat rise that would cause collapse or an unsafe condition in the tunnel. The protection should be based on the criteria provided in this document and after consultation with local Authorities of applicable codes.

TUNNEL TYPE	LINING UNSTABLE GROUND	LINING STABLE GROUND[1]	CEILING	ROADWAY SLAB	DUCT WALLS	CROSS PASSAGES[2]	FAN ANCHORAGES	CEILING SUPPORTS
1	X		X	X		X		X
1A	X			X	X	X		
1B	X		X			X		X
1C	X		X			X		X
1D	X					X	X	
1E	X		X		X	X		X
2	X		X			X		X
2A	X		X			X		X
2B	X					X	X	
2C	X			X		X		
2D	X			X		X	X	
2E	X			X	X	X		
2F	X		X		X	X		X
3	X		X	X		X		X
3A	X		X			X		X
3B	X		X			X		X
3C	X			X		X		
3D	X					X	X	
3E	X			X	X	X		X
3F	X		X		X	X		
4	X		X	X		X		X
4A	X		X			X		X
4B	X		X			X		X
4C	X			X		X		
4D	X					X	X	
4E	X					X		
5[3]	X		X	X	X	X	X	X
6[4]	X		X		X	X		X

Table 4.1 : Typical levels of protection based on tunnel type

Notes : 1. SG = Stable Ground and is assumed to be constructed in stable rock
2. Cross Passages used only for twin tunnel construction
3. Interior protection dependent on ventilation system refer to Type 3
4. Interior protection dependent on type of ventilation refer to Type 1

5.1 GENERAL

The following discussion is focused on the types of linings used for road tunnels and may be applicable to other types of tunnels and underground structures. This discussion is in general and is an attempt to illustrate the various behaviour of lining subjected to intense heat from a single fire event.

5.2 STRUCTURAL ELEMENTS

Construction materials used for main and secondary structures must be non-combustible or very little combustible (Euroclass A1 or Euroclass A2, s1, d0) from the point of view of reaction to fire. Lightweight roof structures may have less severe fire reaction requirements (i.e. Euroclass C) since the loss of these does not represent any risk to safety provided that fire propagation risks are limited (class A2 when tested to EN13501). All materials used for internal fire proofing linings must be non-combustible (class A1) when tested to EN13501.

This section specifies the minimum level of fire resistance of materials to ensure the safety of persons, including the emergency and rescue services engaged in their work. The tunnel owner may specify higher levels of resistance in order to provide improved fire resistance for the tunnel and limit both the extent and cost of repairs and closure period following a fire.

Time/Temperature curves are to be used as appropriate justification of the fire resistance of structures and certain items of equipment.

Fires in which the temperature rise is relatively slow, but which may have long durations are characterised by the standard ‘cellulosic’ Time/Temperature curve as defined in ISO 834.

Fires involving heavy goods vehicles may have a much faster temperature rise, particularly if they involve highly combustible materials (even if they are not classed as hazardous for the purposes of transport).

Such fires are characterised by modified hydrocarbon time/temperature curves such as the Rijkswaterstaat (RWS) and Hydrocarbon Increased (HC_{inc}) curves described in 2.3.1, which reach 1200°C within 10 minutes and may reach 1300°C or 1,350º shortly afterwards.

Materials used to provide structural fire protection in buildings may not be suitable for use in tunnels because they may fail (by either melting, burning or disintegrating) at temperatures above 1,200ºC. Regardless of the applicable design time-temperature curve in a tunnel project, the melting temperature of structural fire protection materials shall be at last 1350°C.

5.3 OBJECTIVES AND FIRE RESISTANCE LEVELS

Fire resistance required for structures and equipment is designed to provide the following main objectives:

- Protection of users inside the tunnel for the time taken for them to reach the exit.
- Maintain a safe environment for the emergency and rescue services.
- Maintain electricity supply and communications on either side of the fire.
- Prevention of flooding by surrounding ground water into the tunnel or catastrophic collapse of the structure.
- Protection of structures or buildings, which are in close proximity to the tunnel.
- Maintain ventilation capacity and design ventilation requirements.

5.4 FIRE RESISTANCE LEVELS

In order to meet these objectives without unnecessary additional costs, the following four levels of fire resistance from the French Inter-ministry circular 2000-63 [5.1] may be considered:

Level N0

No risk of progressive collapse in the event of a local failure. The loss of one element should not result in a transfer of load, which is likely to cause other parts of the structure to fail.

Level N1

This level corresponds to the majority of fires excluding the most violent ones. It should be used for structures which are important for emergency action to take place.

In tunnels where all types of vehicles are allowed, level N1 corresponds to resistance to the ISO curve during 2 hours.

Level N2

This level corresponds to high intensity fires, with a very quick development. It should be required for structures which must resist the most violent fires during the period required to allow evacuation and action by the emergency services.

In tunnels where all types of vehicles are allowed, level N2 corresponds to resistance to the HC_{inc} curve during 2 hours.

Level N3

This level corresponds to the most onerous fire exposure conditions and applies to structures, which must resist the most violent fire throughout the prescribed exposure period.

In tunnels where all types of vehicles are allowed, level N3 corresponds to resistance to both the ISO curve during 4 hours and the HC_{inc} curve during 2 hours.

Tunnels Reserved for Passenger Cars

Where only passenger cars and vans are allowed, with average fire loads of 7MW each, levels N1, N2 and N3 are identical and correspond to resistance to the ISO curve during 1 hour.

5.5 EVIDENCE OF FIRE RESISTANCE OF PROTECTED STRUCTURES

The level of fire resistance of structures and equipment must be proven by testing, reference to previous testing, by calculation or by a combination of all three of the above.

Extrapolation based on specific testing should not be done, and also special care should be taken when interpolating between different tests representative for other fire scenarios (e.g. addressing a cooling down phase adequately).

In Europe, the European norm EN 13381-3 may be used to determine the contribution of fire protection to the fire resistance of structural concrete members exposed to the ISO curve. This EN standard is recommended also outside Europe, but locally other standards might apply.

Concerning higher temperature-time fire curves such as RWS and HCinc, no standard exist. However several guidelines have been published to provide fire test method for RWS and HCinc. References are made to:

- The fire testing procedure 2008-Efectis-R0695 (September 2008) [5.2] which is the first published RWS test method, and adopted in NFPA 502 [5.3];
- The CETU guidelines on passive fire protection systems (published in 2013 in French and updated and translated in English in 2017) which provide another HCinc test method for applied protection to concrete members [5.4]. These guidelines have been written by CETU and the 3 French approved laboratories (CERIB, CSTB, Efectis France). The proposed test method is based on the ISO test of the EN 13381-3.

These publications highlighted the importance of:

- The dimension of the tested concrete slabs used for the application of fire protection materials;
- The type of concrete used for the tested slab;
- The fixation method of the tested fire protection material (type and number of anchors, wire mesh, etc.) which shall be identical to the one installed in the tunnel;
- The presence of joints in between at least two panels when board protection; during the fire test, any thermal leaks through these joints will be assessed.
- In case of spray materials, the number of applications (amount of layers) when preparing the test specimen; this amount of layers must be respected while applying the spray material in a real tunnel.;
- The temperature recordings by thermocouples; they shall be done at least:
  - At the interface in between the concrete and the fire protection material;
  - At the bottom of the reinforcement;
  - On the non-exposed face of the concrete slab.

The above two documents are aligned on quite a few topics, but also there are apparent differences, e.g. the dimensions of the slabs, the evaluation of the thermocouples readings (average and maximum temperatures), furnace pressure and moisture conditions. More harmonisation on international level is highly welcomed.

5.6 MINIMUM REQUIREMENTS FOR MAIN STRUCTURES

The main structure of the tunnel must satisfy Level N0 when local failure alongside the source of the fire will have no harmful consequences for the safety of users or cause structural failure. In other circumstances, a higher level of fire resistance must be provided.

Level N1

This level applies to structures supporting a roadway or an area, which is accessible to the public above it.

It also applies when stability of the structure is necessary in order to maintain the structural stability of an adjacent tube when there is direct communication or escape to the outside of the tunnel
This level shall also apply if local structural failure is likely to cut a ventilation duct which is important to allow action by the emergency services.

Level N2

This level applies when the structure is required to maintain the stability of another tube or separation from it when there is no direct communication with the exterior.

