Promat

Tunnel & Underground Structure Fire Protection
Board Lining Solutions

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etex building performance

Promat

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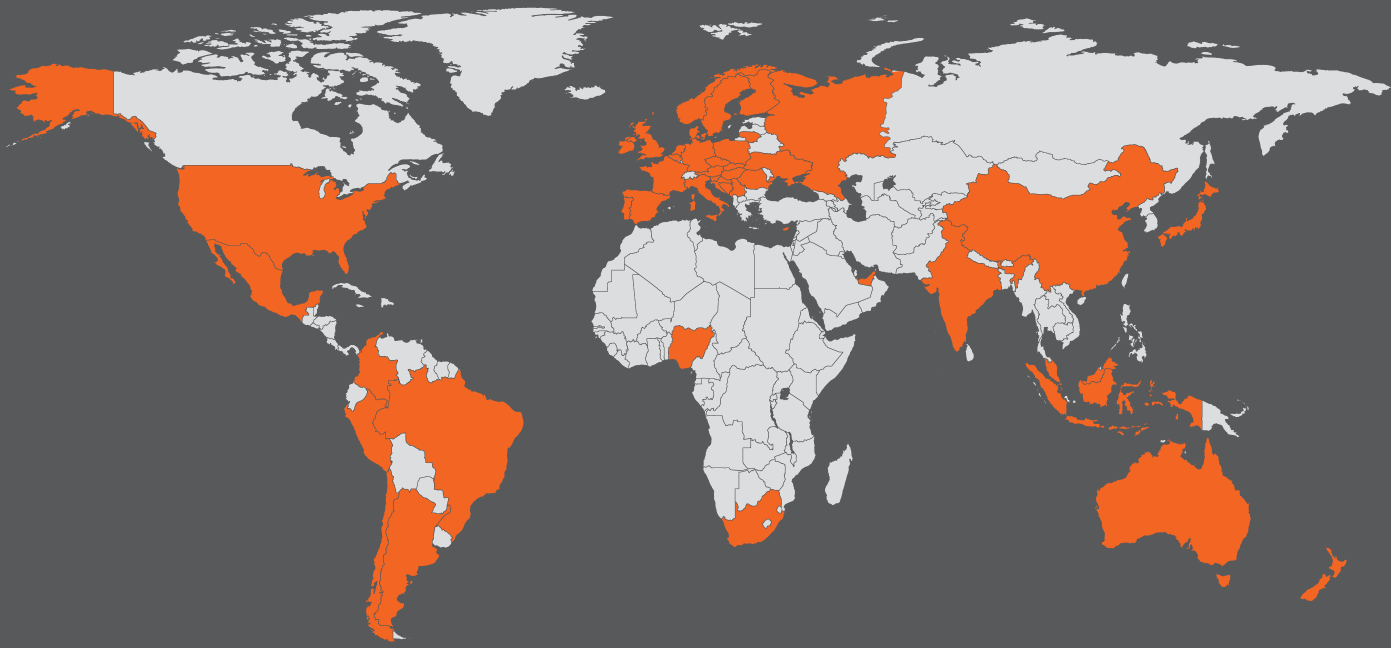


1.1 Who is Etex

Promat companies are subsidiaries owned by Etex, a Belgian industrial group that specialises and markets high quality building materials and systems.

Founded in Belgium more than 110 years ago, Etex currently operates 107 factories and 102 companies (including 8 R&D centres) across 42 countries, employing m ore than 15,000 people.

1.1.1 Structure

Etex's structure reflects more than a century of geographic growth and product diversification. Today the group approaches the market as an organisation with global divisions. By 2017, all Etex subsidiaries worldwide have been integrated within these four divisions, each targeting a well defined business segment:

- Etex Building Performance
- Etex Industry
- Etex Façade
- Etex Roofing

Etex Building Performance
Fibre cement and gypsum building boards, fire protection and dry construction systems

Etex Industry
Industrial solutions with high performance thermal insulation and passive fire protection

Etex Façade
Fibre cement façade materials

Etex Roofing
Roofing systems, fibre cement slates and corrugated sheets, clay and concrete tiles, roofing components

In each of the four business divisions, Etex has set out ambitious goals to sustain and strengthen its market leadership for its unmatched range of products and systems. Promat products and solutions are included in the first two divisions. Both tunnel fire protection and building technical construction are business segments of Etex Building Performance division.

1.1.2 Vision and strategy

Etex continuously strive to be the innovative leader in sustainable and affordable building solutions with a strategy based on these four pillars:

1.2 What drives Etex

At Etex, the way business is being conducted just as important as its offering. The group is driven by a people-oriented philosophy and act accordingly, in a responsible, safe and sustainable way.
http://www.etexgroup.com/en/what-drives-us/inspiring

1.2.1 Social commitment

The principles of sustainable development are foremost in people's minds. Etex focus on the following aspects which can have the most impact:

a) Workforce safety
Safety comes first at Etex. With a formal set of guidelines to establish safety standards and frameworks, all employees are responsible to work ceaselessly on machine safety, procedures and their behaviour towards zero accidents worldwide. As a result of these efforts and other measures, the frequency rate of accidents in the global operation of Etex companies has decreased each year.

b) Asbestos policy
Although asbestos has been banned from Etex production processes in the past, the group has instigated a mandatory policy for all companies to assist asbestos victims by compensation, landfills management, exposure prevention, or support of medical and scientific research. http://www.etexgroup.com/en/what-drives-us/social-commitment/asbestos

c) Energy reduction
Innovation and striving for lower production costs leverage any environmental efforts. For example, the heavy energy usage plants are implementing the ISO 50001 energy management standard to help reduce energy consumption in a systematic way. Etex also help customers reduce their carbon footprint with eco-friendly solutions.

1.2.2 Community relations

Being a global group, Etex's numerous stakeholders are key to the group's success. That is why the companies have acted as responsible citizens in their local communities. In 2011, Etex introduced a Code of Conduct of the ethical rules and guidelines for contributors on the community work.

Having teamed up with international Non Governmental Organisation (NGO) and local partners, Etex helps build homes for those in need all over the globe. http://www.etexgroup.com/en/what-drives-us/community-projects

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 and economic for both the tunnel owner/operator and the local community.

A number of questions to address when considering the design performance of the tunnel structure:

- In the event of a fire will the occupants be able to escape to a place of safety free from the effects of explosive spalling concrete or even partial collapse of the tunnel. Will the structure collapse, causing collateral damage to other parts of the tunnel and rendering additional risk to the lives of emergency services personnel.
- In the event of a fire can the functionality of services such as emergency lighting, smoke extraction systems ect be maintained under extreme temperatures.
- Importantly there is the socio/ economic damage caused as a result of taking a tunnel out of use. Such economic cost is not related solely to the repair or rebuilding of the structure, more usually it is the knock-on impact of loss to business, traffic diversions ect which result in the largest costs to the community.

Whilst tunnel fires may vary widely, it has been proven through a number of independent studies including the Runehamar large scale fire tests conducted in association with the UPTUN research programme, that temperatures can reach 1350°C and heat fluxes up to 300kW/m^2 irrespective of the types of goods being carried. With the general increase in traffic volume the risk of an incident involving fire is increasing. They may be small with the ignition of a small vehicle carrying a low fire load, or large and intense from the ignition of a Heavy Goods Vehicle) HGV. With the general increase in traffic volume and the transport of hazardous and non hazardous goods that still have a high fuel load, the risk of an incident involving fire is increasing.

2.1 Fire damage in tunnels

Fires in the Mont Blanc, Tauern, St. Gotthard and Channel Tunnels previously have shown that the intensity of real tunnel fires can be far greater than expected. The damage to structure and long closure periods and loss of revenues can have catastrophic consequences to both the tunnel itself as well as the surrounding environment. In an immersed tube tunnel, loss of the joint seals in a fire would destroy the tunnel.

Mont Blanc Tunnel, Italy, after fire

In the case of Mont Blanc Tunnel, there was severe spalling of the structural concrete. During the fire which occurred inside the St. Gotthard Tunnel in 2001, a 250m long section of the structure actually collapsed, hampering the activities of the rescue services. Although these tunnels passed through rock and experienced severe spalling, there was no total collapse, however, if they were immersed tube tunnels, the structural damage could have resulted in flooding of the tunnels with all the associated implications.

It should be noted that after the fire in the Channel Tunnel, the only thing standing between total loss and a situation where effective repair could be carried out was the thin grout layer between the concrete structure and the water bearing rock layer, so severe was the spalling of the concrete. A very slim margin to rely on, but a risk which could easily have been alleviated had the correct passive fire protection systems been included, complementing the active systems that were installed.

Structure damage after fire in Channel Tunnel, UK

In the scenario of Channel Tunnel, the economic damage was estimated to be over twice the cost of the actual tunnel repairs. The direct repairs to the tunnel cost an estimated €87 million while the additional costs in lost business, replacement of infrastructure, materials (e.g. lorries, train carriages etc) together with the impact of the tunnel closure on other. The estimated total loss of revenue to Eurotunnel during the period of closure was approx €200million. Total estimated cost inclusive of impact on local communities closer to €1 billion. Compared to Mont Blanc a simple road tunnel, the differences of damage are not so marked, with the cost of repair being approximately €206 million and the economic cost at some €250 million.

However, the socio economic impact has to be considered on a wider basis rather than simply the tunnel itself. The estimates of the effects on the local Italian economy around the area of the Mont Blanc Tunnel were estimated at €1.75 billion. Therefore, in any risk analysis, the socioeconomic costs need to be accurately identified and carefully assessed.

A list of road tunnel fire history worldwide is available on Appendix page 59.

2.2 European guidelines on tunnels

2.2.1 Structural requirements for road tunnels

Following the spate of aforementioned catastrophic fires in European road tunnels, it became apparent that the international tunnelling community had severe reservations on the safety and operations of tunnels. In 2001, therefore in 2001, a paper was released by PIARC (The World Road Association) titled RECOMMENDATIONS OF THE GROUP OF EXPERTS ON SAFETY OF ROAD TUNNELS to present the following prognosis:

"To ensure safety in road traffic, the necessary structural, technical and organisational measures need to be taken. All safety measures have to correspond to the latest technology and apply to all concerned, i.e. to road users, traffic control and emergency services, infrastructure and vehicles.

The following objectives have also been set for attaining the optimal level of safety in road tunnels:

- *Primary objective – prevention*
  To prevent critical events which endanger human life, the environment and tunnel installations.

- *Secondary objective – reduction of consequences*
  As a result of events such as accidents and fires, to create the ideal prerequisites for
  - *people involved in the incident to rescue themselves,*
  - *the immediate intervention of road users to prevent greater consequences,*
  - *ensuring efficient action by emergency services,*
  - *protecting the environment, and*
  - *limiting material damage."*

The document concludes with the following statement:

"Fires in tunnels not only endanger the lives of road users, they can also cause damage to structural components, installations and vehicles, with the result that the tunnel concerned may have to be closed for a considerable length of time."

The above paper made tunnel stakeholders acknowledge the frailty of the safety issues associated with the operation of their own specific tunnel and in particular the concerns with mitigating the consequences of structural damage and the impact this has on the environment due to extended diversion routes.

Notwithstanding the above report and the consequences of the catastrophic fires, it was also recognised within the European tunnelling community that a wide range of operational and safety standards, regulations and structural requirements existed in many different countries. The community believed that this led to confusion and had to be standardised.

This standardisation process led to the introduction of the European Directive in 2004 in a document titled DIRECTIVE 2004/54/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL ON MINIMUM SAFETY REQUIREMENTS FOR TUNNELS IN THE TRANS-EUROPEAN ROAD NETWORK.

2.2.2 Objective of European Directive

The objective of the directive was primarily to harmonise and introduce minimum safety standards for road tunnels in Europe and was primarily targeted at tunnel stakeholders. The document also intended to make stakeholders fully aware of the risks to life, structure and the economic and environmental impacts associated with the operation of unsafe tunnels.

Article 1 of the document states:

"The Directive aims at ensuring a minimum level of safety for road users in tunnels in the Trans-European Road Network by the prevention of critical events that may endanger human life, the environment and tunnel installations, as well as by the provision of protection in case of accidents."

The aim of this statement was to raise stakeholder awareness of *"risk"* and the consequences of *"risk"* with special significance placed upon the risk of fire and the consequences to life, structure and the environment.

Article 3 gives guidance on how to reduce the consequences of risk namely by:

"Implementation of Risk Reduction Measures… the efficiency of these measures shall be demonstrated through a risk analysis in conformity with the provisions of Article 13."

This statement suggests that *"Risk Reduction Measures"* need to be implemented but their *"Efficiency and Performance Requirements"* needs to be assessed through risk analysis techniques. However, it is pointless incorporating Risk Reduction Measures unless the effectiveness of these *"Risk Reduction Measures"* is known.

Article 13 states:

"Risk Analyses, where necessary, shall be carried out by a body which is functionally independent from the Tunnel Manager. A risk analysis is an analysis of risks for a given tunnel, taking into account all design factors and traffic conditions that affect safety, notably traffic characteristics and type, tunnel length and tunnel geometry, as well as the forecast number of heavy goods vehicles per day."

In conclusion, the objective of European Directive was primarily to make tunnel stakeholders more *"risk averse"* in generic operational risks with particular reference to the consequences of fire.

2.2 European guidelines on tunnels

With reference to tunnel structures, the European Directive states: *"The main structure of all tunnels where a local collapse of the structure could have catastrophic consequences shall ensure a sufficient level of fire resistance."*

In this statement, specific reference is made to the main structure forming the tunnel and the need for a sufficient level of fire resistance. The ambiguity here is what can be deemed to be a sufficient level of resistance. This level of resistance can only be assessed if we know what the magnitude of fire risk represents.

This fire magnitude can only be assessed through risk analysis and the document refers to Article 13 above. The European Directive repeatedly refers to Article 13 in an attempt to harmonise standards. In principle the European Directive introduces Risk Management techniques to introduce minimum safety standards for roads on the Trans-European Road Network.

2.2.3 Risk Management

With specific reference to tunnel structures, we know that:

THE RISK = FIRE
THE CONSEQUENCES = STRUCTURAL COLLAPSE

But how do we derive the solution to satisfy the requirement of *"…ensuring a sufficient level of fire resistance"*?

The European Directive, as explained above, refers to Risk Management techniques and makes specific reference to risk analysis. However, other Risk Management tools are required to derive a solution. Risk Analysis and in particular, reference to tunnel structural integrity unfortunately only identifies the *"probability and magnitude"* of the risk. It does not conclude the consequence.

Promat, in joint partnership with leading consultants in the field of Risk Management of structures, has developed a suite of tools which has the tunnel stakeholders to make key decisions to ensure compliance with the European Directive. These include:

- Risk Analysis – risk impact (probability and magnitude)
- CFD & FEA Modelling – structural impact and consequence
- Consequential Analysis – economic and environmental impact

Resulting in the optimisation of

- Risk Reduction Measures

However, it must be emphasised that not all tunnels require Risk Reduction Measures in order to meet the requirements of the European Directive. Indeed, if the *"probability and magnitude"* of the risk is small, consequential analysis is not required. This eliminates the need for Risk Reduction Measures and the Risk Management function is therefore complete. The Risk Analysis tool is therefore a fundamental and powerful tool in setting the constraints for Risk Management and similarly the need or otherwise for structural Risk Reduction Measures.

2.2.4 Risk Analysis

Almost all risk assessment tools use the explicit risk assessment formula:

$$\text{RISK} = \Sigma \text{ FREQUENCY} \times \text{CONSEQUENCE}$$

However, this approach makes no specific reference to the magnitude of the risk. Furthermore when considered with specific reference to fires in tunnels, it cannot determine consequence. There is potential consequence to tunnel structures from the risk of fire but this does not give guidance in assessing the level of the risk reduction measure. This can only be achieved in assessing the frequency (probability) and magnitude of the fire risk (fire load or heat release rate).

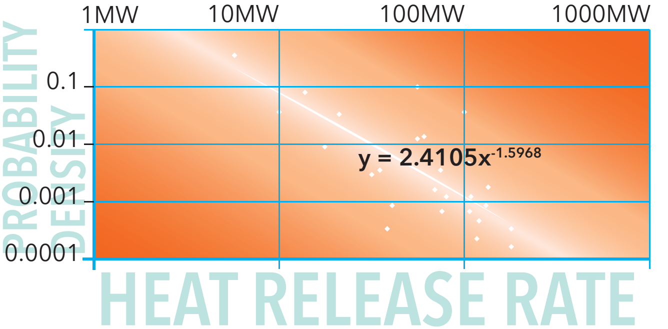
Promat, along with an independent consultant, has developed a Risk Analysis tool which allows the probability and fire magnitude risk to be determined for any type of tunnel. This approach, originally pioneered in the UK following the introduction of the European Directive, has been used widely throughout the world to derive design fire sizes for structural resistance in tunnels.

Output from this Quantitative Risk Analysis (QRA) model results in a *"Probability - Fire Size Matrix"* as below:

Heat release rate	Probability	Years
5MW	0.325	3.08
15MW	0.056	17.92
25MW	0.056	17.79
50MW	0.068	14.60
100MW	0.023	42.92

Using a balanced approach, analysis of the matrix determines the *"design fire size"* and, as shown in below figure, sets the Structural Design Criteria in the consequential analysis using Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) tools to assess the need or otherwise for Risk Reduction Measures.