This level shall also apply if local structural failure is likely to cut a ventilation duct which would compromise safe shelters and their access-ways to the exterior.

Level N3

This level applies to immersed tube tunnels or tunnels located below the water table which are at risk of flooding in the event of local structural collapse. This also applies if local failure of the structure is likely to result in catastrophic collapse, damage at the surface or likely to affect the stability of an adjacent structure.

The Dutch Ministry of Transport (Rijkswaterstaat RWS) has minimum requirements for fire safety measures in tunnels, amongst which thermal protection of the structure is a mandatory requirement.

5.7 LINING, MATERIAL TYPES AND FIRE BEHAVIOUR

The following types of (concrete) lining can be considered:

- Horseshoe Tunnels
  - Cast in-situ concrete lining
- Circular Tunnels:
  - Cast in-situ concrete lining
  - Segmental lining with gaskets and packers.
  - Cast iron linings with lead seals
- Box/rectangular Tunnels
  - Cut and cover tunnels
  - Immersed tunnels including joints

Concerning damage to the lining of a circular (and horseshoe) tunnel, the load is mainly transmitted as compression in the hoop direction. The parameters affecting the remaining strength of the tunnel are:

- amount of segment remaining after spalling, which is impossible to predict or determine accurately
- temperatures reached during the fire and consequential concrete strength loss
- tunnel deformations and tunnel - ground interaction
- possibility of rehydration of cement
- position of damage within the ring relative to possible disturbed ground outside the lining
- squatting of the ring.

For a rectangular tunnel, where the load is transmitted mainly by bending, the parameters affecting the strength of the tunnel are:

- the possibility of spalling revealing the reinforcement
- the temperature reached in the reinforcement during the fire (with or without spalling)
- the amount of concrete remaining to transmit normal force
- temperatures reached during the fire and consequential loss of strength and stiffness.
- ability to redistribute the load after damage to part of the tunnel (creation of hinges)
- possibility of rehydration of cement

5.7.1 Loads

In order to discuss the behaviour of the fire damaged structural element it is necessary to deal with the loads on the structure. On a tunnel the main loads are normally water load and ground load. For a discussion of fire resistance also the thermally induced load must be taken into account.

It shall be noticed that the definition of fire resistance is duration (time) of a specified fire, which results in a reduction of the strength of the structure to a level corresponding to the magnitude of the load at a specific point of time. The fire will influence the load due to the thermal expansion and the load may influence the spalling and thereby the remaining strength.

Water and Ground Load

The water and ground loads are generally regarded as unaffected by the fire. However, for very long duration fires the ground may be heated so much that the load is affected (for bored tunnels). Strong heating may also influence the water pressure. For most fires and especially for thick concrete lining the heating at the outside of the tunnel (extrados) will be marginal.

Water and ground load can be taken from design assumptions, from geometrical information or from measurements. The load will vary along the alignment. As the design of the segments will be uniform or stepwise uniform the fire resistance will depend on the location in the tunnel.

Water- and ground load will result in normal force and moment in the lining. For circular and horseshoe shapes tunnels it is aimed that the load is transmitted as normal force as far as possible. For rectangular tunnels the moment action will be more pronounced.

Thermal Load

A thermal load derives from the restricted expansion of the material due to the heating.

Distinction must be made between 1. Internal stresses, which may be contributing to the explanations of reduction of strength and in some theories to the spalling and 2. The external overall loads on the segment, which are added to the water and ground load.

In addition to the deformation from thermal expansion also transient deformation, creep and deformation due to loading and loading history should be taken into account.
It is particular important to take into account the reduced stiffness of the concrete. At the position where the temperature is highest the stiffness is reduced most. Therefore the thermally induced load may have its largest contribution from the middle range temperature increases.

The stresses from thermal expansion come only from restrained expansion; the elastic, plastic and stiff body deformations tend to relieve the thermal loads on the structure. Particularly segmental lining has the ability to deform. Interaction with the stiffness of the ground is particularly important for segmental lining in relatively soft ground. The weakened stiffness of the ring will transfer more load to the ground and deformations will be allowed to relieve the thermal stresses.
Also here it is worth to notice the boundary condition of strain compatibility.

In the concrete cross section the areas with the highest stiffness will attract the loads, which is fortunate, as the strength is also available here.

Moment Action

Ideally bored tunnels are subjected to hoop load, i.e. a unidirectional load (the term axial load is used even though a ring is not an axis). But due to limited (small) overburden, variation in ground stiffness, cross passage joints etc. the segments are subjected to a certain moment. These moments are generally not a problem for the relatively thick segments. However, during the fire the cross section is decreased, the strength in the remaining cross section is decreased and the moment capacity is therefore decreased. More important, due to the spalling and the heating at the intrados, the line (curve) of action of the hoop force moves towards the extrados. The contact point between the segments is at the centre line. This means that the segment is subjected to an increased moment.

In turn the moment will cause a deformation of the segment (in interaction with the stiffness of the ground) and the contact point will move slightly towards the extrados, but this leads only to a slight reduction of the moment.

For bored tunnels ground-structure interaction may to some degree relieve some of the loads occurring during a fire. For immersed tunnels the tunnel-ground interaction is normally in terms of the (hydrostatic) ground load and the foundation. Cut and cover tunnels may have similarities with bored tunnels or immersed tunnels depending on their shape.

For rectangular tunnels the moment action is more pronounced, depending on the load and the geometry of the tunnel. The load on immersed tunnels will in most cases be dominated by a hydrostatic water pressure, which will tend to give compression in walls, roof and bottom and negative moments in the corners of the rectangle and positive moment at mid-span of walls, roof and bottom.

With respect to fire the critical point is often the centre span of the roof, as it often will have a positive moment activating the inside reinforcement in tension and at the same time this point of the tunnel is subjected to the maximum heating of the fire.

The fire will heat up the concrete and reinforcement and the moment capacity will gradually decrease as the strength and stiffness of the inside reinforcement is lost.

In case of spalling the reinforcement may be directly exposed to the fire and the moment capacity is immediately lost. As the spalling may take place within the first minutes of the fire, this type of structure is vulnerable towards fire damage.

Even though the moment capacity at mid -span is reduced to nearly nothing, it may not lead to total collapse of the tunnel. The mid -span may be regarded as hinge and the loads may be carried by increased negative moment at the corners.

For immersed tunnels further development of the damage will result in flooding. For cut and cover tunnels the consequences will depend on the use of the surface over the tunnel.
Narrow tunnels e.g. single track railway tunnels may have the ability to carry the load after damage at mid-span, whereas wide tunnels e.g. road tunnels may be too wide to carry the redistributed load.

In practice it is common to fire protect the roof and the upper part of the walls for immersed tunnels by fire isolation material. The fire protection prevents both unacceptable heating of the reinforcement and also spalling. When using performance-based approach in structural design or fire safety engineering, it is possible to determine the surfaces to be protected. For instance, some tunnels have been protected only on the ceiling and the upper part (1 meter to 1,5 meter) of the walls.

Immersed tunnels can in some cased be pre-stressed by cables in the axis direction. Damage of these cables can also result in lost functionality of the tunnel.

5.7.2 Segmental capacity

Normal Force

In the ideal situation the load on a bored tunnel segment is a perfect hoop load, and the product of the area and the factored strength determines the capacity of the segment. In case of a fire damaged cross section the spalled area is of course disregarded and the heated areas contribute with their remaining strength as far as the strain compatibility allows it. The capacity towards normal force can be expressed in terms of MN or in a normative value, which is 100% at the start of the fire.

A curve describing the development of the remaining strength during and after the fire can be established. The curve will have a steep decrease at the time of spalling, a more gradual decrease during the remaining heating and the decrease is expected to continue some time after the fire has ceased.

Normal Force and Moment

Due to the moment action mentioned in the section concerning the load, the capacity will be further reduced. The well-established calculation of concrete or steel for combinations of normal force and steel can be used. The calculation is due to the heating complicated by the fact that the segment does not have the same properties all over the cross section. The capacity can be expressed as the maximum uniformly distributed load or simply by a relative figure, which is 100% at the start of the fire.

The curve describing the development in reduction of capacity will be more pronounced than the one only taking normal force into consideration.

Biaxial or triaxial loading condition

For the design of tunnel lining it will in most cases be sufficient to consider a uniaxial loading. For circular tunnels the main load will be in the hoop direction and for rectangular tunnels the main load is normal force perpendicular to the tunnel axis and moment around the axis. The normal forces in the tunnel axis direction come from forces built in during construction and prestressing.