Figure 1 Probability density vs Heat Release Rate (HRR)



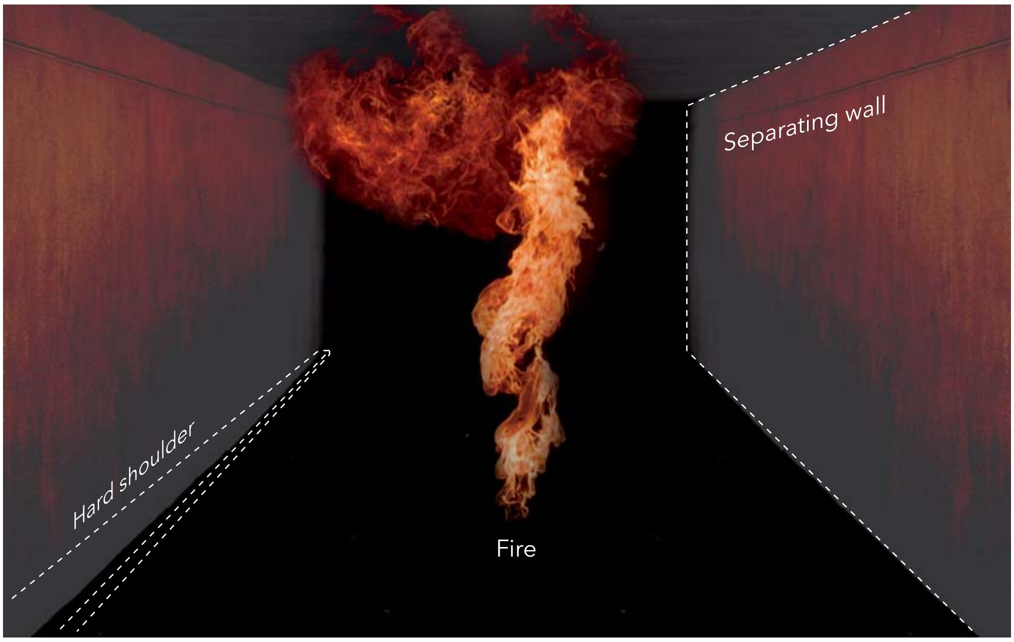
To summarise, the risk reduction process can be concluded at this stage if the *"Probability - Fire Size Matrix"* shows that the risk is small. In this it was concluded that the probability of the 100MW fire lay within the design life of the tunnel. CFD and FEA was then used to assess the structural performance from such a fire load.

2.2.5 Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA)

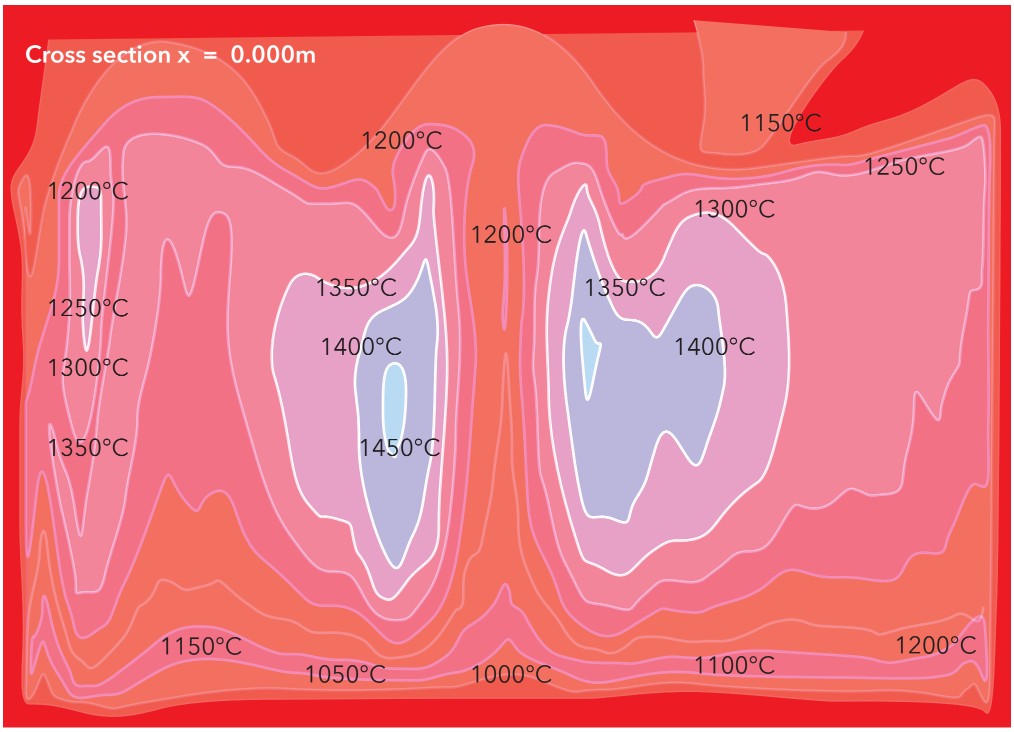
Following risk analysis, if it concludes that the probability and magnitude of the fire risk may result in consequential structural damage, an assessment of this consequential damage needs to be undertaken. Promat, along with independent consultant and Efectis laboratories, have pioneered the coupling of CFD and FEA to assess the structural damage resulting from the output of the risk analysis.

Coupling of these two design tools allows individual structural components to be assessed in detail with fires located at various locations across tunnel cross sections.

Figure 2 Fires and temperatures located at various locations across tunnel cross sections



The CFD component develops the temperature constraints at the boundary of the structure for a fire at any location in a tunnel, important for wide tunnels formed from many structural components.



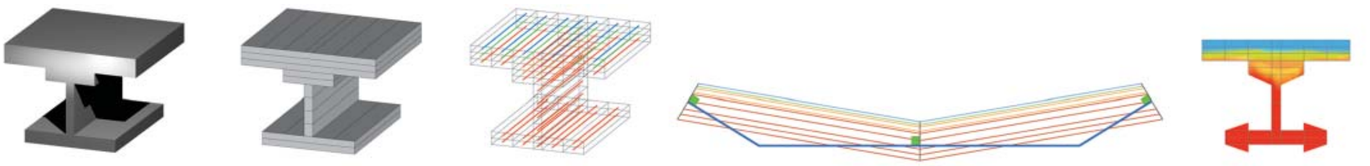
The FEA component allows detailed time dependent failure analysis to be assessed for all components forming the structure and allows detailed assessment up to the point at which the structure is no longer self supporting and failure mechanism begins. For complex structures such as cut and cover (C&C) tunnels, this is crucial to determine the weakest element.

Continued on next page

For complex structures such as cut and cover and immersed tube tunnels, specific failure criteria can be derived for individual structural components.

The CFD and FEA approach has been accepted by the European tunnel community as current best practice in assessing structural resilience of tunnels. It has been presented at various symposia on catastrophic fires in tunnels.

Figure 3 Structural beams for tunnel systems



Real beam | Subdivided beam | Mechanical model, truss elements | Mechanical model | Mesh for thermal analysis, 2D

2.2.6 UPTUN WP4 tunnel system structural response

Objectives and results of analysis by Efectis Building & Construction Research in collaboration with UPTUN are:
- Insight into the structural performance of loadbearing elements
- Define structural procedures to reduce critical behaviour
- Investigate damage mitigation of the loadbearing structures
- Preserve the functional characteristics of structures
- Optimise repair and recovery procedures.

Please contact Promat for more information.

Following consequential analysis, a full assessment of Risk Reduction Measures can be evaluated. If the analysis concludes that no significant structural damage is likely to occur, then no Risk Reduction Measures are required. However, if the analysis concludes that severe structural damage is likely as a consequence of the fire magnitude derived from the Risk Analysis, Risk Reduction Measures will then be required.

Output from this tool allows the performance requirements for each component forming the tunnel, structure to be determined, resulting in an optimisation of the Risk Reduction measure. This enables the designer to provide the most cost effective solution for benefit of the stakeholder.

This approach, once again pioneered following the introduction of the European Directive has been used universally throughout Europe to assess the performance of tunnel structures.

2.2.7 Economic & Environmental impact

Another factor in assessing the structural resilience of tunnels is the need to assess the economic and environmental impact following failure due to fire.

As described on page 6, the loss of tunnel operations due to structural collapse can have severe economic and environmental impact on local and national communities.

Promat, in collaboration with an independent consultant, has developed a model which allows an economic dis-benefit analysis for any tunnel to be assessed. This analysis determines the potential loss in operational revenue and combined with the Computational Fluid Dynamics (CFD) and Finitel Element Analysis (FEA) model, the environmental and economic impact to the community and country to be evaluated. This could be a major factor in assessing the need for structural or asset protection against the risk of fire.

2.2.8 Risk Reduction Measures

In real terms, for existing tunnels, there are TWO (2) main approaches to introducing Risk Reduction Measures:

1) Board lining applied methods (as discussed in this document)

2) Spray applied solutions (see a separate document)

Output from the CFD & FEA analysis will set the design constraints for either solution and may even be a combination of both types in order to provide the best and cost effective approach for any specific tunnels. PROMATECT®-H and PROMATECT®-T board lining application for tunnel structure is the best solution for flexibility and assurance of protection.

2.2.9 Conclusion

Existing European Legislation and Current Best Practice (PIARC) requires tunnel stakeholders to assess structural risks in their particular tunnel. Current experience suggests that all stakeholders should assess these structural risks by the use of risk assessments. However, Risk assessments do not fully assess the complete understanding of the risk and therefore consequential analysis is required.

The suite of Design Tools developed by Promat, along with an independent consultant and Efectis laboratories, serve to assist stakeholders to appreciate their obligations regarding Legislative Requirements and Best Practice.

The Design Tools include:
- Quantified Risk Assessments
- CFD and FEA Analysis
- Economic and Environmental Impact Analysis
- Design of Risk Reduction Solutions

These tools will also allow Promat to work through team integration with stakeholders in assessing the probability, magnitude, consequence, economic and environmental impact of the fire risk for any type of tunnel. Stakeholders will be enabled to fully assess, through a Risk Management process, compliance with the European Directive and engage in current best practice.

2.3 Spalling

Information of this section is sourced from Efectis BV The Netherlands.

Spalling is an umbrella term, covering different damage phenomena that may occur in a concrete structure during fire. These phenomena are caused by different mechanisms: pore pressure, thermal gradient, internal thermal micro-cracking, cracking around reinforcement bars and strength loss due to chemical transitions. In different combinations of these mechanisms, possible spalling phenomena include violent spalling, progressive gradual spalling, explosive spalling, corner spalling and post cooling spalling can occur.

Spalling of concrete during fire causes serious damage to concrete structures, with significant economic costs and risk to human life. New developments in concrete technology such as improved grain size distribution and the application of extra fine particles have resulted in concrete types with improved durability, strength and workability. However, these high performance concrete types have been shown to be more susceptible to spalling during fire than ordinary concrete types. The problem of spalling in buildings has been known for decades and further highlighted by recent intense tunnel fires in Europe. As a consequence of severe damage due to spalling and the non-operational time of tunnels after a fire, the fire resistance of newly developed concrete types has been questioned.

2.3.1 Heating rate and internal stresses

During a tunnel fire, air temperatures can rise to over 1300°C within just a few minutes. Compared to building fires, this is a much more severe situation, giving a large thermal shock to the structure. For the design of buildings, there is worldwide agreement on the use of the ISO-834 *"standard"* fire, which prescribes a slower temperature development. This and a few other design fire curves for tunnels are shown in page 21 (Figure 9). Although usually a less expensive solution is obtained by using a lower fire curve, this may well lead to unsafe situations. Recent full scale tunnel fire tests carried out by the UPTUN consortium, for example, have shown that fire temperatures may quickly reach 1300°C to 1400°C. This is a critical issue because many insulation materials cannot withstand temperatures above 1200°C or may be unable to withstand the thermal shock of such a rapidly developing fire, and may therefore be unsuitable for protection of a tunnel lining.

During heating, stresses develop inside the concrete cross-section. Thermal gradients and moisture pressure lead to mechanical stresses that may cause internal and external cracking as well as spalling of concrete.

2.3.2 Spalling of concrete

Spalling of concrete is one cause of damage to the structure. Other causes of damage that develop during fire exposure are internal cracking, irreversible plastic and creep strains and chemical transitions. These forms of damage might eventually lead to collapse due to a failure mechanism like bending, shear, anchorage or buckling.

Often when concrete is damaged in a real fire the damage is called spalling. In many cases this is not correct. Other failure mechanisms such as shear failure can also lead to severely damaged concrete.

"Real" spalling can occur in different forms, each of which is caused by a specific combination of the following mechanisms:

- Pore pressure rises due to evaporating water as the temperature rises.
- Compression of the heated surface due to a thermal gradient in the cross section.
- Internal cracking due to differences in thermal expansion between aggregate and cement mix.
- Cracking due to differences in thermal expansion/ deformation between concrete and reinforcement bars.
- Strength loss due to chemical transitions during heating.

The mechanisms act on different scales:

i) Macro-level
Concrete considered as a grey homogeneous material with uniformly distributed material properties. On this level, the thermal stresses that result from the thermal gradients over the cross section must be considered, taking into account the actual geometry, support conditions and loading configuration.

ii) Meso-level
Concrete considered as a mix of aggregate and cement mix, each with its own material properties. On this level, the cracking due to differential thermal expansion between aggregate, mortar and reinforcement must be considered.

iii) Micro-level
Cement mix, aggregate particles or interface layers considered as a mix of chemical constituents. On this level, the pore pressures and the degradation of mechanical properties due to chemical transitions and dehydration must be considered.

During fire tests the observations of spalling of concrete cover a wide range. These are such as follows, in random order, and so on:

- Observation of spalling with slow (1°C/minute) or fast (250°C/minute) heating, from gradual to explosive spalling, cracking along or through aggregate grains.
- Spalling in the beginning of the fire or after some time.
- Stopping after some time or progressing.
- Stopping at the reinforcement level or continuing far beyond it.

The different observed spalling phenomena are described herein, including their relationship to the previously mentioned mechanisms (Breunese & Fellinger, 2003). Below is a summary of the important relations between mechanisms and spalling phenomena:

Type of spalling	Pore pressure due to evaporation of moisture	Compression due to thermal gradient	Internal cracking due to different thermal expansion of aggregate cement paste	Cracking due to different thermal deformation of concrete-steel	Strength loss due to chemical transitions
2.3.2.1 VIOLENT SPALLING	√	√	√		
2.3.2.2 SLOUGHING OFF			√		√
2.3.2.3 CORNER SPALLING				√	
2.3.2.4 EXPLOSIVE SPALLING	√	√			
2.3.2.5 POST COOLING SPALLING			√		√

2.3.2.1 VIOLENT SPALLING

Violent spalling is the separation of small or larger pieces of concrete from the cross section, during which energy is released in the form of pieces and small slices of concrete popping off with a certain speed, and also a popping or cracking sound. This type of spalling is caused by pore pressure and thermal gradients. Internal cracking on the meso-level also influences this spalling process. The surface compression during heating can increase due to lateral restraint, reinforcement, prestressing, large concrete thickness and a high heating rate. Pore pressures are dependent on heating rate, moisture content, permeability, porosity and the presence of polypropylene fibres (artificial permeability). Furthermore, an increased ductility of concrete by the addition of steel fibres has sometimes been reported to reduce the risk of this type of spalling. (Fellinger & Both, 1997)

2.3.2.2 PROGRESSIVE GRADUAL SPALLING (SLOUGHING OFF)

Sloughing off is the form of spalling that is caused by strength loss due to internal cracking (mesolevel) and chemical deterioration of the cement mix (micro-level). This type of spalling is related to the attained temperature of the concrete (instead of heating rate). If the concrete is heated to a very high temperature the strength will be too low to carry its own weight, causing small pieces of concrete to fall down without much sound. This type of spalling is likely to occur on a slab heated from below, since gravity will force the cracked pieces of concrete from the cross section.

2.3.2.3 CORNER SPALLING

Corner spalling is the type of spalling that occurs when a corner of concrete breaks off at the location of a reinforcement bar. Inhomogeneous heating of concrete leads to a deformation (ovalisation) of the concrete around the uniformly heated reinforcement bar. This difference in deformation causes splitting stresses in the concrete, leading to splitting cracks that can cause the corner of a column or slab to break off.

2.3.2.4 EXPLOSIVE SPALLING

Explosive spalling is the result of a combination of rising pore pressures and thermal gradients in the cross-section. At the front of heat penetration, a "moisture clog" (an area with high pore pressure) develops inside the concrete. Part of the moisture is pushed further into the colder part of the concrete due to the pressure gradient at the back of the clog. If the heated surface is under compression due to a thermal gradient, the complete heated surface may explode away with a loud bang. This type of spalling is especially likely to occur on structural members heated from more than one side, such as columns and beams.

When moisture clogs are advancing into the concrete from all heated sides, at some point in time the moisture clogs will meet in the centre of the crosssection, creating a sudden rise in pore pressure which may cause large parts of the cross-section to explode. This type of spalling can also occur after a considerable duration of the fire even if the concrete surface has been protected with an insulating layer. (Both, 1999)

2.3.2.5 POST COOLING SPALLING

Post cooling spalling occurs after the fire is over, after cooling down or maybe even during extinguishing (Khoury, 2003). This type of spalling was observed with concrete types containing calcareous aggregate. An explanation is the rehydration of CaO to $Ca(OH)_2$ after cooling, when expansion of over 40% occurs, and moisture is again present on the concrete surface. The expansion due to rehydration causes severe internal cracking on the meso-level and thus complete strength loss of the concrete. Pieces of concrete keep falling down as long as there is water to rehydrate the CaO in the dehydrated zone.

2.3 Spalling

2.3.3 Testing of spalling behaviour

For a spalling test, it is of great importance to simulate the practical situation as closely as possible in the test setup. Only in this way is it possible to draw conclusions from the test although extrapolation of test results is difficult at best. Due to the variety in spalling test results a test should always be performed twice in an identical lay-out. See below figure for example.

Figure 4 Test set up to determine spalling behaviour using a full scale tunnel segment

2.3.3.1 GEOMETRY, PRESTRESSING, CONCRETE MIX AND MOISTURE LEVEL

For the concrete it is important to use the concrete mix and geometry as will be used in the real life conditions. The case of precast circular segments, preferably segments made in the factory should be used. For spalling, the prestressing level is important, and should resemble the actual situation. The moisture level of the concrete should be at least as high as it will be in reality. In general, a specimen with higher moisture content is more likely to spall and therefore give a more conservative test result.

2.3.3.2 AGE OF THE SPECIMEN

The specimen must be old enough to have a moisture content close to the actual situation. This is necessary because spalling is strongly influenced by free water content, porosity and permeability. After 28 days much of the final strength of concrete has been reached, but permeability is still decreasing. For practical reasons it is of course impossible to test segments of many years age. At Efectis laboratories Netherlands, for example, the age of specimens at the time of testing shall be a minimum 90 days as prescribed in test procedure 2008-Efectis-R0695.

2.3.3.3 FURNACE TEMPERATURE

The fire test must be carried out according to a suitable fire curve. It is important to achieve the steep increase in the first 5 to 10 minutes of the test because this gives a high thermal shock to the concrete. It is also important to achieve a sufficiently high maximum temperature because some products used for this purpose may start to decompose at around 1200°C.

2.3.3.4 INSULATION MATERIAL

If a protective layer, such as cementitious spray or board material, is used, it is important to pay attention to the method of fixing the material to the concrete surface. The details are also extremely important and include covering of hollow spaces in the concrete surface, while sufficiently protecting objects that are fixed to the concrete.