The capacity of a bi-axially loaded concrete will be higher than a uniaxially loaded structure, so the consideration of uniaxial conditions will be on the safe side.

For consideration of details the biaxial and even the triaxial conditions might be worth to take into account. An example is the joints of the segmental lining.

Shear and splitting

At the joints the segments have shear and splitting forces. The segment is normally reinforced in this area for these forces.

The calculation of the shear and splitting is following the same principles as design of cold joints. However, with the reduced strength of the concrete and reinforcement this detail comes out as a critical point in the calculations.

Some complications occur in the calculation of a shear failure line through strongly varying strengths and stiffness and from the fact that the shear/splitting reinforcement is heated so much at the intrados side that the bond is doubtful.

The capacity of the joint observed in real fire benefits from the fact that the spalling tend to be substantially less (or not occurring at all) near the joints.

The curve indicating the capacity of the joint can be indicated for points of time during and after the fire as the normal force and moment.

5.7.3 Capacity of elements in bending

Sagging reinforcement is normally positioned close to the heated surface of the concrete, and the assessment of the structural integrity is governed by the reduced, remaining capacity of the reinforcement.

In case of spalling the reinforcement may be exposed to the higher temperatures and even become directly exposed to fire, and consequently lose its strength much more rapidly.

Hogging reinforcement will normally be heated only marginally. The moment capacity can often be calculated by as an equivalent cross-section, where the concrete reduced to less than e.g. 60% of its original strength is disregarded.

For elements subjected to combined bending and normal force, reference is made to the comments above concerning capacity of segments.

5.7.4 Fire Resistance

When the relative curves indicating the capacities of the segment in terms of normal force, moment, splitting and shear are not intersected by the load curve in the same units then the fire resistance has not been reached. A parametric extension of the fire duration until the curves intersect can be made. The duration of the fire, which results in intersection, represents the fire resistance.

It should be noticed that the structure in some cases may have redundancies which can ensure fire resistance even after failure of a single element. For rectangular tunnels reference is made to the description above.

It must be noticed, that a number of the parameters used in the calculation of the fire resistance have large uncertainties. It is advisable to evaluate the importance of the uncertainties. This evaluation can be done in dedicated software, where the uncertain values are modelled as stochastic variables. This can be done with a full representation of the uncertain values as stochastic variables or as a more simple sensitivity analysis, in which the uncertain values can be varied between e.g. +/-1 or two standard deviations or similar.

The result of the fire resistance estimation shall be given with the information of these evaluations.
Safety considerations, i.e. partial coefficients and similar, will strongly influence the fire resistance. The best estimate on the fire resistance will be found by calculation with factors equal to 1 and with central estimates of the material characteristics. A best estimate can make sense in connection with risk analyses. However, for evaluation of structural behaviour and structural safety characteristic values and factors according to the respective codes may be required. In the latter cases the estimated time to failure will be a lower fractile. It shall be taken into account in estimation of characteristic values (and safety) which part of the information has been found by testing - and the uncertainties associated to the tests.

Moreover, such analysis is valid only under the assumption that concrete spalling and/or cracking will not occur. As stated in paragraph 3.1.4, concrete spalling cannot be predicted by numerical tools. If there is a risk of spalling, it needs to be assessed by a fire test on the concrete. Fire resistance analysis of concrete structure should then take into account these experimental results.

5.8 LININGS

5.8.1 Concrete Linings

Concrete linings generally fall into two categories, cast concrete and pre-cast high strength concrete segments or beams. Each type will behave differently under fire exposure conditions.

Cast concrete used for conventionally bored tunnels, for cut and cover or immersed tube tunnels use 'normal' strength concrete (30Mpa - 40Mpa). This type of concrete will begin to lose its strength when its temperature exceeds 380°C. Spalling may also occur under severe fire exposure conditions in tunnels.

In addition, the temperature of the steel reinforcement within the concrete (particularly the soffit) will begin to lose its strength when its temperature exceeds 250°C.

In order to prevent loss of strength and stiffness (and potentially spalling) of tunnel linings, measures should be taken to prevent rapid temperature rise of the structure or lining. One of the most common solutions is to apply an insulating coating (passive fire protective coating). Other solutions exist such as addition of polypropylene fibres but are not discussed in details in this document. The advantage of passive fire protective coating is to not damage the concrete and optimize the repair work after a fire (see paragraph 3.1.3).

This structural fire protection system may be either a proprietary spray applied material or a rigid or flexible board system fixed to the tunnel lining.

The advantages of passive fire protection systems are, amongst others:

- Prevents rapid temperature rise in the structure
- Prevents loss of strength and stiffness of the load bearing concrete lining
- Prevents chemical degradation of the concrete
- If designed properly, the concrete is not compromised
  - Concrete spalling can be prevented
  - Irreversible deflection can be prevented

The structural fire protection system must be capable of limiting the temperature of both the concrete and the steel reinforcement below their critical temperatures under the relevant fire exposure conditions (time-temperature curve).

In immersed tube tunnels, consideration must also be given to the critical temperature of both immersion and segment joints in order to maintain the structural stability of the tunnel under the relevant fire exposure conditions.

In mechanized tunnelling, tunnels are usually lined with high strength pre-cast concrete seg-ments (55 - 90Mpa), which under fire exposure conditions, will begin to spall at lower temperatures than cast concrete. Experience has shown that these types of concrete might start spalling at temperature levels well below 250 °C. If the choice is made to avoid any concrete damage and reduce the repair constraints, it is therefore necessary to prevent this type of concrete from exceeding temperatures of 180°C to 220°C after 120 minutes of fire exposure under the relevant conditions in order to preserve the full lining thickness for the duration of the fire. However, during a fire test these temperatures are not the only criteria to judge if the system failed or not, and a “no spalling” criterion is also to be controlled.

Pre-cast concrete roof beams may be treated in the same way as pre-cast segments. However, beams are exposed to fire from multiple sides whereas segments or slabs are exposed from one side only. Multiple side exposure of structural elements (such as, but not limited to, beams) causes elevated temperatures at the corners and edges introducing additional risk for early concrete spalling.

Research has been conducted on the effects of fire on unprotected concrete linings which contained polypropylene fibres. Reference is made to test reports 2009-Efectis-R0358 and 2008-Efectis-R0146. In summary it has been concluded that post cooling cracking of the concrete lining will occur at both the inside (fire exposed) and outside (non-exposed) sides of the lining. These cracks can obviously not be seen but repair works have to take them in consideration because they can potentially cause significant mid/long term durability issues. Concerns have also been expressed as to the load bearing capacity of the structure predominantly with regard to its shear force capacity.

5.8.2 Steel Linings

Steel linings will begin to lose their structural strength when its temperature exceeds 500°C - 550°C. If the mechanical properties of the steel structure are to be strictly preserved, it is therefore necessary to limit the critical temperature of steel linings below this temperature under the relevant fire exposure conditions by the use of an insulating coating or lining in the same way as for concrete linings. A safe limiting temperature, also aiming at preventing irreversible deformations, application of which makes further structural analyses superfluous, for steel linings is 350°C [5.5].

If the lining is constructed using segments, consideration must be given to the critical temperature of the tunnel joints and seals in order to maintain the structural integrity of the tunnel under the relevant fire exposure conditions.

5.8.3 Cast Iron Linings

Cast iron linings may be treated in the same way as steel linings with respect to their critical temperature.

In ‘wet’ cast iron lined tunnels, consideration must be given to the tunnel seals which may have a lower critical temperature that the lining (for example, lead seals will begin to melt at approximately 300°C).

5.8.4 Masonry Linings

Masonry linings are generally considered to be fire resistant. However, under the most onerous fire exposure conditions, consideration may be given to the use of an insulating coating to prevent extensive damage or collapse.

Where masonry linings are used on walls separating two adjacent tubes where the adjacent tube is used as a means of escape, the use of an insulating coating may also be considered.

5.8.5 Gaskets

The water tightness of segmental lining is generally ensured by use of gaskets. In most cases the gaskets are placed near the extrados, but in some cases a supplementing gasket has been placed also at the intrados. The gaskets have no load bearing effect but a failure of the gaskets will lead to more or less water inflow and subsequent repair. It will not be possible to replace the gaskets, so the water tightness will have to be established by other means. It should be discussed how much the tunnel should leak before it is regarded as failed.