For example, a road sign fixed to the tunnel ceiling with steel bolts in fact forms a penetration of the protection layer and may locally introduce heat into the concrete, leading to possible spalling.

Once spalling starts in such a small region, pieces of spalling concrete may rapidly push away the remaining protection material and leave the whole surface unprotected. For the material of the protective layer, a low moisture content during the test is recommended. This reduces the insulation capacity of the material and thus gives a more conservative test result. The layer thickness should be identical in both tests. Interpolation of layer thicknesses is impossible for spalling tests!

2.3.3.5 POLYPROPYLENE FIBRES (PPF)

The latest investigations into the fire performance of concrete show that even the addition of polypropylene fibres (PP fibres) into the concrete mix will not always suffice to reduce water vapour pressure, and thus can have little effect on reducing the incidence of spalling.

It should also be noted that the majority of testing to date on the performance of concrete with the addition of polypropylene fibres has been to the standard cellulosic curve, and not to the greater requirements of tunnel fire curves. Even for these relatively low temperature rise fires, the proportion of PP fibres to concrete mixture required is such that the concrete is often very stiff and difficult to work. It should be further noted that use of PP fibres will result in no provision of insulation to the concrete against rapid temperature rise – which could result in extensive internal and external cracking of the concrete – even where spalling is alleviated, which can effect long term durability of the concrete substantially. Care should therefore be taken to ensure claims for the performance of PP fibres are substantiated by adequate test evidence which shows continuation of long term durability and no loss of concrete strength.

2.3.4 Fire resistance of concrete

Research has shown that concrete structures suffer surface spalling as a result of high compression stresses in the heated outermost layers and by the generation of water vapour at high pressure behind those layers. The probability of spalling increases with compression stress and the moisture content of the concrete. With a moisture content of over 3% of the mass, the probability of spalling is virtually 100%. Explosive spalling presents immediate risks to emergency response personnel in fire situations as well as evacuating tunnel users and the exposure of underlying steel can result in rapid deterioration of strength and load capacity.

It should also be noted that concrete can be heated slowly and spalling will not occur, or will be minimised. However, when heated rapidly, precisely the type of fire seen in tunnels where the onset of fire growth is extremely rapid, rising to very high temperatures, the permeability of the concrete and the ability of the moisture to find its way to the surface determines the onset and severity of spalling.

Rapid rates of heating, large compressive and tensile stresses or high moisture contents (over 5% by volume or 2% to 3% by mass of dense concrete) can lead to excessive spalling of concrete cover at elevated temperatures, particularly for thicknesses exceeding 40-50mm. This water is not only physically present (as moisture), but also chemically bound within the concrete (hydrated water).

Such spalling may impair performance by exposing the reinforcement or tendons to the excessive heat or by reducing the cross-sectional area of concrete. Concrete types made from limestone aggregates are less susceptible to spalling than concrete made from aggregates containing a higher proportion of silica, e.g. flint, quartz and granites, due to their permeability. Concrete made from manufactured lightweight aggregates suffer a lesser degree of spalling. The use of high strength concrete has been introduced as it can reduce the necessary thickness required to obtain a certain structural performance. However, high strength concrete is particularly prone to very severe spalling when exposed to fire. As the thickness of the concrete has already been reduced due to its higher strength, the effects of spalling are even more severe than usual.

The latest investigations into alternative methods of protecting concrete against spalling show that the incorporation of fine denier engineered fibres of polypropylene into concrete will – when added in specific volumes and distributed uniformly – reduce the risk of tensile forces causing explosive failure to parent concrete exposed to the most rigorous fire.

The addition of polypropylene fibres to the concrete require an increased amount of plasticiser, the addition of air entraining agents in order to stabilise the concrete and retardants to prolong the concrete's opening time during its application. Results from fire research tests showed that for macro synthetic reinforced concrete, the addition of polypropylene fibres, with a recipe adjusted for this addition, spalling caused by fire can be minimised. It was also found that the addition of polypropylene alone is not enough to minimise spalling as is often presumed. It should be noted very clearly that the precise concrete recipe and the amount of polypropylene fibres is of great importance.

Based on the opinions of a number of researchers, the use of polypropylene fibres for any specific project should be carefully considered, and the specific concrete mix being used in the project subjected to fire testing to ensure the proposed type, dimension and quantity of fibres will provide the requisite fire performance.

As discussed in Section 2.4.3.4 the majority of testing up to the present time on the performance of concrete with the addition of polypropylene fibres has been to the standard ISO cellulosic curve, with a small number of tests performed to the standard Hydrocarbon fire curve (1100°C) and the RWS fire curve (1350°C). In addition, consideration must be given to the fact that not all polypropylene fibres can be considered equal. The fibres used should be identical to those tested with the same concrete as that being used on the project.

Testing has shown that the use of recycled plastic as polypropylene fibres has less effect than purpose-made materials. Care should therefore be taken to ensure claims for the performance of any particular polypropylene or steel fibres are substantiated by adequate evidence of their performance under rapid growth, high temperature fire.

Continued on next page

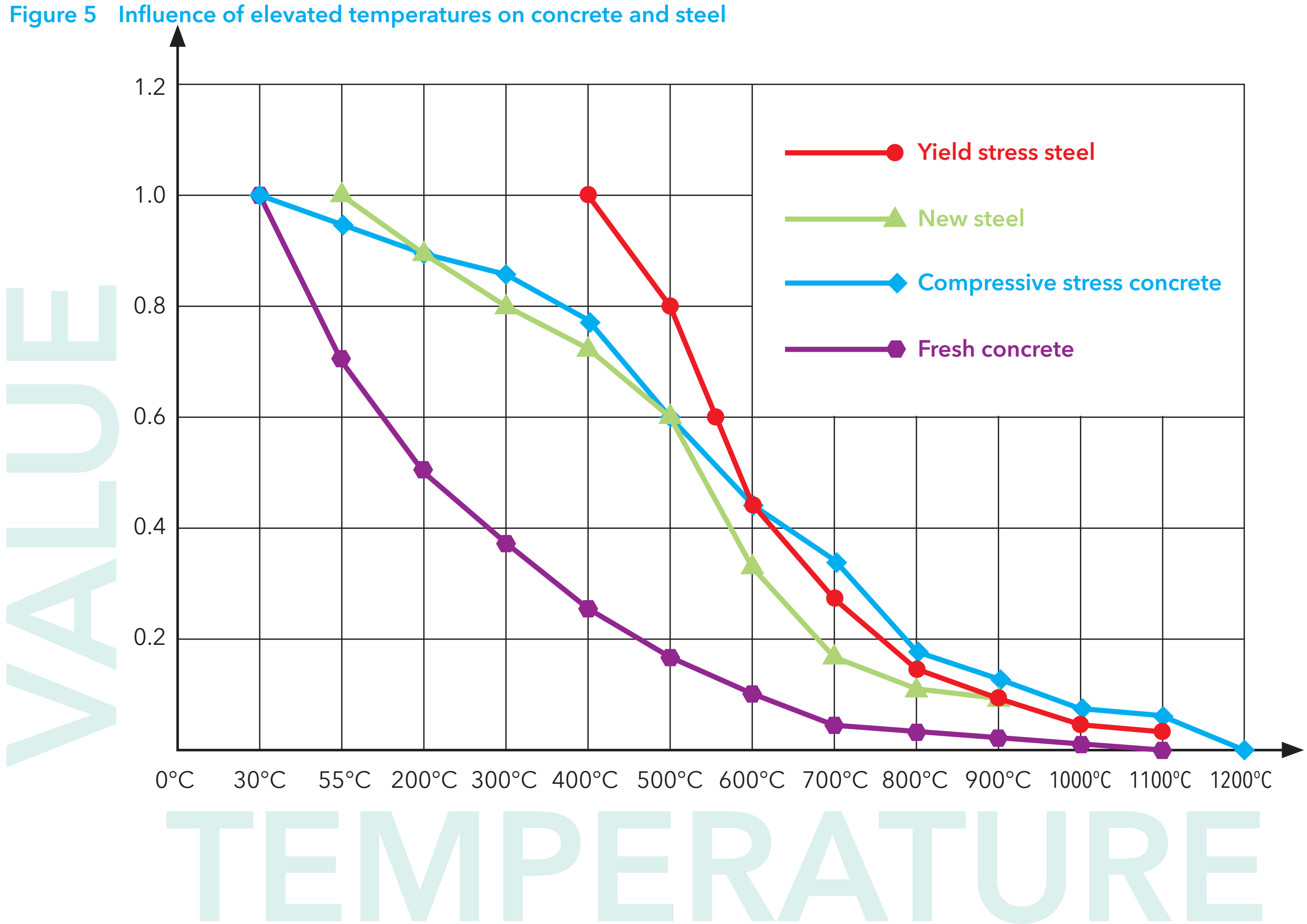
2.3 Spalling

2.3.4 Fire resistance of concrete

Unprotected concrete with a moisture content of over 3% of the mass will suffer surface spalling in a fire, probably after 5-30 minutes. It is also possible for aggregates in the concrete (e.g. quartz) to have undesirable effects on its behaviour in a fire.

The criteria for fire resistance has been drawn up by a number of official bodies. At the tensions at which reinforcing steel is commonly used today, steel starts to lose strength at 500°C.

Figure 5 Influence of elevated temperatures on concrete and steel



Based on the requirements for exposure to an RWS fire curve:

- Temperature on the concrete interface should not exceed 380°C (for some tunnels the limit of this interface temperature could be considerably lower).

RWS-2008-Efectis-R0695 refers to TWO (2) types of testing:

1) For thermal testing the criteria of failure is 380°C on the interface and 250°C on the rebar.

2) For the spalling test it is a requirement to test the actual concrete from the project and proving no spalling.

Other criterias:

- The design of the tunnel section has an effect on fire induced collapse.
- Rectangular tunnels were typically constructed using a grade C30/35 concrete. In more recent times C40/45 is commonly used.
- Failure of rectangular structures is usually due to the premature development of sagging plastic moment caused by elevated temperatures of the concrete and the reinforcement.
- Circular tunnels were constructed from segmented reinforced concrete sections typically use a C50 grade concrete or higher.

2.3.4 Fire resistance of concrete

Continued from opposite page

Other criterias:

- After completion, reinforcement in circular tunnels is more or less obsolete, only required to assist handling during installation.
- The reinforcement in circular tunnels is not required to take tension forces in sagging moment because the concrete is typically in compression.
- The higher strength concrete (C50) suffers a higher percentage and depth of spalling due to fine fillers such as lime stone and fly ash, the reinforcement will however help retard the effect of explosive spalling.
- The depth of spalling under fire conditions is much deeper on these types of circular tunnels.

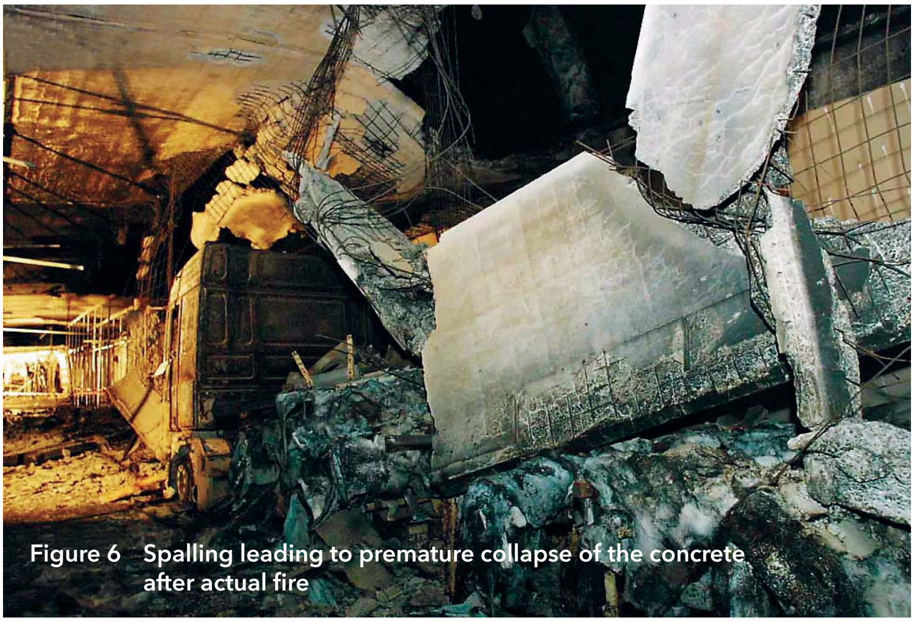


Figure 6 Spalling leading to premature collapse of the concrete after actual fire

Figure 7 Typical lining application of PROMATECT® boards on concrete

2.3.5 Considerations when applying protective materials

In the design of a system to protect concrete, notwithstanding other design requirements the following questions need to be answered to determine the correct material types to be used:

- What type of fire needs to be resisted (e.g. time-temperature curve)?
- How long must the protected structure survive (e.g. duration of time-temperature curve)?
- What is the type of concrete (e.g. cast in place, such as immersed or cut and cover tunnels, prefabricated, circular tunnels) in use?
- The moisture content of the concrete?
- The density of the concrete?
- The aggregates used in the concrete mix itself (e.g. silicious or calcareous)?

The period of time the structure has to be able to survive without failing and the type of fire to be withstood, together determine the thickness of the protection that is required. The requisite protection material thicknesses will be found in the fire test reports provided by the manufacturer of the protective lining materials. These same reports also give guidelines for the points of attachment and the type of fixing to be used.

2.4 Recent innovations in testing

2.4.1 Mobile furnace testing

Figure 8 Efectis full mobile furnace with segment

A mobile furnace is a gas fired insulated device (approximately a 4 x 4 x 3-feet box) which is left open at one of the six sides and can expose a surface to a pre-set time-temperature curve. It has ventilation openings to control the combustible gasses and extract these. It has a sleeve in the side in which a water cooled furnace camera will be installed to be able to visually monitor the performance and behavior of the exposed surface.

The first generation of mobile furnaces were not able to run RWS type fires, for which reason the expected interface time-temperature development was simulated. This was done by running a lower fire curve, with a limited amount of thermal protection on the concrete specimen. The second generation of mobile furnaces however are able to run a full RWS curve, in which case the expected thickness of the thermal protection in practice will be applied for testing.

2.4.1.1 INTERFACE TEMPERATURE VS. REQUIREMENTS

The purpose of these tests are for manufacturers to demonstrate that their proposed fire protection systems meet the temperature requirements.

The advantage of the approach outlined above is that the exact time related spalling temperatures can be defined and that the exact thickness of the passive fire protection system can be determined.

These tests should be compatible with the parameters of the specific tunnel i.e.

- The concrete type and mix design
- The aggregate type (calcareous or siliceous)
- The tunnel diameter
- Anchor type, location, spacing, including washer details
- Joint and gap details between boards
- Mesh type and dimensions, applicable for spray systems
- Concrete surface preparation regimes

Preferably the determination of the exact thickness, based upon the results of the mobile furnace tests, should be done by means of Finite Element calculations.

Mobile furnace tests can be conducted on site, not necessarily in the tunnel, which removes the need for bulky pre-cast segments to be transported to the test laboratory.

The following is a brief description about the Efectis Group and of the Efectis Mobile Furnace test procedure:

Efectis is the expert in fire science, engineering, design and modeling, risk analysis, testing, inspection and certification. Efectis covers all fire safety capabilities and know-how in testing and modeling around the world with offices and laboratories located in France, The Netherlands, Spain, Turkey, USA and the Middle East.

Efectis are the authors of the Rijkswaterstaat (RWS) standard for testing of fire protection for concrete tunnel structures. Many fire tests have been commissioned since the late 1970's, and the Efectis/RWS standard is globally recognized and forms the basis of the relevant requirements in the NFPA 502 standard.

2.4.1.2 THE MOBIFIRE® FURNACE

In 2011, Efectis introduced the MobiFiRe® concept. MobiFiRe® is a mobile fire resistance furnace for on-site testing. The main reasons for its development were the possibility to assess the fire resistance of concrete structures in existing situations, to carry out a number of tests and therefore have a more accurate result, and to avoid expensive and time consuming transportation of large concrete tunnel segments to a fire laboratory.

Different mobile furnaces were constructed to accommodate a range of fire curves, up to the RWS fire curve for tunnels with a maximum of 1350 °C (2462 °F). In the mobile furnaces, Efectis have combined renowned expertise in fire resistance testing with on-site testing. The result of this is a fast and flexible setup which allows the fire test to be performed in a time frame of only a few hours after arrival on site.

Real-time filming from within the mobile furnace allows continuous observation of the tested structure. This can be used to support the analysis of the test. Even more importantly, for concrete test objects observation of the structure enables an instant "stop" of the test when concrete spalling begins. Therefore the damage to the structure can be kept to a minimum. In most cases, only the first few millimetres of the concrete surface need to be repaired.

The test surface of 1 m^2 can be large enough to obtain reliable test results, but small enough to prevent unnecessary damage to the structure. The mobile furnaces can be applied to all kinds of structural elements, such as ceilings, floors, roofs and walls, and is suitable to operate safely even in stand-alone mode with its own gas and electricity supply, data logger and measurement computer.

Key advantages of MobiFiRe®

- Freedom to choose the testing location.
- Testing under fully realistic circumstances.
- Avoid the cost of sending a team to witness a fire test.
- Possibility to test non movable existing structures, such as monuments and tunnels.
- Cost effective selection of passive fire protection system.
- For existing structures, no necessity of 90 days drying time of concrete slabs.
- Easy testing of different alternative fire resistance solutions in real applications.

Projects with application of MobiFiRe®

- Beveren railway tunnel, Antwerp, Belgium
- Kennedy railway tunnel, Antwerp, Belgium
- Koningstunnel, The Hague, The Netherlands
- La Défense tunnel, Paris, France
- Maastunnel, Rotterdam, The Netherlands
- Venray town hall, The Netherlands
- Port of Miami tunnel, USA

3.1 Research & Development drives growth of sophisticated fire protection technologies

Fire protection is divided into two broad categories. These are described as “active” and “passive” systems.

Active fire protection measures are those that use an integrated system consisting of sprinklers and alarms that require electricity, adequate water supply and human intervention to realise their potential in fire situations. Passive fire protection systems do not require power water or human intervention to operate in the event of a fire. They are designed and built into the structure to protect on demand, as and when necessary.