It is beyond the scope of this note to describe the possible types of gaskets, but in many cases the gaskets are made from a rubber compound.

The heating of the gasket depend both on the location and adjacent materials. In case of a steel or cast iron segment the gaskets will be heated more than in a concrete segment. The calculation of the heating of the gaskets can be made together with the determination of temperatures in the segment (in this case in minimum a 2D model).

It may be relevant to ask the producer of the gaskets for specific material information. The following may serve as a guideline for the characteristics of the gaskets subjected to fire:

- For even long duration exposure to about 150°C the appearance of the rubber does not alter, the elasticity is decreased, but in many cases it may serve its purpose also after the fire. This depends of course on the margin of water pressure for which the gasket was designed. Deformations during the fire may in theory influence the long term sealing characteristics.

- For long term exposure to 250°C the rubber becomes brittle and loses all elasticity. As it is probably subjected to high mechanical pressures from the segments during the fire, the gasket will most likely have lost its sealing properties after the fire. A replacement with another sealing medium will be necessary.

Heat ageing and chemical attack may be a problem for the areas exposed. However, only a very small area will be exposed and hence the problem small.

The fire resistance of the gaskets is dependent on the protection. If the gaskets are exposed directly to flames they will be destroyed by fire.

5.8.6 Packers

Packers between the segment rings have the purpose of distributing the load during erection of the segments. The packers are often made of bituminous material or of wood, and hence combustible.

- The bituminous packers may melt and the melted material burns. It is considered that this is a minor problem as the packers will melt relatively slowly and the combusted material will be small compared to the fire load in general. On the other hand the heating, softening and melting of the packers will to some degree relief the stresses originating from the thermal expansion in the longitudinal direction.
- Plywood packers will hardly burn due to the limited surface; the relieving effect from heat of the plywood packers will be small.

5.8.7 Immersed tunnel Joints

For immersed tunnels it is particularly important that joints are well designed and that they are watertight under all load conditions. With respect to fire the joints are normally placed at a position where they are protected against the heat. Otherwise they will have to be protected by fire protection material.

The joint normally has a component of a butyl rubber or similar, in form of e.g. an omega or gina joint. This material cannot withstand fire or heat, as mentioned in the section on gaskets above.

For cut and cover tunnels the joints are often a less critical part of the structure. For joints with rubber components the same comments as above apply. For concrete-concrete or concrete-steel-concrete construction joints, the fire resistance will not be critical.

5.9 SUSPENDED CEILINGS

5.9.1 Concrete ceilings

Loading on concrete suspended ceilings can be limited to the dead load of the ceiling and pressure from the ventilation system. However, numerous tunnels use the ventilation plenum as escape route and means of egress, in which case these loads need to be accounted for.

False ceilings and walls separating ventilation ducts from a tunnel should have a minimum fire resistance (N0) where loss or collapse is prevented.
In other circumstances, where continuity of the suspended ceiling is essential, such as escape routes, higher levels of fire resistance may be required. However, if such partitions are lost in a fire event, the ventilation strategy along with the tenable environment is lost too. Therefore the protection of these partitions shall be considered.

Consideration should also be given to the interfaces between the suspended ceiling/ walls and the tunnel lining, especially if structural integrity is required in order to maintain the stability of the tunnel and allow safe escape.

In voids above suspended ceilings or walls which are used as means of escape, consideration should be given to provide a maximum temperature of 60°C on the upper (non-exposed) side of the structural element.

5.9.2 Steel Ceilings

Where used, steel suspended ceilings may be treated in the same way as concrete ceilings, particularly where the void is used as a mean of escape.

Since the suspended ceiling is unlikely to be fully loaded, a higher critical temperature than that of the lining may be considered.

Suspended ceilings constructed of cast iron or masonry (if used) should meet the same requirements as those for concrete and steel.

5.9.3 Multiple sides fire exposures

For example at the location of smoke inlets, the suspended (concrete) slab gets exposed to fire from both below (the tunnel) and from the top (the smoke extraction duct) because hot gasses are pulled into the duct. In the design stage of such partitions it needs to be taken into account that multiple sides fire exposure to a structure is different from single side exposure. For example, spalling of concrete will occur more rapidly and with much more explosive nature in the case of multiple sided fire exposure.

5.9.4 Loads and structural behaviour

As already mentioned, the suspended ceiling can form the ducts for the ventilation, which is a key safety factor in case of fire. Despite this, in some cases, failure of the ceiling can be accepted just over the fire, but it has to be carefully investigated as the ventilation strategy will be endangered.
Reduction of strength in case of fire is similar to the mechanisms mentioned for the lining. The structural particularities of the ceiling are:

- The structural interface at the tunnel wall supports/ bearings or cast-in reinforcement bars.
- The supports are sensitive to shear failure, movements resulting in loss of supports, and spalling / disintegration of the concrete.

- The suspended ceilings will to some extend (if it remains in place during the fire) protect the main structure from being subjected to the fire ; when the ventilation ducts are used for extraction of the hot gasses, the main structure will also be heated by the gas in the duct.

It is discussed whether a fire protection of a tunnel with suspended ceiling should be on the lower side of the ceiling or on the main structure. As both structures have a specific function in a fire scenario, the answer can be found according to the necessity to preserve one or more functions in reference to the safety strategy.

5.10 SUPPORTED FLOORS AND DECKS

Supported floors and decks will have a high live load due to traffic movement.

Structural integrity of the floor or deck must be maintained where the void below is used for escape. It is also important that the stability is maintained in order to allow the rescue and emergency services to perform their function.

Propagation of fire underneath the supported floor or deck must be prevented (particularly with the flow of burning hydrocarbon spills such as petrol).

If there is another level of traffic below the supported floor deck, consideration should be given to maintaining the stability of the deck under fire exposure.

The floor has normally one or two intermediate supports and will span between the supports and the tunnel wall. In connection with a fire it is of high importance that the rescue forces can use the road (deck) when they enter the tunnel. The degree of damage of the floor may also be one of the determining factors for the decision of resuming the traffic after a closure of the tunnel due to fire.

5.11 Anchorages

Internally in lining and other main structures, bond is necessary to obtain shear and bending capacity. Similar for secondary structural elements like suspended ceilings, finally anchorage is necessary for fixation of equipment like jet fans etc. inside the tunnel.

Large diameter anchors pose a risk, due to heat sink effects, locally increasing the spalling sensitivity of the surrounding concrete.

Cast-in item shall be considered due to failure of their own function (anchorages for installa-tions for jet fans for example may fail and the fans will drop). Furthermore the influence on the segments shall be considered. The thermal expansion etc. of the cast in item can be compared with the concrete, in order to consider damage to the structure from heating of the cast in item. The cast in item can function as a path for the heat into the concrete (for large items only).

On the other hand box-outs hollow parts and smaller voids can function as drains for the migrating water and may reduce the spalling in this area.

Anchorages for fire protection product are discussed in section 5.12.6.

5.12 MITIGATION TECHNOLOGY FOR TUNNEL STRUCTURES

5.12.1 Bored Tunnel (Horse Shoe Tunnel) in stable rock conditions

For in-situ concrete lining and sprayed concrete lining, it is verified through experimentation on actual tunnels that horseshoe tunnels are generally not prone to severe damages in fires, water flood and structure collapse. These cases are: EUREKA Repaaford Tunnel (Norway), Memorial Tunnel (USA), Nihonzaka Tunnel (Japan), Mont Blanc Tunnel (France Italy), Tauern Tunnel (Austria), UPTUN – Runehamar Tunnel (Norway).

5.12.2 Example of Circular Bored Tunnel (Shield Tunnel)

Figures 5.1 shows the Trans-Tokyo Bay Expressway Tunnel in Japan (TTB) standard cross-section and Figure 5.2 shows the same of Elbe Tunnel of Germany, respectively. On the one hand, the 4th Tunnel has an outer diameter of 13.75m, and an inner diameter of 12.35m (segment thickness of 70cm).