It is the research and development of passive fire protection that Promat has devoted many years and considerable resources. Today, Promat is long recognised worldwide as the leading provider of passive fire protection systems, a reputation reinforced by more than six decades of cutting edge research and development.

Promat runs continual investigation programmes at the Innovation & Technology Centre (ITC) in Avignon, France. The ITC testing laboratories are accredited to EN45001. Its furnaces are state-of-the-art and offer multiple possibilities for the testing of construction systems under development. Promat also has R&D facilities in Austria, Australia, Belgium and Malaysia, which are used extensively to ensure all Promat systems are suited to the global markets we serve.

All Promat materials are manufactured in accordance with accredited EN ISO9001: 2000 and ISO14001 quality and environmental management systems. Comprehensive testing of all Promat products and systems has been carried out by independent and nationally approved laboratories around the world in order to meet the relevant sections of 2008-Efectis-R0695 (RWS), BS476, AS1530, EN, ISO etc, as well as many other international test standards.

The accumulated knowledge and technical expertise is available to all clients and customers who specify Promat passive structural fire protection. Full technical and sales support teams are available to provide information and assistance to help in the design and installation of all Promat fire protection solutions.

Passive + Active – A holistic approach

In some countries, risk and cost benefit analyses are used to consider the application of Fixed Fire Fighting System (FFFS) as a measure to assist in making infrastructure both safer, and more durable in the event of an incident. However, for various political, economic, technical, and social reasons, it is recognised that FFFS may not be the most appropriate measure to adopt in all circumstances.

These reasons can include where a road tunnel has a dedicated fire service to provide a similar response in a timely manner, where government directive asserts that FFFS will not be applied in that particular country’s tunnels, or where FFFS will not be maintained and operated to the degree of reliability and availability required. Where FFFS are installed, it is critical that they be correctly designed, installed, integrated, commissioned, maintained, tested, and operated with a high level of reliability and availability, so that the systems are available for use as required.

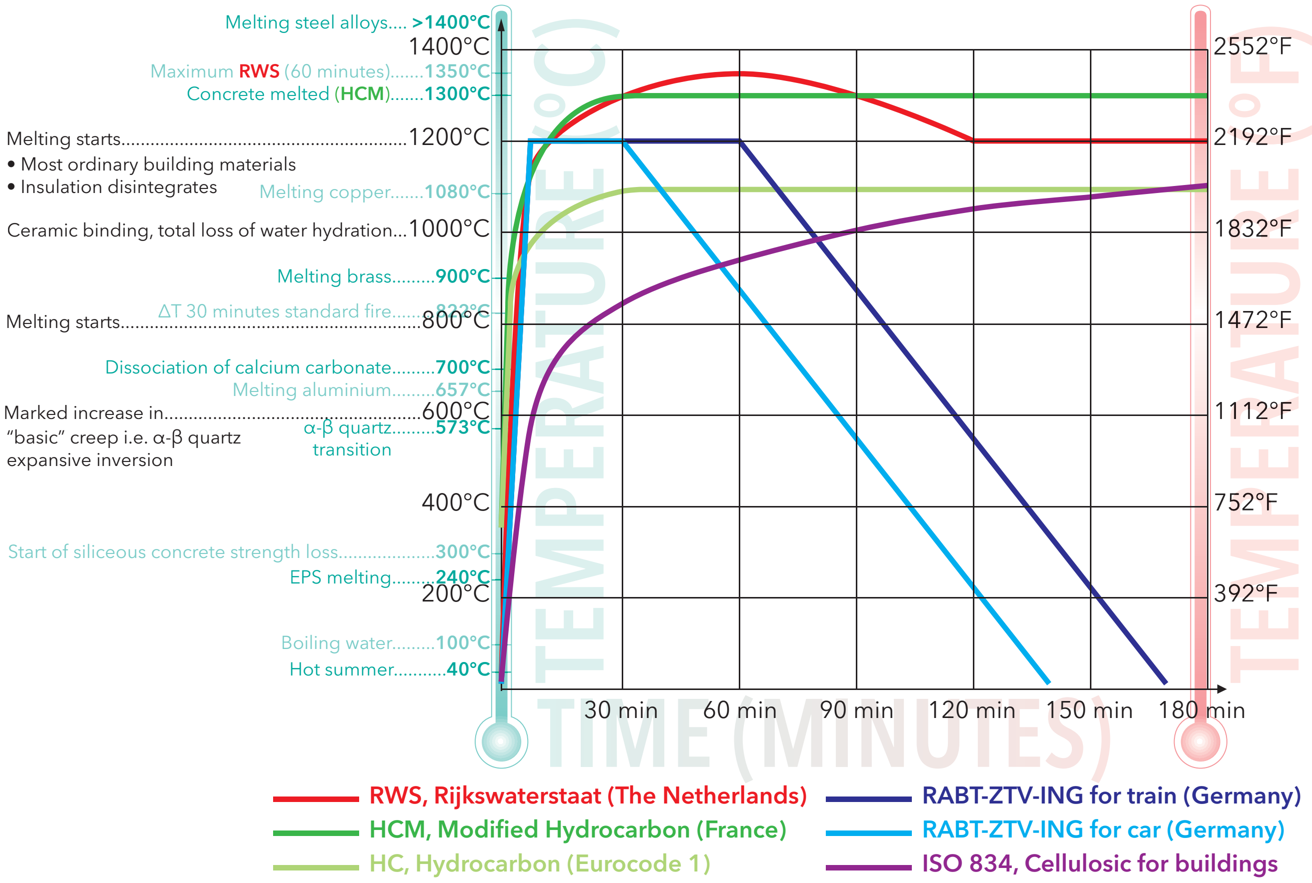
FFFS reacts to conditions caused by a fire such as heat, smoke or light and then tries to control the blaze. This is usually done either by drenching via a sprinkler system, by creating a warning via a smoke alarm, or by activating a fire defence system such as a fire curtain amongst others.

FFFS systems are undoubtedly very effective, but have the inherent disadvantage of being dependent upon each of the various elements of the chosen system working, as and when they should. Any vandalism of the water feed mechanism, damage to the operating valves, lack of maintenance or simply ignorance, can render the system inoperative. It would be unwise, therefore, to construct a tunnel’s fire defence around a single system that cannot always be guaranteed.

A passive fire protection system, insulates the structure against exposure to extreme heat from fire, thereby preventing the tunnel from any type of collapse. Such protection can buy significant time for the tunnel users to escape.

It is also the time in which fire fighting services can arrive at the scene, safely enter and remain in the tunnel in order to contain and extinguish the conflagration.

Figure 9 Comparison of time-temperature curves and the behavior of some common materials at high temperatures



Many passive fire protection materials also provide added benefits such as thermal and acoustic insulation. However, to optimise fire protection, active and passive systems should be seen as complementary, not competitive. Legislation frequently recognises this by allowing them to work in tandem.

3.2 Design fire

In recent years, a great deal of research has been undertaken internationally to ascertain the types of fire which can occur in tunnels and underground spaces. This research has taken place in both real tunnels, and under laboratory conditions. As a consequence of the data obtained from these tests, a series of time/temperature curves for the various exposures have been developed and are detailed in Figure 9.

Whilst research in tunnel fire phenomena continues, it should be noted that existing data indices show that the severity of fires within tunnels is higher than would be experienced in open air conditions as well as normal buildings. By comparing heat release rate (HRR) data (understood by many to be a good measure of fire severity) from tests carried out on different vehicle types, wooden crib fires, fuel oil tray experiments etc, and comparing the results from tests within tunnels to those with the same tests carried out in the open air, the conclusion is that a tunnel can increase the HRR for a given fire load by up to four times. Further experimentation shows that the increase will vary with the ratio of the fire width to the tunnel width in a cubic manner.

The methods of ventilating a tunnel can also have a marked effect on the HRR of the burning items, and thus should be factored in to any proposals when designing the type and period of fire protection being specified.

3.2 Design fire

3.2.1 Cellulosic fire curve

Standard fire tests to which most specimens of elements of construction are subjected are based on the use of the Cellulosic time-temperature curve, as defined in various national standards, e.g. ISO 834, E119, BS 476: Part 20, DIN 4102 and AS 1530. Although there are other types of fire test curves, e.g. BS 7436, the curve as detailed below is the lowest used in normal practice. This curve is based on the burning rate of the materials found in general building materials and contents.

Table 1 Cellulosic fire curve

Time	Furnace temperature	Time	Furnace temperature
0 minute	20°C	90 minutes	1006°C
5 minutes	576°C	120 minutes	1049°C
10 minutes	678°C	150 minutes	1082°C
15 minutes	738°C	180 minutes	1110°C
20 minutes	781°C	210 minutes	1133°C
30 minutes	842°C	240 minutes	1153°C
45 minutes	902°C	300 minutes	1006°C
60 minutes	945°C	360 minutes	1006°C

The time period for Cellulosic fires, with durations of tests up to six hours, is far in excess of those for Hydrocarbon and RWS fires. However, the much slower rise in temperature leads to much less damage on concrete structures. The temperature development of the Cellulosic fire curve is described by the following equation:

$T = 20 + 345* \text{Log}(8*t + 1)$

3.2.2 HC, Hydrocarbon fire curve

Although the Cellulosic fire curve has been in use for many years, it soon became apparent that the burning rates for certain materials, e.g. petrol, gas, chemicals etc, were well in excess of the rate at which, for instance, timber would burn. As such there was a need for an alternative exposure for the purpose of carrying out tests on structures and materials used within the petrochemical industry. Thus the Hydrocarbon fire curve was developed. Initially, this time-temperature curve was developed separately by various gas and oil companies. All had slight differences.

However, the curve as detailed in page 21 (Figure 9) reflects the relationship between time and temperature generally used in contemporary testing today. The Hydrocarbon fire curve is applicable where small petroleum type fires might occur, e.g. car fuel tanks, petrol or oil tankers, certain chemical tankers.

Although the Hydrocarbon fire curve is based on a standardised type fire, there are numerous types of fire associated with petrochemical fuels, some of which are detailed below:

- Cloud fire
  A transient fire resulting form the ignition of a cloud of gas or vapour and not subject to significant flame acceleration via the effects of confinement or turbulence. It can therefore only occur after a relatively slow release of hydrocarbon and in an open, free space.

- Fireball
  The rapid turbulent combustion of fuel as an expanding, usually rising ball of flame. It is more intense than a cloud fire and can be close to an explosion.

- BLEVE
  A Boiling Liquid Expanding Vapour Explosion which results from the sudden failure of a vessel containing a pressurised liquid at a temperature well above its normal (atmospheric) boiling point, e.g. LPG tanker.

- Pool fire
  A turbulent diffusion fire burning above a horizontal pool of vapourising fuel under conditions where the fuel vapour of gas has zero or little initial momentum. A burning pool fire is extremely difficult to control. It may accompany a jet fire where burning liquid is spilling from the jet stream.

- Running fire
  A fire from a burning liquid which flows by gravity over surfaces, such as following the slope or camber of a road tunnel.

- Spray or jet fire
  A turbulent diffusion flame resulting from the combustion of a fuel continuously released with some significant momentum in a particular direction.

Table 2 Potential duration of fire

Fire types	Potential duration
Cellulosic fire	Hours
Hydrocarbon fire, cloud fire	Seconds
Hydrocarbon fire, fireball or BLEVE	Seconds
Hydrocarbon fire, pool fire	Hours
Hydrocarbon fire, running fire	Hours
Hydrocarbon fire, spray fire	Hours
Hydrocarbon fire, jet fire	Minutes

Hydrocarbon fires are different from Cellulosic in the manner in which the temperature increase is far more rapid and that after the initial 30 minute rise, the temperature follows an almost straight horizontal line. It is the rapidity of the rise in temperature that poses the greatest risk to a tunnel structure. The temperature development of the hydrocarbon fire curve is described by the following equation:

$T = 20 + 1080* (1 - 0.325*e^{-0.167t} - 0.675*e^{-2.5t})$

Table 3 HC, Hydrocarbon fire curve

Time	Furnace temperature	Time	Furnace temperature
3 minutes	887°C	60 minutes	1100°C
5 minutes	948°C	90 minutes	1100°C
10 minutes	1034°C	120 minutes	1100°C
30 minutes	1098°C	>120 minutes	1100°C

The figures given in above table should not be confused with those relating to those of the Modified Hydrocarbon fire curve in below table now used in some countries. The latter has a temperature rise similar to that of the RABT, but with a higher maximum temperature, reaching 1300°C, only slightly under that achieved using the RWS curve. This Modified Hydrocarbon exposure is part way between RWS and RABT requirements and is much more severe than exposure to the standard Hydrocarbon fire curve detailed within such standards as UL 1709, AS 1530: Part 4: Appendix B, BS 476: Part 20: Appendix D etc. The temperature development of the Modified Hydrocarbon fire curve is outlined by the following equation:

$T = 20 + 1280 * (1 - 0.325 * e^{-0.167t} - 0.675 * e^{-2.5t})$

Table 4 HCM, Modified Hydrocarbon fire curve

Time	Furnace temperature	Time	Furnace temperature
3 minutes	1047°C	60 minutes	1300°C
5 minutes	1120°C	90 minutes	1300°C
10 minutes	1222°C	120 minutes	1300°C
30 minutes	1297°C	>120 minutes	1300°C

3.2.3 RABT-ZTV-ING fire curve

The RABT-ZTV-ING fire curve was developed in Germany as a result of a series of tunnel fire test programmes such as the Eureka project. In the RABT-ZTV-ING curve, the temperature rise is very rapid up to 1200°C within five minutes, faster than the Hydrocarbon fire curve which rises to 1100°C. The duration of the 1200°C exposure is shorter than other curves with the temperature drop-off starting to occur at 30 or 60 minutes, see page 21 (Figure 9). The RABT-ZTV-ING fire curve can be adapted to meet specific requirements. In testing to this exposure, the heat rise is very rapid, but is only held for a period of 30 minutes, similar to the sort of temperature rise expected from a single truck fire, but with a cooling down period of 110 minutes. If required, for specific types of exposure, the heating period can be extended to 60 minutes or more, but the 110 minute cooling period would still be applied. The inclusion of the controlled cooling period after the 30 and 60 minute period or heating is very important, as the cooling process can often lead to rapid deterioration of the concrete or any protection system.

Table 5 RABT-ZTV-ING fire curve

Time	Furnace temperature	Time	Furnace temperature
0 minute	15°C	30 minutes	1200°C
5 minutes	1200°C	140 minutes	15°C

3.2.4 RWS (Rijkswaterstaat) fire curve

The RWS fire curve was developed by the Rijkswaterstaat in the Netherlands. This curve is based on the assumption that in a worst case scenario, a fuel oil or petrol tanker with a fire load of 300MW lasting up to 120 minutes could occur. The RWS fire curve was based on the results of testing carried out by TNO in the Netherlands in 1979.

The difference between RWS and Hydrocarbon fire curves, bearing in mind that they both use similar fire load materials, is that the latter is based on the temperatures that would be expected from a fire occurring within a relatively open space. Where some dissipation of the heat occurs, however, the RWS fire curve is based on the level of temperature expected when a fire occurs in an enclosed area, such as a tunnel, where there is little or no chance of heat dissipating into the surrounding atmosphere. The RWS fire curve simulates the initial rapid growth of a fire using a petroleum tanker as the source, and the gradual drop in temperatures to be expected as the fuel load is burnt off.

In the Netherlands, the RWS fire curve is applied for durations up to 120 minutes, at which time it is assumed the fire load has reduced sufficiently for fire fighting personnel to be able to gain access to the source and start their attempts to extinguish the fire. However, in Switzerland, where tunnels through mountains tend to be far longer in length and more remote in location, the RWS fire curve is also applied, but often extended to 180 minutes exposure. The failure criteria for specimens exposed to the RWS time-temperature curve is that the temperature of the interface between the soffit of the concrete and the protective covering should not exceed 380°C and the temperature on the reinforcement should not exceed 250°C. For certain types of high performance, e.g. high strength concretes, it has been found through testing that interface temperatures as low as 200°C are required in order to prevent the concrete from spalling.

In the context of a European research programme on tunnel safety, comprehensive large scale tests were carried out in the abandoned Runehamar road tunnel in the western part of Norway in September 2003. Semi-trailer fires, similar in size to the fires occured in both Mont Blanc and St. Gotthard tunnels, were a particular consideration. The Runehamar tests were conducted by the Swedish National Testing & Research Institute (SP) in collaboration with partners UPTUN: TNO Building & Construction Research from the Netherlands and the Norwegian Fire Research Laboratory (SINTEF/NBL).

Table 6 RWS (Rijkswaterstaat) fire curve

Time	Furnace temperature	Time	Furnace temperature
3 minutes	890°C	60 minutes	1350°C
5 minutes	1140°C	90 minutes	1300°C
10 minutes	1200°C	120 minutes	1200°C
30 minutes	1300°C	>120 minutes	1200°C

See Appendix page 61 for the complete information of Runehamar tests and gas temperatures in collaboration with UPTUN: Large scale fire test in Runehamar Tunnel, Norway.

3.3 Specification of NFPA-502 2017 Edition standard

Regardless of tunnel length, acceptable means shall be included within the design of the tunnel to prevent progressive collapse of primary structural elements in accordance with this standard to achieve the following functional requirements in addition to life safety:

- Support firefighter accessibility
- Minimize economic impact
- Mitigate structural damage

The structure shall be capable of withstanding the temperature exposure represented by the Rijkswaterstaat (RWS) time-temperature curve or other recognized standard time temperature curve that is acceptable to the Authority Having Jurisdiction (AHJ) after an engineering analysis.

During a 120 minute period of fire exposure the following failure criteria shall be satisfied:

i) Regardless of the material the primary structural element is made of, irreversible damage and deformation leading to progressive structural collapse shall be prevented.

ii) Tunnels with concrete structural elements shall be designed such that fire-induced spalling, which leads to progressive structural collapse, is prevented.

Structural fire protection material, where provided, shall satisfy the following performance criteria.

a) Tunnel structural elements shall be protected to achieve below performance:

- The concrete is protected such that fire-induced spalling is prevented.
- The temperature of the concrete surface does not exceed 380°C (716°F).
- The temperature of the steel reinforcement within the concrete (assuming 25mm/1 inch) does not exceed 250°C (482°F).
- The lining temperature for steel or cast iron structural elements will not exceed 300°C (572°F).

b) The material shall be non combustible in accordance with ASTM E136 (standard test method for the behaviour of materials in a vertical tube furnace at 750°C) or by complying with internationally accepted criteria acceptable for the AHJ when tested in accordance with:

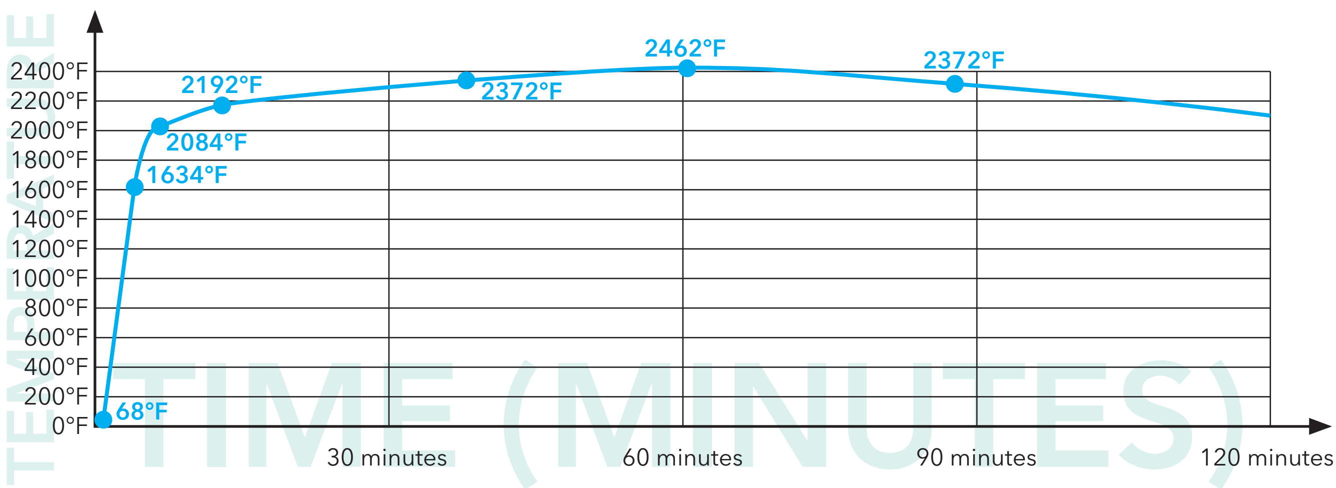
- ASTM E2652 (standard test method for the behaviour of materials in a tube furnace with an air flow stabilising cone shaped 750°C),
- ISO 1182 (reaction to fire tests for products – non combustibility test) or
- BS 476: Part 4 (non combustibility test for materials).

c) The material shall have a minimum melting temperature of 1350°C (2462°F).

d) The material shall meet the fire protection requirements with less than 5% humidity by weight and when fully saturated with water, in accordance with the approved time–temperature curve.

Both PROMATECT®-H RWS-HCM and PROMATECT®-T matrix engineered calcium silicate-aluminate board lining fire protection systems meet or exceed the requirements of NFPA-502 2017 Edition Standard for road tunnels, bridges and other limited access highways.

Figure 10 Rijkswaterstaat (RWS) time-temperature curve in accordance with NFPA-502 2017 Edition Standard for road tunnels, bridges and other limited access highways



3.4 Time-temperature curve versus Megawatts

Information of this section is sourced from *ITA Working Group 6 – Structural fire protection for road tunnels, Report No. 18. April 2017.*

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

Passive structural 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:

3.4.1 Height and width of the tunnel

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.

3.4.2 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 to 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.

3.4.3 Location of 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.

3.4.4 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.

3.4.5 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.

3.4.6 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.

Continued on next page

3.4 Time-temperature curve versus Megawatts

3.4.6 Recent research and modelling

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.

Recent research has however revealed the possibility to calculate the maximum ceiling temperature, based on some of parameters 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. Based on the simplified models, they 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 positioned 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.

3.4.7 Concerns about megawatt output of bus fires

There is a growing concern about the rather low megawatt (MW) predictions of bus fires which are listed in several national and international standards and guidelines.

See page 30 for more information and the result of jet fire/hose stream testing conducted by Promat to anticipate different fuels such as the MW output of bus fires.

Table 7 Simplified models of Heat Release Rate (HRR)

Height of tunnel	Elevation of fuel-load	Area of fire	Heat Release Rate (HRR)	Maximum temperature	Types of vehicle: Area of fire
4.5m	1	7.2m^2	5MW	206°C*	Car: 1.6m x 4.5m
4.5m	1	9.0m^2	15MW	558°C*	Minivan: 1.8m x 5.0m
4.5m	1	38.3m^2	35MW	1006°C*	Bus (small/old): 2.55m x 15.0m
4.5m	1	38.3m^2	50MW	1350°C	Bus (new/ski): 2.55m x 15.0m
4.5m	1	38.3m^2	50MW	1350°C	LGV: 2.55m x 15.0m
4.5m	1	38.3m^2	100MW	1350°C	HGV: 2.55m x 15.0m

* Higher if the flame touches the wall

3.5 Overview of various international performance requirements

Throughout the world, fire development in a tunnel will be the same under the exact same circumstances. In other words, how would the fire know in which country the tunnel is located? The same applies to the structural lining and other materials that should survive a tunnel fire, e.g. cables, fire doors. The same material will behave in the same manner under the exact same fire circumstances, regardless of the country it is in.

In light of this commonality, a degree of harmonisation of fire protection requirements for tunnels might be a reasonable expectation. However, below table indicates that there are still substantial differences in requirements, in terms of design fire curves and thermal failure criteria for concrete protection. Although the EU research programmes (UPTUN, DARTS, FIT etc) have contributed a lot to harmonisation, there is still much work to be done in this respect.

Country	Code/ standard	Traffic type	Fire curve	Construction method	Concrete type	Temperature criteria
Austria	OVBB	All types	RWS, 3 hours	Any methods	All types	• T interface <350°C • T rebar <250°C at 40mm concrete cover
France	CETU	Road	• N0: None • N1: ISO 2 hours • N2: HCM 2 hours • N3: ISO 4 hours and HCM 2 hours	Any methods	All types	Bus (new/ski): 15m^2 @ 2.55°C
Germany	RABT-ZTV	Road	RABT 30+110 cooling down	Any methods	All types	T rebar <300°C
		Rail	RABT 60/90+110			

Continued from opposite page

Country	Code/ standard	Traffic type	Fire curve	Construction method	Concrete type	Temperature criteria
China	GB 50016	Hazardous goods	• L >1500m; RABT 120+110 • L >500mm yet ≤1500m; RABT 90+110 • L ≤500mm; HC, 2 hours	Any methods	All types	• RABT: T interface <380°C • RABT: T rebar <300°C at 25mm concrete cover • HC: T interface <380°C • HC: T rebar <250°C at 25mm concrete cover
		Non hazardous goods	• L >3000m; RABT 120+110 • L >1500mm yet ≤3000m; RABT 90+110 • L >500mm yet ≤1500m; HC, 2 hours			
Italy	UNI 11076	All types	RWS	Any methods	All types	• T1: T rebar average <200°C, maximum <250°C • T1: T interface average <330°C, maximum <380°C • T2: T rebar average <250°C, maximum <290°C • T2: T interface average <380°C, maximum <420°C • T3: T rebar average <300°C, maximum <350°C • T3: T interface average <430°C, maximum <460°C
The Netherlands	RWS 2008-Efectis-R0695	Road	RWS	• Immersed, cut-and-cover (C&C) • Bored or drilled	• Cast in place • Pre-fabricated	• T interface <380°C • T rebar <250°C at 25mm concrete cover • No spalling
Singapore	LTAS	Road, e.g. KPE Tunnel	RWS	Immersed	Cast in place	• T interface <380°C • T rebar <250°C
UAE	Unspecified	Road, e.g. Palm Jumeirah Tunnel	RWS	Cut-and-cover (C&C)	Cast in place	• T interface <380°C • T rebar <250°C
UK	BD78/99	Road	RWS	• Immersed, cut-and-cover (C&C) • Bored or drilled	• Cast in place • Pre-fabricated	• T interface <380°C • T rebar <250°C at 25mm concrete cover • No spalling
USA	NFPA 502	Road	RWS	• Immersed, cut-and-cover (C&C) • Bored or drilled	• Cast in place • Pre-fabricated	• T interface <380°C • T rebar <250°C at 25mm concrete cover • No spalling

4.1 Bored tunnel using concrete segments

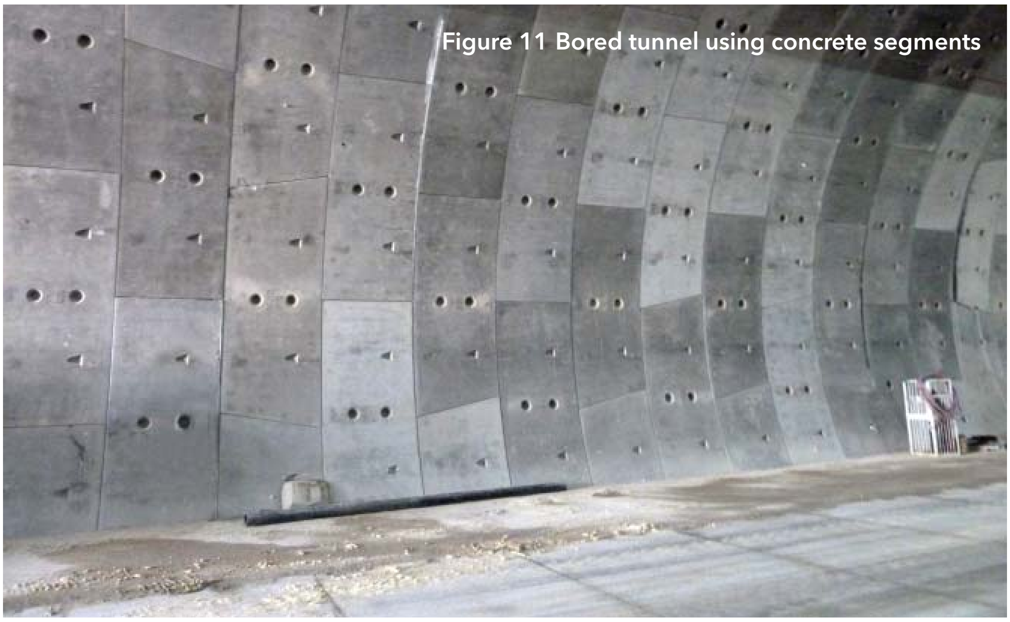


Figure 11 Bored tunnel using concrete segments

A bored tunnel refers to a construction method for tunnels which involves drilling a tube-like passage through the earth. It usually refers to tunnelling through rock, as blast tunnelling is no longer widely used. Bored tunnels are created using a full face boring machine which has cutting teeth at its front. It creates the tunnel opening while passing waste material through to the rear. Many types of tunnel boring cut small sections which are progressively enlarged. A full face tunnel boring machine (TBM) cuts the complete cross section of the tunnel in one pass.

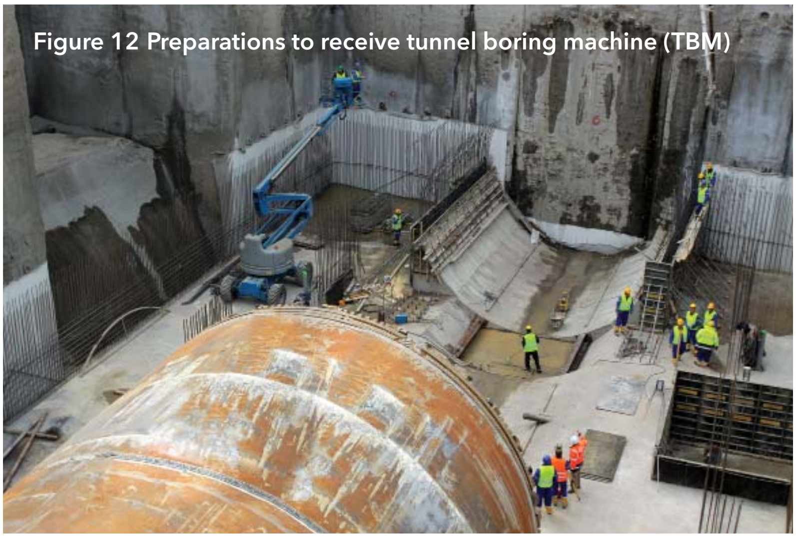


Figure 12 Preparations to receive tunnel boring machine (TBM)

The TBM consists of a long machine with a circular cutting head that rotates against the face of the tunnel. Attached to the cutting head is a series of steel alloy disk cutters that gouge out the rock on the face as the machine rotates. The cutting head is pushed forward by hydraulic power. TBM provides several advantages over drilling and blasting. The tunnel can be bored to the exact size desired, with smooth walls, thus eliminating the condition called overbreak, which results when explosives tear away too much rock.

Figure 13 Reinforced shaft and TBM

The use of TBM also eliminates blasting accidents, noise, and earth shocks. Workers need not be concerned with fumes or noxious gases and can clear away broken rock without stopping for blasting intervals. A TBM can advance about 76 metres (about 250 feet) a day, depending on the diameter of the tunnel and local geology. Despite these advantages, TBM has some drawbacks. They are very costly and the cutting head must be the same diameter as that required for the tunnel.

Often the TBM is part of a long train of machines. At the rear are stored circular concrete sections, which are installed as the TBM moves along its preplanned route. In this way, the tunnel is simultaneously lined as it is drilled.

4.2 Immersed tunnel

The immersed tube is a construction method using pre-fabricated tunnel sections. While the ends of each section are sealed, it is lowered into position under the water and attached to other sections. It is sometimes called a sunken tube.

Another method of underwater tunnel construction uses a caisson, or watertight chamber, made of wood, concrete or steel. The caisson acts as a shell for the building of a foundation. The choice of one of three types of caissons – the box caisson, the open caisson or the pneumatic caisson – depends on the consistency of the earth and the circumstances of construction. Difficult conditions generally require the use of the pneumatic caisson, where compressed air is used to force water out of the working chamber.

Figure 14 Immersed tunnel

Another method of constructing underwater tunnels, such as those like the Noord tunnel in the Netherlands, have been built by fabricating short tunnel sections in a trench in or near the riverbed or seafloor. Each section, after completion is then sealed at the ends, floated out and located in position, where it is then sunk onto the river or sea bed. After submerging, the sections are then attached in line by oversized bolts to the previously sunk section. Heavy, thick concrete walls prevent the tunnel from floating once the water is pumped from the completed sections.

4.3 Cut-and-cover (C&C) tunnel

Figure 15 Cut-and-cover (C&C) tunnel

A construction method which involves excavating a large trench, building a roof structure, then covering it with earth. Commonly used for subways and in relatively flat locations.

Cut -and-cover method can be constructed in various ways. Examples of this method can be either top down or bottom up.

Promat recognises that road tunnel linings may be required to meet prescriptive light reflectance requirements. They must also be resistant to regular mechanical cleaning operations to remove surface contaminants such as dust from rubber tyres in order to prevent flash fires from occurring.

Both PROMATECT®-H RWS-HCM and PROMATECT®-T have been developed to meet all these requirements. The products inorganic, non combustible matrix engineered mineral boards reinforced with selected fibres and fillers, which will provide thermal performance and resistance to both hot and cold thermal shock from simultaneous fire exposure and, when treated with suitable coatings, water impingement from fire hoses or fixed firefighting systems. Both PROMATECT®-H RWS-HCM and PROMATECT®-T materials will prevent concrete linings from spalling and structural steel elements from weakening during exposure to the intense heat generated in a tunnel fire.

5.1 Application of protective materials

In the design of a system to protect concrete, the following questions need to be answered to determine the correct material types to be used.

- What type of fire needs to be resisted? For example, the time/temperature.
- How long must the protected structure survive? For example, the duration of time/temperature curve.
- What type of concrete? For example, cast in place (immersed or C&C tunnels), prefabricated or circular tunnels.
- How is moisture content of the concrete?
- What is density of the concrete?
- What are the aggregates used in the concrete mix itself? For example, silicious or calcareous.

The period of time the structure has to be able to survive without failing and the type of fire to be withstood, together determine the thickness of the protection that is required. The requisite protection material thicknesses will be found in the fire test reports provided by the manufacturer of the protective lining materials. These same reports also give guidelines for the points of attachment and the type of fixing to be used.

Jet fire/hose stream testing

Many larger vehicles are relying on different fuels such as Compressed Natural Gas (CNG) ITA Working group 6 go on to say about buses (see adaption on opposite page).

Based on such information, and in anticipation of more rigorous testing for the different fuels being used and hence our tunnel structures being threatened, Promat has already conducted jet fire/hose stream testing in accordance with ISO 22899-1. To simulate fire fighting activities Promat has also undertaken hose stream testing in accordance with ASTM E119-07 (ave pressure 2.8 BAR).

Figure 16 Jet fire and hose stream testing *(right)*

"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."

5.2 Board materials for fire protection tunnel lining

Board materials can be easily checked for thickness and thus the application can be guaranteed to meet with the specifications as per the tested constructions. Many independent tests demonstrate that these boards, being mechanical fixed are not aff ected by suction and wind loading from passing traffic with boards remaining in place without any adverse effects. Boards are completely unaffected by combustion by-products of traffic passing through tunnels, and are also unaffected by casual water if they become wet and subsequently dry out. With waterproof coating they can also be used as a conduit for water, ensuring the excess runs off into the tunnel drainage system rather onto the road surface.

Board protection systems will also act as a form of filter during exposure to fire, ensuring that chlorine and other gases given off by burning rubber and plastic used in the construction of modern vehicles, and which are extremely corrosive in nature, do not have direct access to attack the concrete and reinforcement of the tunnel linings.

Using PROMATECT® board products ensures that condensation as a result of wet tunnels does not form on the exposed surface of the boards, but rather this small amount of moisture is absorbed by the boards and then evaporated into the surrounding air. The absorption of water into PROMATECT® boards has no adverse effect on their performance once dry.

Board systems in general require little maintenance. Where access is required to periodically inspect the concrete substrate, boards can quickly and easily be removed and reinstated, thus maintaining the fire protection layer at all times.

Following criteria for thermal failure can be specified in order to correctly and adequately design the required material type and thickness:

- Maximum allowable interface temperature.
- Maximum allowable temperature of the reinforcement, along with the cover on the reinforcement.
- Maximum allowable interface heating rate (°C per minute).
- Maximum allowable temperature of the unexposed side of the concrete slab, in case of escape route protection.