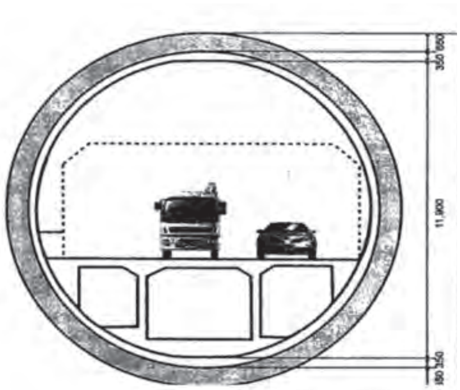


Figure 5.1 : Standard TTP Cross-section [5.6]

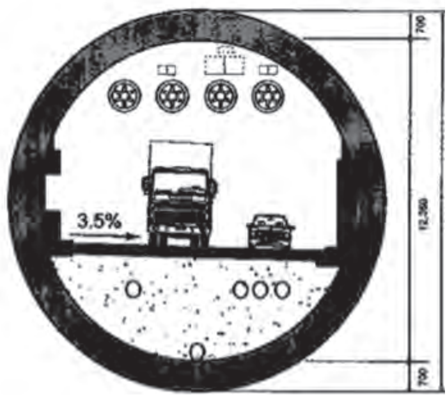


Figure 5.2 : Standard Cross-section of No.4 Elbe Tunnel [5.7]

When to compare the main characteristics of these two tunnels :

- In TTB tunnel, there is a secondary lining of 35cm thickness. Therefore, the effective inner diameter of the tunnel has become smaller than that of No. 4 Elbe Tunnel.
- On the other hand, in No.4 Elbe tunnel, without using a secondary lining, it is planned to install fire resistant material, and therefore, the effective space above the carriageway is larger than that of TTI3 Tunnel.

Both these tunnels are underwater tunnels, that it is necessary to consider the buoyancy of the tunnel bodies. In TTB Tunnel, this secondary lining plays the role of counter weight suppressing buoyancy, in addition to the protective effect it provides on the segment itself. Therefore, it has become possible to use the passage below the carriageway as escape route and an access path in emergencies.

On the other hand, it is necessary to adopt anti-buoyancy policies using passage below the carriageway as a counter weight. As described in the above two categories of examples, there exist two approaches for shield type road tunnels with large cross sections.

5.12.3 Mitigation measures for protection of ceilings in the Liefkenshoek Road tunnel

In road tunnels ceiling ventilation ducts are installed for transverse ventilation, semi transverse ventilation and some kinds of longitudinal ventilation lateral flow, semi lateral flow, or partially in longitudinal flow systems.

There are two different cases in the structure of this ventilation duct (i) the duct is a part of the tunnel's structure itself, which basically receives stress and strain, and (ii) the duct is not a part of the structure in terms of live loads.

Ad (i) This structure should be well heat resistant as the ceiling duct is a part of the structure and the entire structure would be influenced in case the duct is damaged. This is mainly the case for immersed tunnels and tunnels of rectangular cross-section with cut and cover construction method (Figure 5.3).

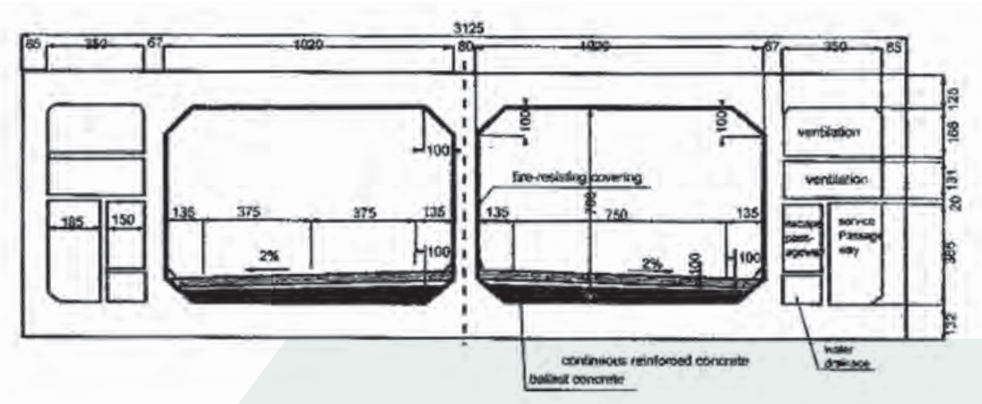


Figure 5.3 : Cross section of Liefkenshoek Road Tunnel, Antwerp, Belgium

Ad (ii) In the following case, see Figure 5.4, the suspended slab making up the lower part of the ventilation duct, is not a critical part of the load bearing structure.

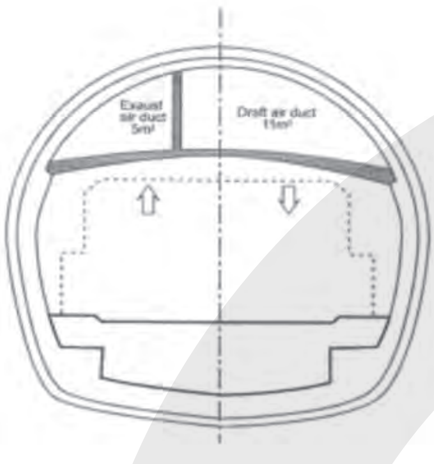


Figure 5.4 : Typical cross section of horse shoe, transverse ventilation tunnel

5.12.4 Mitigation measures for protection of anchorages in traffic space

Regarding to fire protection for suspending structures and other systems attached to the ceiling or walls, PIARC described below.

All the fittings used for the fixing of equipment to the structures should be considered in relation to the fire situation. This means that use of the usual plastic plugs and similar devices should be prohibited. This material will either soften or melt at high temperatures, resulting in flames. Further research will have to demonstrate to what extent special plastic is suitable for fixing equipment inside the tunnel.

Also steel plugs and anchors should be checked for their behaviour during a fire situation. The tensile stress reduces at high temperatures. The calculation of these anchors should be based on the maximum temperatures at which the anchoring should be still properly working.

A distinction must be made between major equipment, which should remain in function during an emergency situation, and equipment whose functions may not be needed during or after a major disaster.

The minimum requirement is that heavy equipment should not fall down when evacuating users or rescue personnel are in the tunnel. This means that no heavy item must fall under 400°C-¬450°C during the time necessary to fight fire (in a tunnel, such temperatures can produce a radiation level of about 5 kW/M2 which is the maximum tolerable value for firemen).

As aluminium loses its strength at a temperature of approximately 550°C, it

is recommended to consider the use of aluminium materials in a tunnel critically. Alternative materials are steel and stainless steel.
Especially, jet fans located at tunnel ceiling or sidewall for ventilation and smoke control are one of the heaviest equipment. If the temperature rise is sufficiently high, the fixing part at the top of ceilings for fans may be impaired and equipment may fall down to carriageway.

Therefore, this heavy equipment should be mounted on the crossbeam which are fixed at side wall. Because of temperature distribution at side wall is slightly lower than temperature at ceiling (Figure 5.5).

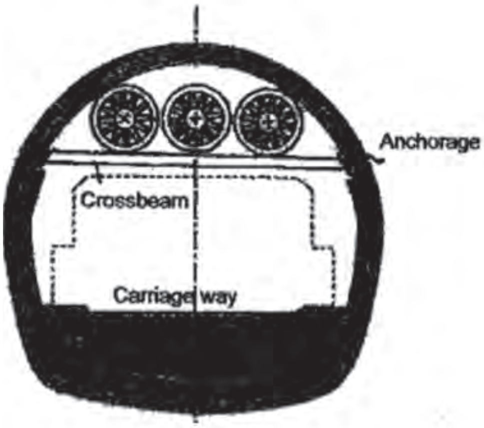


Figure 5.5 : Typical support system for ventilation fans

Anchors will cause a heat sink into the concrete, potentially causing the concrete to spall. In such an event the fire protection material is pushed from the concrete lining, exposing the load bearing structure to a fully developed tunnel fire. In such a scenario the load bearing capacity of the tunnel lining is endangered. Anchor details like this need to be designed properly and heat sink effects have to be taken into account.

5.12.5 Protection of Structural Elements

When installing fire prevention material in road tunnels, it is necessary to consider the following requirements, in addition to the thermal insulation, as the most important aspects of the passive fire protection system performance:

(A) Installation strength

Interior of traffic tunnels face severe dynamic pressure differential due to passing traffic and piston effect in ventilation ducts. Numerous tunnels have had face pressure differentials measured in the order of magnitude of 2 kPa. On the other hand, it is reported that rail tunnels experience approximate pressure differentials of 6 kPa when high speed trains pass the tunnel. Therefore, reciprocal differentials of this nature should be withstood by the fire protection material including the fixation materials and sub-frames. Test evidence by an authorised lab should be presented.