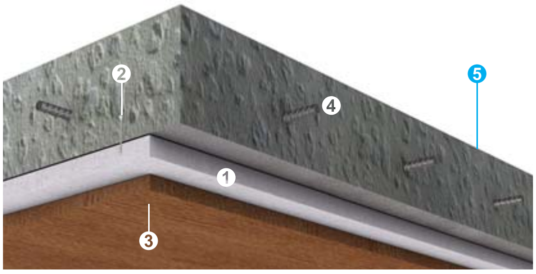
Depending on the specific project related requirements a combination of the above thermal design criteria can be made.

Table 8 Comparison of fire protection solutions for tunnel and underground structures

Item	Passive systems	PP fibres	Fixed fire-fighting systems
Rebar insulation	Fully insulated to predetermined and predesigned maximum critical temperature requirements.	No rebar insulation.	No rebar insulation.
Insulation to structure	Limit heat input into the tunnel structure, preventing damage and/or collapse.	Do not prevent heat input into the structure. Collapse can occur rapidly under severe fire exposure.	No insulation to structure.
Bond between steel and concrete	Maximum temperatures not exceeded at reinforcement.	At 300°C the bond between rebars and concrete will significantly reduce.	At 300°C the bond between rebars and concrete will significantly reduce.
Replacement of concrete after fire	Only the passive system itself must be replaced after severe fire event.	All concrete exposed to temperatures exceeding 380°C must be replaced. Even in event of small fire (T interface >160°C) repairs will be required because the PP fibres will have melted.	Systems will incur damage in event of fire and will need repair or replacement after a major fire. They are only effective if activated within minutes of fire outbreak.
Long term durability, chlorides	No adverse effect on the durability of concrete structures.	PP fibres create small channels in the concrete, due to the hydrophilic properties, enabling chlorides and sulphates to penetrate the concrete and attack the rebars.	Not applicable.
Area of post fire event damage	Relatively small area of damage.	Post fire event (T interface >380°C), damaged area will extend beyond area directly affected by fire.	Can only reduce damage to tunnel structure if activated soon after fire commences.
Spalling prevention	Designed to reduce temperature increase on and within concrete structure, are therefore able to prevent spalling.	All tests with PP fibres to date show spalling of the concrete specimen. PP fibres do not stop structural damage, due to high temperatures (micro cracks occur even at 150°C).	Spalling only prevented if WBFSS activated within minutes of fire outbreak by suppressing the fire.
Influence on concrete properties	No adverse affect on concrete structural properties.	PP fibres reduce compressive strength leading to brittle failure. Melted fibres will also lead to reduced pull out strength of anchors.	Only effective with early activation.
Affect on workability of concrete	No adverse effect on the workability of concrete.	Workability decreases with increasing concentration of fibres. 3kg/m^3 of fibres dehydrates the concrete mixture severely, making it difficult to pump or pour.	Not applicable.
Ability to withstand range of fires	Able to withstand all types of fires, up to the most severe RWS fire.	Even a smouldering fire will cause dehydration of the top layer, causing aggressive spalling as temperatures increase.	Not proven to be effective in large fires, e.g. multi-vehicle or HGV fires. Not all systems tested to severe fires, e.g. RWS, HCinc.
Influence on the clearance of the tunnel cross section	Passive systems are relatively thin, <60mm depending on requirements.	Require larger cross sections, bigger TBM, more tubing segments, larger volumes of excavated soil etc. Sacrificial linings containing PP fibres can be over 250mm thick.	Will not influence tunnel cross section but require adequate clearance for piping and nozzles.
Quality control	Produced under quality controlled conditions.	Quality control problematic because the requirement to achieve even distribution of PP fibres throughout the concrete mix is difficult to achieve on site. This may lead to unpredictable performance.	Components may be produced in controlled facilities, but performance and reliability are dependent on ongoing service and maintenance.

6.1 Lost formwork method

Figure 17 PROMATECT®-H RWS-HCM boards laid with the smooth face down using lost formwork *(see illustration at the right)*



1. One layer of 27.5mm thick PROMATECT®-H RWS-HCM boards
2. Stainless steel screw
3. Loadbearing formwork
4. Steel reinforcement
5. Tunnel concrete slab

6.1.1 Lost formwork with horizontal PROMATECT®-H RWS-HCM boards directly fixed on tunnel concrete slab

Application of lost formwork is installed as follows:

i) Laying the boards on the loadbearing formwork

The PROMATECT®-H RWS-HCM boards should be laid with the smooth face down (Figure 17) as this will provide the fair faced finish after completion of the tunnel. It is very important to align the first row of boards alongside a straight edge reference marker, which is screwed to the formwork (Figure 18). The rest of the boards are laid next to each other, with butt joints, utilising the previous row as the next starting point or datum. No special treatment on the joints is required (Figure 19).

If the dimensional and squareness tolerances on the boards are too large, gaps occur while laying the boards as the tolerances tend to accumulate and add up. In order to avoid this effect, the boards are cut to tight tolerances in the factory, such that gaps in between the boards will be minimised. Where the tunnel is designed with sloped sections, the so-called haunches, the edges of the boards are simply cut at an angle and installed butt jointed (Figure 20).

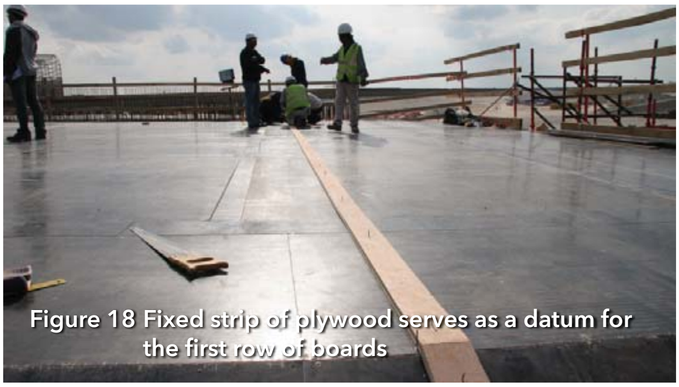


Figure 18 Fixed strip of plywood serves as a datum for the first row of boards

In order to minimise tolerances by cutting on the job site, there are two options. One is to lay the boards on the formwork, draw the cutting line (e.g. at the end of a section) and cut all boards in one go alongside a datum on the formwork. The second option is to pre-cut the boards in a dedicated on site workshop. The boards can either be installed using staggered joints or straight joints. Experience from contractors indicates that staggered joints result is less gaps between the boards This method allows compensation for certain tolerances, whereas the straight joint method does not allow for much compensation.

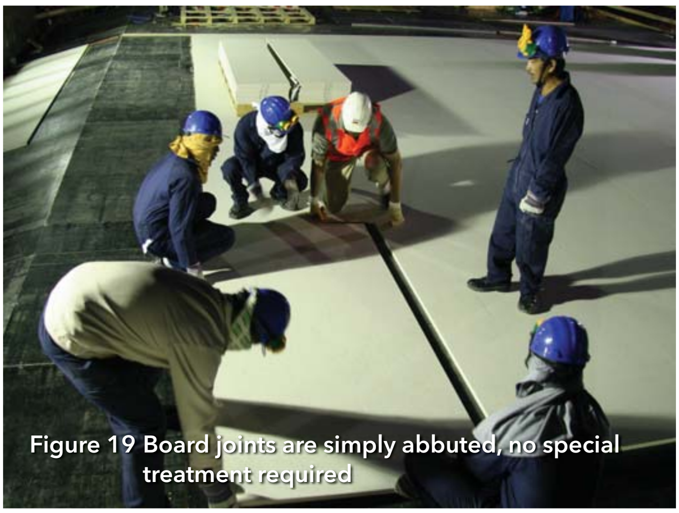


Figure 19 Board joints are simply abbuted, no special treatment required

Figure 20 Boards cut to an angle at the haunches

Locations of the screws are marked on the boards as shown at right, using a template and a spray can of paint.

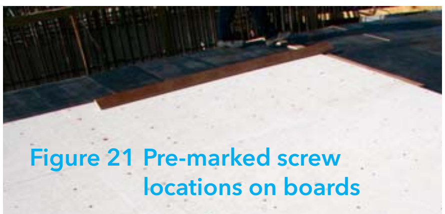


Figure 21 Pre-marked screw locations on boards

6.1 Lost formwork method

6.1.1 Lost formwork with horizontal PROMATECT®-H RWS-HCM boards directly fixed on tunnel concrete slab

ii) Installing the first layer of reinforcement

Prior to inserting the stainless steel screws, the first layer of reinforcement should be installed on the stools (spacer blocks creating concrete cover thickness). In this way the screws are always protected from foot traffic (Figure 22).

iii)Inserting stainless steel screws partially in the boards

50mm long screws are inserted to a depth of 20mm, through the openings in the reinforcement; the remaining 30mm projects out of the board creating the anchorage to the concrete after it has been poured (Figure 23). Several options are available to ease the installation of screws:

- Screws can be supplied on a plastic strip, which is fed into the screwing machine, for increasing installation speed.
- Battery-powered screwdrivers can be equipped with depth guiding devices to ensure the correct depth of 20mm.
- Battery operated screw guns with extended reach are used for this operation. This allows the installer to stand up whilst inserting the screws. These screw guns also use collated screws (available in strips of 30) that provide much faster installation speed.

A combination of the above features can be custom made prior discussion with local power tool suppliers.

The screw types for the lost formwork are 5mm long 50mm chipboard screws, with a countersunk (CSK) head type. The design of a screw has major influence on mechanical performance and fire performance, in combination with PROMATECT®-H RWS-HCM boards. Among others, properties like shaftdiameter versus thread-diameter, sharpness of the tip and distance of the winding (thread) will influence the stickability of the screws and the performance of the final system.


Figure 22 First layer of reinforcement installed before insertion of steel screws

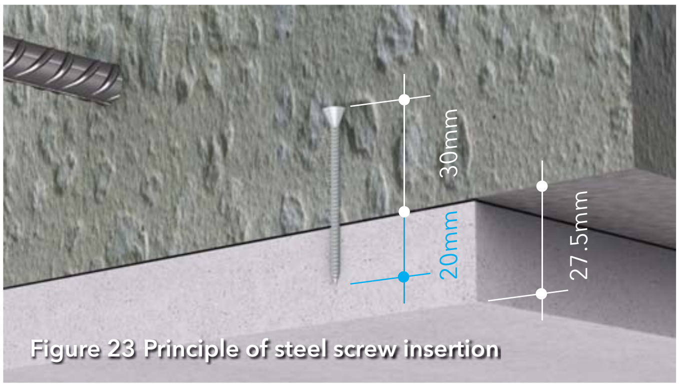


Figure 23 Principle of steel screw insertion


Figure 24 Installaton option of collated steel screws

The number of screws should be in the region of 12 screws per m². In order to ensure the same fire performance in practice, the exact same set-up as during the fire test should always be followed, including fixing materials.

The screw pattern of a full size board of 2500mm x 1250mm (Figure 25 for example) has an average of 12.8 screws per m². The majority of the boards are laid on the formwork in their standard full size dimension. Some boards will have to be cut to size in order to cover the whole surface of the formwork and to connect to the walls and construction joints. Where cut to size boards are used, the following criteria should be followed:

- Minimum quantity of screws should be 12 screws per m².
- Distance from the board edges should be minimum 50mm.
- The screws for cut pieces should be evenly distributed over the board surface. In other words, the spacing distances in X and Y direction should be optimised as close as possible.

For example, a screw pattern on a cut to size board of 1675mm x 1090mm where all criteria are followed, the board surface area is 1.83m² and that means the minimum member of screws should be 22. Please consult Promat on the screw pattern for full board sizes other than 2500mm x 1250mm.

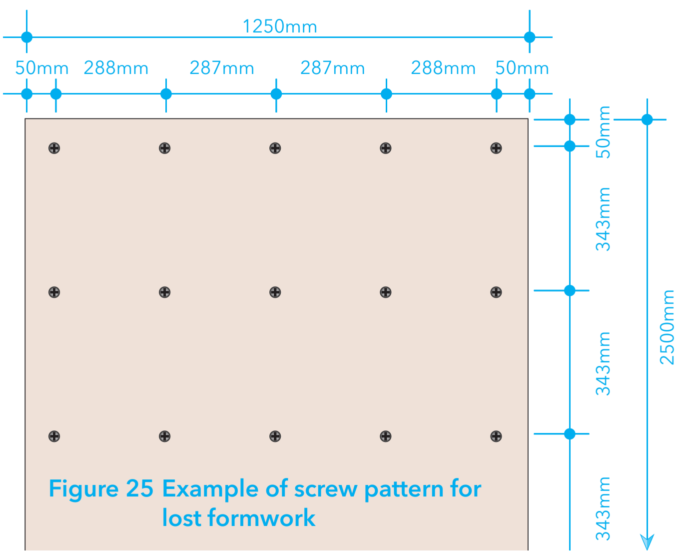


Figure 25 Example of screw pattern for lost formwork

Figure 26 Pouring the tunnel concrete

Figure 27 Formwork extraction from the cured concrete

Continued from opposite page

iv)Pouring the tunnel concrete

Before the concrete is poured, the PROMATECT®-H RWS-HCM boards must be hosed down to remove accumulated site debris and to moisten the boards to minimise water absorption from the concrete mixture. Excessive water should also be removed from the surface of the boards prior to the pouring of the concrete (Figure 26).

The formwork can be installed up to 90mm from the side walls. Depending on the expected load, the PROMATECT®-H RWS-HCM boards can span a maximum distance of 90mm. At this location, care should be taken with the vibrating action during pouring of the concrete. This way allows the formwork much easier to be extracted later as it will not get jammed between the walls.

During vibration of the concrete, the machinery being used is best kept away from the board surface.

v) Extracting the formwork after concrete is sufficiently cure

As the PROMATECT®-H RWS-HCM boards already formed a barrier, there is no adhesion between the formwork and the cured concrete. Therefore it is easy to extract the formwork (Figure 27).

6.1.2 Lost formwork with horizontal PROMATECT®-T boards directly fixed on tunnel concrete slab

The lost formwork method can also be applied using PROMATECT®-T boards. The installation is similar to that prescribed of PROMATECT®-H boards.

It is the most competitive lost formwork option in the market, capable of withstanding the Rijkswaterstaat (RWS) fire curve exposure, with additional advantages as follows:

- The high thermal performance of PROMATECT®-T boards is unmatched. Thickness of the fire protective layer can be reduced to lower the interface temperature on the concrete surface thus providing a higher level of structural safety.
- PROMATECT®-T boards can be supplied with the reverse side indicated in red coloured X-marks indicated for insertion of steel screws. For example, a standard size board of 2500mm x 1200mm can be supplied with five rows of eight X-marks. The tolerance on each X-marked location is ±10mm.
- Half size PROMATECT®-T boards, e.g. 1250mm x 1200mm, can be supplied for easier handling.
- PROMATECT®-T boards can be cut to tight tolerances in the factory to suit the application for lost formwork.

6.1 Lost formwork method

Application of lost formwork using both PROMATECT®-H RWS-HCM and PROMATECT®-T boards has been recommended in the past projects for many advantages:

- Formwork savings

  The shuttering material only has to have loadbearing properties. There is no need to apply coated plywood sheets as the PROMATECT® boards are already laid on top of the formwork and just as long the formwork elements are installed properly, levelled and flush.

  As the tunnel concrete will not be in direct contact with the formwork (i.e. no slippery surfaces), there is no need for demoulding oil. The plywood sheets will remain clean and can be recycled.

- Easy installation

  Joints between boards only need to be butt jointed. No special treatment (e.g. fillers or mastic) is necessary from a fire resistance performance point of view. The cement water will not run through the joints. Where gaps of more than 1mm occur, mastic can be used for sealing to prevent water leaking from the cement through the gaps and causing stains.

  Vertical wall boards can be installed using the lost formwork system.

  Curves in the tunnel can easily be dealt with by cutting the boards on the formwork at an angle to accommodate the curve.

  Openings for manholes in the PROMATECT® board lining (as shown below) and end-walls can easily be made by installing coated formwork instead. After striking the formwork, standard size PROMATECT® boards will close the opening by post fixing the board into the opening. See the following page 37 (Section 6.2).

  PROMATECT® boards provide a heavy duty floor surface. The abrasion resistance is such that the surface can withstand the exposure to people walking and working on top of it, even in wet conditions. Also, the weight of bundles of reinforcement steel and pallets of materials will not cause any damage to the boards. This assumes the PROMATECT® boards are adequately supported by the formwork.

  Rapid installation method rates for PROMATECT® boards of 150m^2 per man/day have been reported on European tunnel projects.

  The installation of lost formwork method does not interfere with other construction activities.

- Tunnel services and special shapes

  Anchor systems for services, e.g. jet-fans (see page 51, Figure 51). can be fixed onto upper surface of the boards prior to casting the concrete. Services, pipes, tubes etc can be included within the depth of the concrete.

  After the formwork is extracted, more services can be installed onto the PROMATECT® lining from below. Anchors can be installed through the boards into the concrete, thus providing a continuous fire protective layer.

  Special shapes in the concrete structure can easily be accommodated, e.g. beams.

- Other benefits

  As the PROMATECT® boards are usually installed in early stages of a tunnel construction, the construction phase is benefited from some level of fire protection.

  Lost formwork method using PROMATECT® boards can provide a flush ceiling finish. No obstacles such as anchor heads will occur on the soffit of the tunnel.

Figure 28 Opening of manholes in the PROMATECT® board lining

6.2 Post cladding method

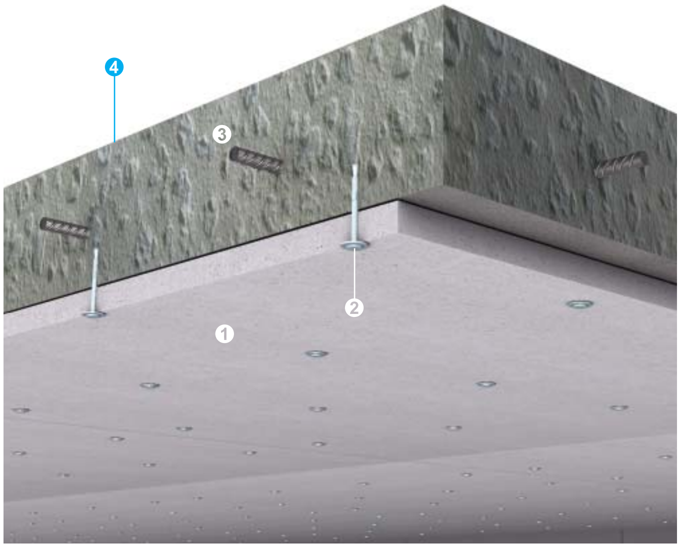
Figure 29 Post construction cladding installation in Zeeburg Tunnel, the Netherlands

❶ One layer of PROMATECT®-H RWS-HCM or PROMATECT®-T boards

❷ Expansion anchor bolts or alternative fixings in suitable length and at appropriate centres, used in conjunction with washers to avoid penetration of the bolt head into the boards

❸ Steel reinforcement

❹ Tunnel concrete slab with minimum 25mm cover to the reinforcement (cladding thickness concrete grade and type dependant)



In many instances, the construction method used to build a tunnel prohibits the installation of the PROMATECT®-H RWS-HCM boards using the lost formwork method. It is also the case that many older tunnels may simply require upgrading.

Promat has developed and tested systems for the protection of concrete where the fire protection boards are applied after the structure has been completed. An example of such a post construction method was the Zeeburg Tunnel in the Netherlands (as shown above).

6.2.1 Post tunnel construction with PROMATECT®-H RWS-HCM or PROMATECT®-T boards

PROMATECT®-H RWS-HCM boards are available in dimensions up to 3000mm x 1250mm and PROMATECT®-T boards up to 2500mm x 1200mm.

Both PROMATECT® boards should be installed with the fair face of the board looking down into the tunnel. The boards should be placed into position and carefully supported while the holes for the bolts are being drilled and the bolts inserted. Although PROMATECT® boards are relatively small in size, the thicker boards are of a reasonably substantial weight, e.g. a 1200mm x 1200mm x 27mm thick PROMATECT®-H RWS-HCM board weighs approximately 36kg, so installation should be considered to be operated by two persons.

PROMATECT®-T boards can be curved at site, depending on diameter of the tunnel and thickness of the boards. Where a thicker board is required to provide the specific fire resistance performance, it is possible to install PROMATECT®-T boards in multiple layers of thinner boards in order to make up the required thickness while still allowing the boards to be curved at site.

An example of curved post cladding method is the Clyde Tunnel in Glasgow, Scotland (pictured at the right) where the boards were used to line the cast iron tunnel sections.

Figure 30 Curved post cladding of cast iron tunnel lining sections in Clyde Tunnel, Glasgow, Scotland

Continued on next page

6.2 Post cladding method

6.2.1 Post tunnel construction with PROMATECT®-H RWS-HCM or PROMATECT®-T boards

It is likely that the concrete to which the PROMATECT® boards is being fixed would not be completely flat. Care needs to be taken when fixing the boards to ensure the removal of any large nibs of concrete. In addition, the bolts fixing the boards should be carefully tightened to avoid over turning and cracking of the boards where positioned on uneven surfaces.

Bolts should be installed a minimum of 100mm from edges of the boards, and should not be located directly in the corners of the boards. Bolts should be offset to avoid cracking or breakage at the corners.

Bolts used in the installation of PROMATECT® boards should be used in conjunction with washers of a minimum of 20mm diameter, or should have their own integral washer, to prevent the heads of the bolts being driven into the surface of the boards. These washers should be manufactured of the same material type as the bolts to ensure that corrosion does not occur.

Avoid the positions of the reinforcement within the concrete when drilling holes into the concrete. For example, the PROMATECT®-H RWS-HCM boards should be properly supported when drilling takes place as far as possible to ensure the rear face of the boards do not "blow" at the exit point of the drill bit.

Minimum requirements for anchors used to secure PROMATECT® boards:

- M6 in diameter.
- Made of stainless steel of 316 grade or higher.
- Minimum 30mm anchor depth penetration into the concrete.
- Expansion action of the anchorage shall be within the concrete, not within the PROMATECT® boards.
- Can be supplied with a nut and washer head to facilitate removal of the PROMATECT® boards when required.
- Suitable for use in tension zone of concrete, e.g. cracked concrete etc.
- Suitable for use where anchors will be subject to positive and negative pressure fluctuation, e.g. dynamic loads

6.2.2 Steel framing

Tests have been carried out on systems for both horizontal and vertical applications where the PROMATECT®-H RWS-HCM or PROMATECT®-T boards have been fixed to a steel sub-frame. The type of steel used as the framing is of course dependent upon environmental conditions of the tunnel but would generally be of a grade of stainless steel consistent with the corrosion resistance requirements.

The steel frame for horizontal applications is generally designed with a number of considerations in mind. For example, should the frame be fixed directly to the concrete structure or should it be a free span across the width of the tunnel (see illustration of Figure 34 on page 42 and Figure 35 on page 43). The frame could consist of either Z-sections or top hats (Omega sections) positioned at nominal 600mm or 625mm centres fixed directly onto the concrete soffit or it could consist of steel channels or hollow sections if it is to span across the tunnel.

In either case, the fixing of the steel frame would be subject to the exact same considerations as for the direct fixing of PROMATECT® boards (prescribed in bullets on this page).

Fixing type, centres and depth into the substrate depends upon the type of framing system and is subject to the fire resistance performance requirements and substantiation by fire test reports. Please consult Promat for details pertinent to any specific installation.

It is not possible to provide a definitive statement on the types of steel framing for vertical wall systems, as these are again dependent on a number of factors, e.g. the fire resistance performance requirements of the system etc. Consideration must be paid to the same factors affecting horizontal applications, with both orientations required to resist the effects of wind loading and suction induced by the passage of traffic.

The framing systems employed tend to be designed on a project by project basis because the section size of the framing is determined by the effects of suction forces, as well as the height of the construction, and the need for protection to any services that may be located behind the lining system. Thus the dimensions and shape of the steel supporting section are determined by the section modulus required to be capable of resisting the compressive loads, bending moments and other forces which may be imposed on the wall lining.

6.2.3 Preparation of boards

Wherever possible, PROMATECT®-H RWS-HCM or PROMATECT®-T boards should be processed and made ready for installation when delivered to installation site. The preparation works should be carried out in a suitably equipped workshop either at an off site location or, if the conditions permit, at an on site location. However, provision for remedial work should be made available at the installation site should there be necessity to make changes to dimensions and edges.

The board preparation works include the following:

- Cutting of the boards to size according to the requirements of the installation site plan.
- Pre-drilling of holes to make the boards ready for securing of impact anchors. The position for holes for various board boards are pre-determined according to the anchor layout plan. Suitably prepared templates must be used to drill the anchor layout on each board.

6.2.4 Installaton of boards

With the smooth face of the PROMATECT® boards facing down, the boards are held in positions flat against the substrate with suitable clamping and lifting equipment, e.g. a board lifting hoist.

Figure 31 Board lifting hoist for post cladding boards in tunnel

Drill into the concrete to the required anchor depth. Whenever required, a rebar detector should be employed to ensure that hitting of the reinforcing bars – due to discrepancies in concrete cover – is avoided. Anchor positions should be adjusted to accommodate this situation. However, the required board area to anchor ratio should be maintained at all times.

Insert impact anchors into the pre-drilled holes, and knock the anchor into position until the washers are in tight contact against the PROMATECT® board surface. Visually inspect that the anchors are tight and secure. Any dislodged anchors must be replaced. Care shall be taken not to over drive the anchor and damage the boards. Place the next board tightly abutting the installed board and repeat the process. Repeat installation of boards outwards from the inner tunnel wall and towards the outer tunnel wall. See Figure 32 below for examples of machine drilling the concrete.

Care must be exercised to ensure that the butt joints between boards are as close as possible. Visually judged gaps of 1mm to 3mm are acceptable. Gaps shall not exceed 3mm. Where gaps cannot be kept within the maximum due to site discrepancies, a proprietary tunnel joint compound should be used where necessary to make good any minor joint misalignment.

If a situation arises where it is impractical to use pre-drilled PROMATECT® boards as templates, the template used for off site drilling can be used to facilitate the simultaneous drilling of both the boards and the anchor positions. Thereafter secure the impact anchors as prescribed. Pre-cut or cut on site boards shall be prepared to suit site conditions for boards along the junction with tunnel walls.

Figure 32 Tunnel concrete drilling machines

6.2 Post cladding method

6.2.5 Suspended protective membrane system

Many tunnels, especially older city ones, were built using a C&C method and constructed by means of steel and/or concrete roof beams with a concrete slab or a composite steel/concrete slab on top of the beams. In many tunnels, the space between the beams is utilised to install pipes, cable trays and other services.

In refurbishing such a tunnel, a protective membrane system is the most feasible option technically and commercially.

6.2.5.1 MEMBRANE SYSTEM COMPONENTS

A protective membrane system either consists of a steel frame suspended from the loadbearing structure or, depending on the span of the tunnel ceiling, is supported alongside the walls (pictured examples below). The steel frame should be designed such that it can cope with:

- The dynamic load cycles coming from passing traffic.
- The additional weight of PROMATECT® boards, also taking into account the potential additional weight of water which may be absorbed into the boards.
- The elevated temperatures in case of fire and still retain its function.

Designer of the suspended steel frame has TWO (2) options for the horizontal load bearing members:

1) The use of C, Z or Omega-section profiles

2) The use of a trapezoidal steel decking

Typically the design of such a suspended steel frame is conducted by local structural engineers. The PROMATECT® boards are screwed from below to the suspended steel frame, either the profiles or the trapezoidal steel sheets.

Fire tests have shown that when exposed to an RWS fire curve, for example, the temperature of the steel frame can still reach some 300°C. At this temperature the steel frame in the fire test maintained its mechanical stability. Due to this elevated temperature, the thermal expansion of the steel members could potentially introduce gaps between boards possibly causing thermal leaks.

In order to address this issue, the protective membrane systems are equipped with cover strips at the joints. These cover strips can be installed either behind or in front of the boards. If the latter option is chosen, Such advantage is that no intermediate strips are required and the installation rate can be increased.

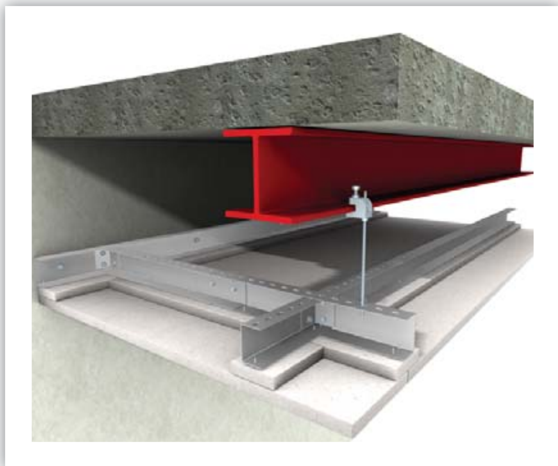
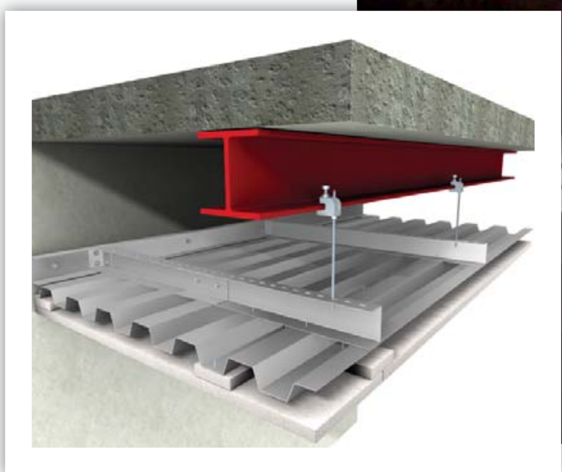


Figure 33 Examples of suspended protective membrane system for tunnel ceiling



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6.2.5.2 THERMAL DATA

Fire tests have been conducted on both systems as described above, i.e. a frame with profiles and a frame with the trapezoidal steel decking. In both situations the PROMATECT®-T boards have been attached from below, using cover strips at the joints.

During these fire tests temperature recordings, have been taken on and within the following locations of the suspended protective membrane system:

- Reverse side of the boards
- Reverse side of the trapezoidal steel sheet*
- The C-profiles*
- The HEA 350 I-profile which supported the concrete slab, simulating a large steel beam*
- The lattice girder which supported the concrete slab, simulating a light weight steel support member*
- The surface of the concrete**
- Air temperature in the cavity of the system

The temperature development on above individual members are available from Promat for request.

**The elevated temperatures on the steel members are of particular interest to the structural engineer when designing the suspended steel frame. The required steel dimensions can be calculated based on the mechanical load, the span, the loading system, the required safety factor and the maximum temperature.*

***The temperature on the concrete surface is of interest to address the reaction of the concrete when exposed to these elevated temperatures. In accordance with the RWS fire curve standard, for example, the maximum allowed temperature on the concrete surface is 380°C for cast-in-place concrete which is often applied in such tunnels. If the temperature on the concrete in a particular project is set at a certain maximum, Promat can advise on the required material thickness of the PROMATECT®-T boards, in order to meet the design criteria.*

Finally, the air temperature in the cavity of the system can be used to analyse if the maximum allowable temperature on services is exceeded.

Critical services in tunnel for example, are regularly installed behind such protective membrane system. These services can be feeding jet fans, emergency lighting and other power operated systems that should maintain full functionality when exposed to fire. In the design of a protective membrane it should be determined if the maximum allowable temperature on such services is exceeded.

It should be noted that the maximum failure criteria for the structural members discussed here can vary widely. As stated above, cast-in-place concrete is perceived to be safe below 380°C, whereas loadbearing structural steel beams are able to withstand elevated temperatures up to 550°C, depending on the mechanical load, the span, the loading system and the required safety factor.

Fire test results have shown that the maximum recorded temperatures on the steel members and the concrete surface are in line with their respective maximum failure criteria.

Non fire resistant services, however, can only take some 130-160°C. Therefore it could be a more economical option to design the fire resistance performance of a protective membrane system so that all the suspended steel frame, the steel and concrete beams, and the concrete slab are sufficiently protected rather than to protect the services separately.

6.2 Post cladding method

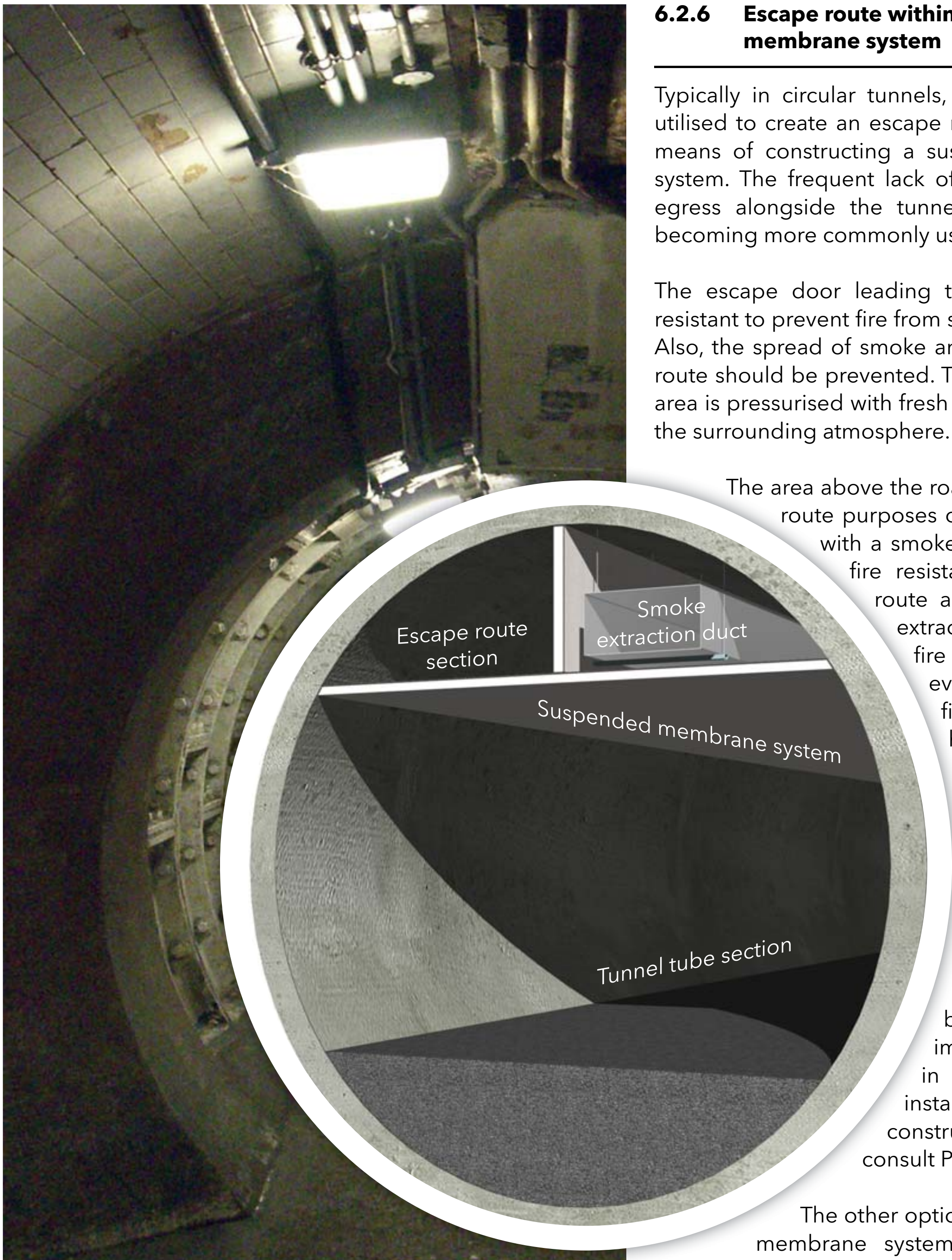

Figure 34 Principle of an escape route for circular tunnels

6.2.6 Escape route within the suspended membrane system

Typically in circular tunnels, the tunnel roof space can be utilised to create an escape route above the tunnel tube by means of constructing a suspended protective membrane system. The frequent lack of space to provide a means of egress alongside the tunnel tube means this method is becoming more commonly used in this type of tunnel.

The escape door leading to the stairwell should be fire resistant to prevent fire from spreading into the escape route. Also, the spread of smoke and toxic gasses into any escape route should be prevented. To achieve this, the escape route area is pressurised with fresh air, creating an over pressure to the surrounding atmosphere.