(B) Prevention of secondary effects

As tunnel temperature is extremely high, fires, smokes and toxic gases may occur. Hence it is necessary to use materials that are non-combustible (class A1) when tested to EN 13501. Also note the comments made in par 3.3.2, related to non-suitable products for passive fire protection in tunnels.

(C) Harmful effects of material

It is necessary to assure that the material is free from harmful effects to humans during tunnel construction. Materials that are produced in production facilities, having an NEN-ISO 14001 (environmental) certificate are therefore preferred. Also note the comments made in par 3.3.2, related to non-suitable products for passive fire protection in tunnels.

(D) Constructability

As far as construction cost and quality assurance of fire prevention material are concerned, it is necessary to minimise loss in installation, control of rebound water volume (for sprayed systems), consideration for adjustment of standard measurements in panel type fixation are exercised. Further, to prevent hindrance to fire resistance qualities, construction standardisation is adopted.

(E) Freezing and thawing resistance

Especially when the fire prevention materials are fixed in tunnels where temperature differentials year around are severe, the protection material is subject to reciprocal effects of drying (thawing) and wetting (freezing) due to precipitation outside the tunnel. Therefore, it is important that freezing and thawing resistance in these materials is evaluated.

(F) Water leakages and humidity

With reference to point (E), fire protection materials in tunnels can get wet due to (minor) leaks in the structural concrete tunnel lining, which will cause a situation where the fire protection materials will get fully saturated with water. High relative humidity or water spray due to passing vehicles (in case of wet road surface) will also cause water absorption of the fire protection material.
It is reported that some water saturated fire protection materials will not be able to withstand a fire anymore. This is due to the fact that the water evaporates (expansion ratio from water to steam is 1:1700) and the vapour cannot escape through the pores, creating pore pressure build up in the material itself, causing a spalling effect and decomposition of the material, just like concrete will spall.
Test evidence by an authorised lab should be made available, proving that fire protection materials can meet the fire protection requirements with less than 5% (by weight) humidity and also when fully saturated with water.

(G) Repair and Maintenance

Tunnel linings often get washed and cleaned on a regular basis. The materials used should be resistant to cleaning actions coming from brushes, water pressure and the use of mild detergents. Tunnel linings should also be easily repairable to avoid downtime of the tunnel. In the aftermath of a limited tunnel fire, the material should be inspectable by the manufacturer to determine the level of degradation of the material and the necessity to replace it, or not.

The tunnel owner might consider it necessary to inspect the tunnel lining, for cracks and leakages, especially (but not exclusively) near/around joints. This can have implications on the (partial) removability of protection systems, and/or non-destructive inspection techniques (e.g. acoustic). The choice for a proper fire protection system can seriously be affected by these specifications. Spot checking for (more than micro) cracks, leakages and deformations are recommended.
In any case, inspection of the tunnel structures has to be done and recorded before implementing fire protection.

5.12.6 Type of Fire Protection Materials

As far as the fundamental concept of fire resistant policies are concerned, considering the temperature rise of between 1,000ºC – 1,350ºC within a short period by vehicle fire, it is common to allow for temperatures as high as the permissible temperature of fire resistant materials of around 1,350°C, in case of concrete and reinforcements. The melting temperature of fire protection materials shall be greater than 1350°C.

Spray Type

The application process of Spray type systems involves a number of stages.

First, the concrete surface needs to be cleaned to remove dirt, dust, demoulding oil etc. A wire mesh is then mechanically fixed to the concrete which will serve as a retaining system, should the spray mortar lose its bond to the concrete surface, during the lifetime of the tunnel. Vibrations and sagging of the tunnel may cause spray system to detach from the concrete lining, hence the use of wire mesh. A keycoat provides a better adhesion to the concrete surface. The sprayed on material can be left as a sprayed finish or can be trowelled to a smooth finish, to receive an optional paint system as a final finish.
Fundamental performance of the spray type fire protection material is as follows :

(A) Major characteristics

- Even in case of complicated cross sections, construction is simple
- At narrow locations like pipe sleeves, construction is very appropriate
- Renovations are simple at places where concrete is damaged after the concrete surface has been cleaned to create a proper bond

(B) Cases needing improvement

- It is necessary to make adjustments if the adhesion of concrete lining varies due to surface conditions. This may mean that a mechanically fixed wire mesh, made out of stainless steel or plastic coated steel, has to be installed
- Since the finished surface is not flat, cleaning is troublesome, and again if flat surfaces are needed for certain cases, then special considerations should me made
- To ensure a homogenous finish and resistive effects at required level, then it is necessary to maintain a consistent level in technical standards
- Thickness control of the applied material must be carefully controlled.

(C) Basic performance

1. Organic coatings [5.8]

- Organic coatings produce toxic fumes and dense smoke under fire conditions, which make them unsuitable for use in tunnels where life safety is an important consideration.

2. Inorganic coatings [5.9]

- Inorganic coatings are produced as factory controlled cement/ vermiculite premixes, which are sprayed, applied directly to the internal surfaces of the tunnel lining.
- Vermiculite cements are essentially inorganic materials and therefore will not burn, produce no smoke or toxic fumes and are certified non combustible.
- They can be spray applied quickly to the tunnel surface and if damaged, can be easily repaired (by hand in small areas) after the surface has been properly prepared
- Their fire performance is very predictable and often provides protection to the concrete substrate for periods of time in excess of its intended fire rating.
- Instances have been documented where vermiculite cements have prevented concrete substrates from spalling under extreme fire conditions for periods of up to 24 hours, at which time the concrete/fire proofing interface has reached an equilibrium.

Panel / Board systems

The most commonly used system to protect concrete tunnel structures from fire is the use of fire protection boards. The thickness of passive fire protection boards is engineered to suit the fire requirements of the project. Such boards always need to be mechanically attached to the concrete lining.

Specific properties of board systems for the fire protection of concrete structures are listed below:

- Board materials can easily be checked for thickness and thus the application can be guaranteed to meet with the specifications as per the tested constructions.
- Being mechanically fixed, board systems can cope with the dynamic loads from passing vehicles (pressure / de-pressure loads)
- In general, cement based board materials are unaffected by water ingress in the tunnel and combustion gasses.
- Board systems in general require no maintenance. In the case that the concrete substrate needs to be inspected, when properly designed and installed, the boards can be removed and reinstated, thus maintaining the fire protection layer at all times.
- Board materials are produced in factories, ensuring the quality of the material and a correct composition. Most board materials are produced in NEN-ISO 9001 and NEN-ISO 14001 certificated factories.

Two methods of installing boards systems can be defined :

(1) Lost shuttering method: the boards will be installed in the form-work, on top of the load bearing plywood. Screws are partly inserted into the fire rated boards to create a bond between the panel and the concrete. After the reinforcement is installed the concrete can be poured. After the extraction of the form-work the fire rated boards will stick to the concrete thus creating the fire protective layer. The screws are anchored into the concrete creating a firm bond. Due to the very low labour costs of this system, it's intensively used in cut & cover and immersed tunnels, rather than having to apply a fire protection layer afterwards.

(2) Post installation: in both new and existing tunnels the post installation method can be chosen. The boards can be installed, either directly to the concrete or on a sub-frame. We can note that :

- Calcium silicate boards are suitable for installation on flat concrete substrates.
- Calcium silicate aluminate boards may be installed on curved concrete substrates and have an improved thermal performance over conventional board systems.

The installation of fire protection materials should be done with anchors having the following properties:

- The diameter should be limited to maximum M6, in order to reduce the heat sink effect through the steel anchor into the concrete. It is reported that thicker anchors can create a local spalling effect of the concrete; this local effect is only temporary because the spalling will spread all over the surface once a small part of the concrete is directly exposed to fire.
- The use of stainless steel anchors is recommended. Types that can be used are A4, 316, 1.4401 and 1.4571. In some countries even higher requirements are applicable by code.
- If necessary a washer must be used to avoid a pull through effect when the system is exposed to dynamic loads
- The anchors should be suitable for use in the tension zone of concrete (cracked con-crete)
- The anchors should be suitable for use under dynamic loads

5.12.7 Development of Fire Resistant Concrete

With the objective of protecting the tunnel structure from high temperatures in case of fires, fire resistant concrete has been developed, having upgraded the quality of concrete. In one such method, it has been attempted to increase the fire resistance of concrete by mixing chemical compounds to those existing in concrete. For example several tunnels have been built in Europe these last 10 years adding polypropylene fibres to the concrete. As a result, these tunnels have been assessed to be fire resistant without the use of fire protection.

In case of fire, the temperature rise in the concrete will lead to damages. Repair works will be necessary to re-establish the initial structural performance if needed.

5.13 CURRENT PRODUCTION LISTS OF FIRE RESISTANT MATERIALS

Many materials are currently manufactured for the protection of structural elements in a tunnel structure. Many materials are similar to those used for the traditional protection of buildings in providing a certain fire rating as required by local codes and ordinances. These local regulations should be consulted in the selection and type of material to be used for protection of the structural elements of a tunnel system.

MATERIAL	TYPE MATERIAL	TYPE CONST	ATTACHMENT
Calcium silicate board	Panel	Pre-manufactured panel	Anchor bolts for post fixed system
Calcium silicate board	Panel	Pre-manufactured panel	Screws for lost formwork system
Calcium silicate aluminate board	Panel	Pre-manufactured panel	Anchor bolts for post fixed system, either flat or post curved (flexed) into radius of tunnel
Calcium silicate aluminate board	Panel	Pre-manufactured panel	Screws for lost formwork system
Cement based spray-on systems	Spray mortar, cementitious vermiculite or perlite based Cement / additives / fibres	Spray	Applied onto flat or curved tunnel lining

Table 5.1: Typical fire protection materials for tunnels

6 >> Summary and recommendations

The goal of the Working Group is to provide guidelines and recommendations to ensure fire resistant tunnels contributing to the global safety level, reduce non-operational time and economic loss after a fire and to prevent the catastrophic collapse of the structure.

- The Working Group has also acknowledged that many of the member nations have already in place strict guidelines for the protection of underground structures, and the Working Group hopes to enhance those standards by providing the following recommendations to be used as guidelines for the protection of road tunnels.
- These recommendations were developed by an extensive review of codes, regulations, ordinances, research and case studies of tunnel fires. These guidelines are intended to provide criteria for the protection of existing as well as new road (highway) tunnel in construction. The information provided herein, may be applicable to other types of tunnels, providing careful consideration is made as to the tunnel usage, and types of materials that are transported within the tunnels. These guidelines are not intended for passenger rail tunnels, which will be covered in a parallel document to be developed by the Working Group in the future.

In agreement with PIARC, the Working Group recommends that the design criteria presented in table 6.1 be used according to the type of structure and traffic in the tunnel.

	MAIN STRUCTURE				SECONDARY STRUCTURES[4]			
Traffic Type	Immersed or under/inside superstructure	Tunnel in unstable ground	Tunnel in stable ground	Cut & Cover	Air Ducts[5]	Emergency exits to open air	Emergency exits to other tube	Shelters[6]
Cars/Vans	ISO 60 min	ISO 60 min	[2]	[2]	ISO 60 min	ISO 30 min	ISO 60 min	ISO 60 min
Trucks/Tankers /HGV	RWS/ HC_{inc} 120 min[1]	RWS/ HC_{inc} 120 min[1]	RWS/ HC_{inc} 120 min[1]	RWS/ HC_{inc} 120 min[1]	ISO 120 min[1]	ISO 30 min	RWS/ HC_{inc} 120 min	RWS/ HC_{inc} 120 min[7]

Table 6.1: Joint recommendations of PIARC and ITA

Notes :

[1] 180 min maybe required for very heavy traffic of trucks carrying combustible goods

[2] Safety is not a criteria and does not require any fire resistance (other than avoiding progressive collapse). Taking into account other objectives may lead to the following requirements:
- ISO 60 min in most cases
- No protection at all if structural protection would be too expensive compared to cost and inconvenience of repair works after a fire (e.g. light cover for noise protection)

[3] Safety is not a criteria and does not require any fire resistance (other than avoiding progressive collapse). Taking into account other objectives may lead to the following requirements:
- RWS/HC_{inc} 120 min if strong protection is required because of property (e.g. tunnel under a building) or large influence on road network
- ISO 120 min in most cases, when this provides a reasonably cheap protection to limit damage to property
- No protection at all if structural protection would be too expensive compared to cost and inconvenience of repair works after a fire (e.g. light cover for noise protection)

[4] Other secondary structures should be defined on a project basis

[5] In case of transverse ventilation

[6] Shelters should be connected to the open air

[7] A longer time may be used if there is a very heavy traffic of trucks carrying combustible goods and the evacuation from the shelters is not possible within 120 min

The document provides guidelines for the thermal protection of the various elements of a tunnel. This is due to the fact that there are so many tunnel sub-systems and types of interior structural elements, it would be impossible to identify each and every type and provide a specific fire protection system for them.

Among the main conclusions, we can highlight the following:

- The mechanical resistance of structural concrete elements (wall, ceilings, partition walls, cast-in-place concrete etc) will decrease once the concrete surface temperature reaches 380oC ; for steel structural elements, this threshold is set around 550°C ; the corresponding impacts in terms of stiffness and resistance reduction have necessary to be taken into account in the design and especially the dimensioning of the structures in the vehicle fire scenarios; this document provides a few elements and references for the evaluation of these impacts;
- After a fire leading to temperature above these thresholds, the concrete or steel elements will be damaged with visible cracks, but also invisible ones because of their seize or their location in the structural element; repair works will be necessary to replace the damaged elements or stretches and recover the original mechanical performances;
- With rapid heat rise, in accordance to the standard time-temperature curves described in this document, the concrete can spall; this phenomenon is dependant to many parameters and very difficult to

estimate in common practice; because of its possible impact on the structural resistance, it has to be taken into account with a specific evaluation, most likely a representative full scale fire test;

- In sensitive tunnels, i.e. tunnels in unstable ground conditions, or immersed tunnels, the choice can be made, as a precautionary measure, to prevent any structural resistance loss, leading to a thermal protection of the structural elements; the objective is therefore to limit the concrete surface temperature to 380°C (or 180-220 C, for concrete types more sensitive to spalling); such a choice can also be made in general for all kinds of tunnels, to mitigate the risk of a long period of tunnel closure for repair after a fire.
- The documents presents the different types and characteristics of fire protection materials ; it also provides information about their installation;
- More sophisticated assessment methods could be used to develop more economical solutions taking into account other factors influencing like temperature gradients, heating rates, structural load levels,..; performance-based approaches can be of great interest in this objective.

The information provided here is intended to act as a guideline and is for informational purposes. Specific measures for the protection are site specific and must be designed on an individual basis.

Any inquiries in regard to the information presented here should be sent to the International Tunnel Association Working Group 6 via its web site at www.ita-aites.org or to the Animateur of the Working Group Mr. Henry Russell c/o Mott MacDonald at Hen-ry.Russell@mottMac.com, or to the vice-Animateur Mr. René van den Bosch c/o Promat International at rene.vandenbosch@etexgroup.com.

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>> APPENDIX 1 - ROAD TUNNEL FIRE HISTORY

FIRE ACCIDENT'S IN THE WORLD'S ROAD TUNNELS

						CONSEQUENCIES		
YEAR	Tunnel Length	Location Country	Vehicle Where Fire Occurred	Most Possible Cause of Fire	Duration of Fire	Consequences People	Damaged Vehicles	Structures and Installations
1949	Holland 2,550 m	New York USA	Lorry with 11 tons of carbondisulfide	Load falling off lorry Explosion	4 h	66 Injured smoke inhalation	10 lorries 13 cars	Serious Damage Over 200 m
1974	Mont Blanc 11,600 m	France-Italy	Lorry	Motor	15 min	1 injured		
1976	Crossing BP-A6 430 m	Paris France	Lorry with drums of 16 tons polyester film	High Speed	1 h	12 light injuries (smoke)	1 lorry	Serious damage over 150 m
1978	Velsen 770 m	Velsen Nederland	4 lorries 2 cars	Front-rear Collision	1 h 20min	5 dead 5 injured	4 lorries 2 cars	Serious damage Over 30 m
1979	Nihonzaka 2,045 m	Shitzuoka Japan	4 lorries 2 cars	Front-rear Collision	159 h	7 dead 1 injured	127 lorries 46 cars	Serious Damage Over1,100 m
1980	Kajiwara 740 m	Japan	1 truck with 3600 litres of paint in 200 cans	Collision with side wall and overturning	n/a	1 dead	1 truck, 4t 1 truck 10t	Serious Damage Over 280 m
1982	Caldecott 1,028 m	Oakland USA	1 car, 1 coach, 1 lorry with 33000 litres of petrol	Front-rear collision	2 h 40min	7 dead 2 injured	3 lorries 1 coach 4 cars	Serious Damage Over 580 m
1982	Salng 2,700 m	Mazar-e-Sharif-Kabul Afghanistan	Soviet Military column. At least one petrol truck	Unknown, probably mine ex-plosion	n/a	>200 dead	n/a	n/a
1983	Pecorila Galleria 662 m	Gênes Savone Italy	Lorry with fish	Front-rear colli-sion	n/a	9 dead 22 injuries	10 cars	Little Damage
1986	L'Arme 1,105 m	Nice France	Lorry with trailer	Braking after high speed	n/a	3 dead 5 injured	1 lorry 4 cars	Equipment destroyed
1987	Gumefens 343 m	Berne Switzerland	1 lorry	Front-rear Collision	2 h	2 dead	2 lorries 1 van	Slight damage
1990	RØldal 4,656 m	Røldal Norway	VW transporter With trailer	n/a	50 min	1 injured	n/a	Little damage
1990	Mont Blanc 11,600 m	France-Italy	Lorry with 20 tons of cotton	Motor	n/a	2 injured	1 lorry	Equipment destroyed
1993	Serra Ripoli 442 m	Bologne-Florence Italy	1 car+lorry with rolls of paper	Collision	2 h 30min	4 dead 4 injured	5 lorries 11 cars	Little damage
1993	Hovden 1,290 m	HØyanger Norvay	Motor cycle 2 cars	Front-rear colli-sion	1 h	5 injured in the collision	1 motor- cycle 2 cars	111 m insulation material destroyed
1994	Huguenot 3,914 m	South-Afrika	Bus with 45 pas-sengers	Electrical fault	1 h	1 dead 28 injured	1 coach	Serious damage
1995	Pfander 6,719 m	Austria	Lorry with trailer	Collision	1 h	3 dead in the collision 4 injured	1 lorry 1 van 1 car	Serious damage
1996	Isola Delle Femmine 148 m	Palermo Italy	1 tanker with liquid gas + 1 little bus	Front-rear colli-sion	n/a	5 dead 20 injured	1 tanker 1 bus 18 cars	Serious damage, tunnel closed for 2.5 days
1999 14 July	Mont Blanc 11,600 m	France-Italy	Lorry with flour and margarine	Oil leakage Motor	n/a	39 dead	23 lorries 10 cars 1 motorcycle 2 fire engines	Serious damage, tunnel reopens 22.12.2001
1999	Tauern 6,401 m	A10 Salz Salzburg-Spittal Austria	Lorry with paint	Front-rear collision 4 cars and 2 lorries	n/a	12 dead 49 injured	14 lorries 26 cars	Serious damage
2000	Seljestad 1,272 m	E134 Dram-men-Haugesund Norway	The trailer truck that caused the multiple collision had a diesel fire in the engine room before collision	Front-rear colli-sion A trailer- truck pushed a car into 4 cars that had stopped behind another truck	45 min	6 injured	1 lorry 6 cars 1 motorcycle	Serious damage. NOK 1 mill. Tunnel closed for 1 ½ days
2001 28 may	Prapontin 4,409 m	A 32 Torino-Bardonecchia Italy	Romanian truck, loaded with beets	Mechanical problem	n/a	19 injured by smoke	n/a	Closed until 6 June in westerly direction
2001	Gleinalm 8,320 m	A 9 near Graz Austria	Car	Front collision Lorry-car	n/a	5 dead 4 injured	n/a	n/a
2001	St. Gotthard 16,918 m	A 2 Switzerland	Lorry	Front collision Lorry-car	2 days	11 dead	13 lorries 4 vans 6 cars	Serious damage Closed for 2 months

>> Appendix 1 - Road Tunnel Fire History

SOURCES :

CETU:
Incendies de tunnels routiers dans le monde, ayant occasionné des victimes ou dégâts importants, sans matière dangereuse impliquée
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FHWA-RD-83-032 Prevention and Control of Highway Tunnel Fires (appendix)

Longtunnel.com

The model developed by Li and Ingason [2.7, 2.8] is a simple and robust empirical model based on theoretical approach and a large amount of large scale and model scale data. The maximum temperature beneath the ceiling in a tunnel fire is independent of the ventilation velocity if the ventilation velocity across the fire source is very low compared to the heat release rate, and the maximum temperature is just dependent on the heat release rate, however, it approaches to a constant if the part of the flame volume containing the combustion zone is present at the tunnel ceiling. In other words, if V' ≤ 0.19 (Region I), the maximum excess temperature can be expressed as :

$$\Delta T_{\max} = \begin{cases} 17.5 \dfrac{Q^{2/3}}{H_{ef}^{5/3}}, \\ 1350, \end{cases}$$

The dimensionless ventilation velocity: $V' = u_o / w^*,$

The dimensionless plume temperature: $\phi = (T - T_o)/T_o,$

The dimensionless position along the trajectory: $\xi = s / b_{fo}.$

The characteristic plume velocity w* is defined as :

$$w^* = \left(\frac{gQ}{b_{fo}\rho_o c_p T_o}\right)^{1/3}$$

where b_{fo} is radius of fire source (m), *u* is plume velocity (m/s), uo is wind velocity (m/s), *s* is trajectory (m), *b* is radius of fire plume at a given position (m), *g* is the acceleration of gravity (m/s^2), Q is heat release rate (kW), ρ_o is ambient density (kg/m3), c_p is heat capacity (kJ/kgK), T_o is ambient temperature (K), θ is the angle between plume axis and horizontal axis (°), α is tangential entrainment coefficient and β is normal entrainment coefficient.

If the ventilation velocity across the fire source gets larger, the maximum excess temperature beneath the ceiling depends on both the heat release rate and the ventilation velocity, however, it also approaches to a constant if the combustion zone is present at the tunnel ceiling. How to determine which constant to use will be discussed in chapter 3. In other words, if V' >0.19 (Region II), the maximum excess temperature can be expressed as :

$$\Delta T_{\max} = \begin{cases} \dfrac{Q}{u_o b_{fo}^{1/3} H_{ef}^{5/3}}, \\ 1350, \end{cases} \qquad (1)$$

Example Scenario :

An HGV vehicle (Heavy Goods Vehicle trailer) is assumed to start to burn. The ignition can be related to the fact that one vehicle starts to burn (a tire fire or engine problems). The fire can also be regarded as a fire that starts due to a collision of two HGVs. The tunnel height at its maximum is 6 m and the width is 12 m at its widest part. The height from the bottom of the fire load up to the ceiling is 4.8 m. The radius of the fuel in the vehicle, b_{fo}, is 4 m. The fire is assumed to be fuel controlled. The ambient conditions are 10°C. This fire is expected to follow the HC curve. Use the equations (1-3) to calculate the corresponding heat release rate curve and also if the fire duration is assumed to be 120 minutes, what is the corresponding fire load. The longitudinal ventilation is assumed to be 3 m/s. The Hydrocarbon Curve (HC) [3] can be expressed as $\Delta T(t)=1080(1-0.325e^{-0.167t}-0.675e^{-2.5t})$, where t is the time (min).

Solution : *Firstly we assume V' > 0.19 since Q(t) is unknown. This means that Equation (3) is used here. Then we calculate V' using Qmax, which turns out to be greater than 0.19.This means at any time in this scenario, V' >0.19 is fulfilled, which verifies the first assumption. For data with a temperature over 1100°C, it is difficult to determine in which region it lies. However, it is clear that the calculated heat release rate is the minimum value required to obtain such a high temperature.*

If we integrate the curve we find the total energy to be 496 GJ. This would correspond to at least two HGVs. A reasonable conclusion is that this tunnel would be designed to a fire that can resist a collision between two HGVs, and the fire can be very intense for up to 120 minutes. This shows the practical implication of using Equations (1) and (3). These equations become a key to relate information between the standardized time-temperature curves and the fire load in terms of the heat release rate and total energy found in the fire load.

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