The area above the road deck can be used for escape route purposes only or it can also be combined with a smoke extraction duct. In the latter, a fire resistant wall separates the escape route area (fresh air) from the smoke extraction duct. This wall requires fire resistance because in the event of fire it will be exposed to fire temperatures through the hatches in the smoke extraction plenum system.

Such an escape route ceiling can either be constructed out of concrete or steel. Regardless of the selected construction method, the structural integrity of this ceiling during fire is of paramount importance because it provides the most important means of egress in a fire emergency. For those instances where the escape route is constructed out of concrete, please consult Promat.

The other option is to construct the suspended membrane system using a steel frame, which would span from wall to wall, with intermediate hanger rods if mechanically required. The separating wall can also be constructed such that it functions as a support system. For obvious reasons, supporting structures should be avoided in the escape route area.

Figure 35 Loadbearing double layer membrane system suitable for the escape route section

6.2.6.1 MEMBRANE SYSTEM COMPONENTS

The steel frame should be designed such that it can cope with the similar criteria precribed in page 40 (Section 6.2.5.1).

Typically the design of such a suspended steel frame is conducted by local structural engineers.

Apart from its structural integrity in case of fire, an escape route ceiling has an additional thermal criterion in that the maximum allowable temperature on the non-exposed face of the specimen, i.e. the temperature on the floor, should not exceed a certain tenability level. The French Tunnel Fire Safety Standard provides guidance to address this. The maximum allowable absolute temperature on the floor is set at 60°C. This is not a temperature rise above ambient but an absolute maximum.

Promat has designed escape route within the suspended membrane systems for use in tunnels and have fire tested a number of different configurations, using PROMATECT® boards. For example, the escape route system is constructed using a trapezoidal steel sheet as the load bearing layer. From below, PROMATECT®-T boards are screwed to Z-profiles and are combined with high density mineral wool thus providing the required thermal insulation of the system. On top of the trapezoidal steel decking a metal grid is positioned to provide for a flat, unobstructed surface to walk upon (see Figure 35 above). The system described above satisfies the thermal requirement of 60°C on the floor surface as mentioned before.

An additional board can be applied between the trapezoidal steel sheet and the metal grid to obtain even lower temperatures on the floor surface.

6.2.6.2 THERMAL DATA

During the fire tests temperature, recordings have been taken on and within the following locations of the protective membrane system where the escape route section is formed:

- Reverse side of the boards
- The trapezoidal steel sheet*
- The Z-profiles*
- On top of the metal grid where criterion failure is <60°C

The temperature development on above individual members are available from Promat for request.

**The elevated temperatures on the steel members are of particular interest to the structural engineer when designing the suspended steel frame. The required steel dimensions can be calculated based on the mechanical load, the span, the loading system, the required safety factor and the maximum temperature.*

The elevated steel temperatures on the trapezoidal steel sheet and the Z-profiles will cause thermal expansion of the steel members and could potentially introduce gaps between the boards in case a single layer of PROMATECT® boards is installed. However, for thermal insulation reasons the escape route ceiling system is equipped with a double layer of boards which are installed with staggered joints. Therefore the cover strips shown on page 40 (Figure 33) regarding single layer suspended protective membrane system are not required on double layer membrane system for the escape route section.

6.2 Post cladding method

6.2.7 Application of curved and framed sections

PROMATECT®-T boards do not necessarily need to be fixed directly to the concrete soffit of the tunnel. It is feasible for some fire resistance performance requirements to use steel framing members. It should be noted that although the performance of galvanised steel sections is adequate under fire conditions, the aggressive environment encountered within tunnels suggests that the use of stainless steel framing members is preferable.

Both figures here show the PROMATECT®-T boards fixed either directly to the soffit or onto top hat sections. The dimensions of the steel sections and the centres of positioning are dependent on a number of factors, e.g. the fire resistance performance, the installation span, the board thickness, the type of concrete etc.

Figure 36 shows board lining through flat tunnel concrete slab, whereas Figure 37 through curved sections.

PROMATECT®-T boards can be supplied as flat sheets and can be curved on site. Care should be taken to ensure that the PROMATECT®-T board thickness is commensurate with the diameter of the tunnel lining. If the diameter is too tight, it may be necessary to install in a double layer of thinner boards rather than one single board thickness.

Please consult Promat for further details.

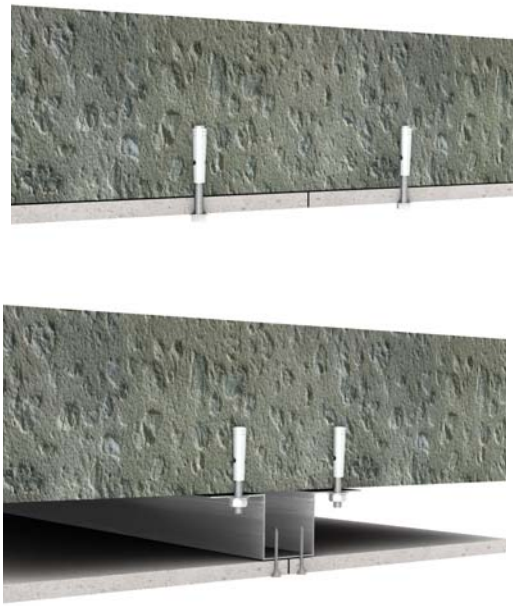

Figure 36
Board lining through flat tunnel concrete slab

Figure 37 Board lining through curved tunnel concrete sections

6.3 Faceted lining method

6.3.1 Faceted lining with PROMATECT®-T boards

Whilst there are various methods available to install faceted lining system, the following is a general guidance.

This system consists of main boards (2500mm x 600mm PROMATECT®-H RWS-HCM or PROMATECT®-T) with 120mm wide backer strips behind both circumferential and longitudinal joints. The backer strips can be affixed to the main boards with staples or screws in accordance with the approval document. Thickness of both main boards and backer strips is as required and determined by fire testing analysis.

The main boards (with backer strips) are mechanically installed to the tunnel surface with anchor bolts. The amount of anchors per board is typically 10 no's. They shall have minimum 30mm embedment into the concrete and a 30mm washer (see Figure 39). An alternative method is to wedge the circumferential strips between the longitudinal strips.

The distance of the anchors to the board edges is 50mm. These anchors are fixed at approximately 600mm centres.

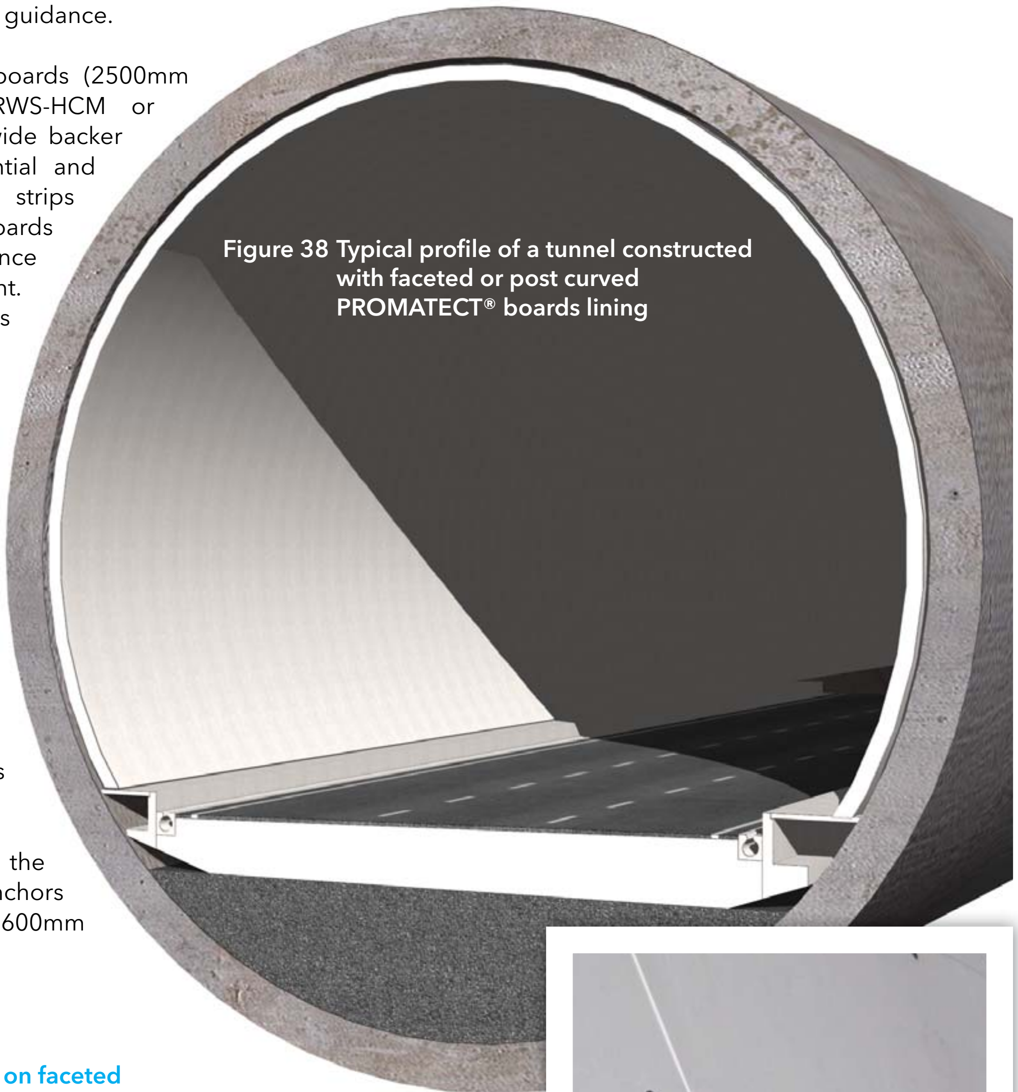

Figure 38 Typical profile of a tunnel constructed with faceted or post curved PROMATECT® boards lining

Figure 39 Layout of anchor bolts on faceted main boards and backer strips

6.3 Faceted lining method

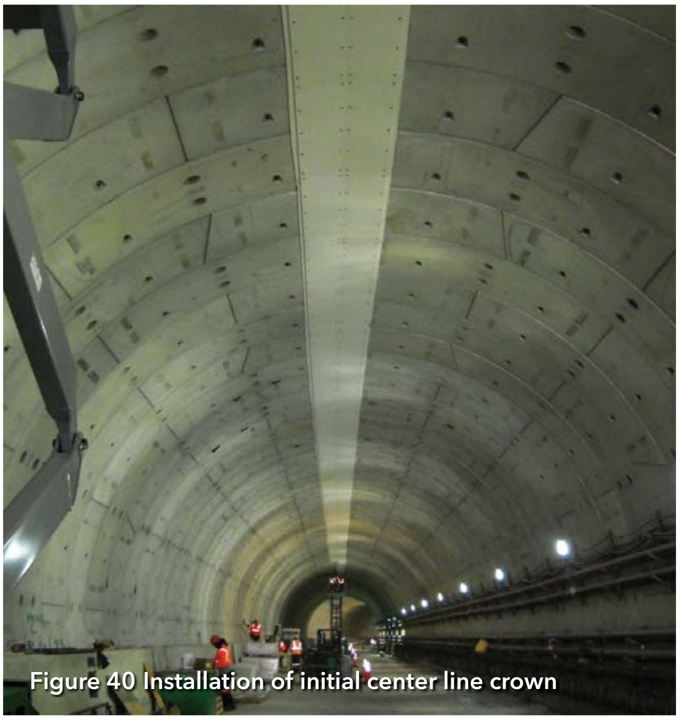
Figure 40 Installation of initial center line crown

d) Bevel the edges with hand held rasp to create small flat area where boards meet (Figure 42).


Figure 42 Beveling edges of the board

e) Pre-drill holes onto the boards as Figure 43.

f) Fix all four backing strips to the board with staples.

g) Bring the first layer board to exact position and fix it with two units of wall jacks.

6.3.2 Installaton of faceted boards lining

Following should be checked prior to installation:

- All board surfaces and edges to avoid damages and imperfection.
- All anchor bolts, washers and nuts for correct dimensions.

The installation sequence of faceted boards lining is to be a top-and-down method. Such is an advantage to prevent the boards from being damaged during handling and securing. The sequence is summarised as follows.

a) Assess the tunnel liner conditions where the boards are installed.

b) Mark the center line by line (see Figure 40 for example).

c) Mark the drilling holes with a template (e.g. wooden strip, drywall screw hammer) as shown in Figure 41 according to installation drawings.


Figure 41 Template for marking drilling holes


Figure 43 Pre-drilling holes onto the board

Figure 44 Setting anchors with pneumatic hammer

h) Drill ten holes for anchors and set the anchors with pneumatic hammer (Figure 44) and hammer element. Hammer the anchors into concrete until their washer touches board and stops rotating. Tighten the stainless steel nut with a battery driver (Figure 45) if a nut system is used.

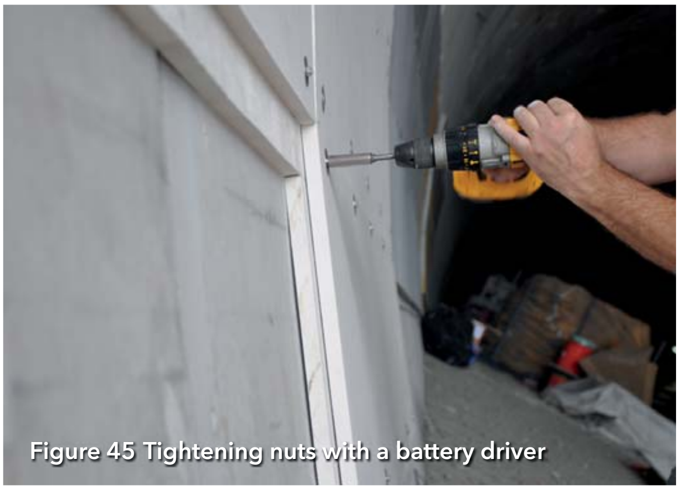

Figure 45 Tightening nuts with a battery driver

i) Bring the second layer board in position, butt jointed to the first layer board.

j) Align butt joint with adjacent boards by using hammer and wood strip to tighten the joints as much as possible without damaging the board edges. If the gap is greater than manufacturer's recommendation, cut the board to the right dimension or replace the board.

k) Drill holes next to the readily installed upper adjacent boards (Figure 46). If the anchors are found fallen into either bolt or shear cones recesses, or near a segment joint, move and reposition them in order to measure minimum 75mm from edge of the concrete. Add the necessary anchors to guarantee a maximum spacing of 575mm according to the tunnel construction plan.

Figure 46 Installing second layer board to the adjacent boards

Figure 47 Sliding backing strips into position

l) Repeat the anchor setting as in step (h).

m) Slide two backing strips into position (Figure 47), if this method is chosen.

6.3 Faceted lining method

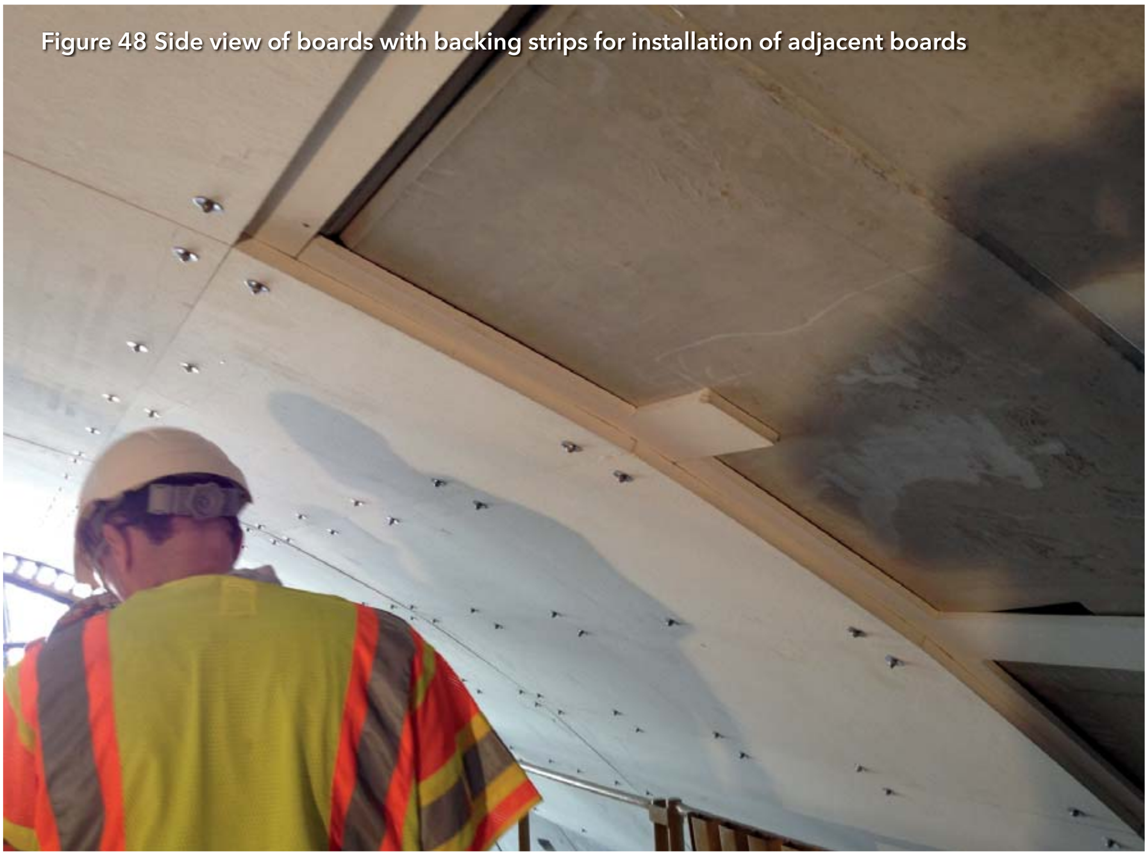

Figure 48 Side view of boards with backing strips for installation of adjacent boards

Figure 49 Installation of boards through a curvy tunnel

n) Drill five holes for anchors and set the anchors with pneumatic hammer and hammer element. Hammer the anchors into concrete until their washer touches board and stops rotating. Tighten the stainless steel nut with battery driver if a nut system is used.

o) Repeat steps (i–k) for adjacent boards.

p) The last board in a ring must be cut to the right width, leaving a gap of not more than 25mm measured from the walkway and jersey barriers. See Figure 48 above for example.

Attention shall be paid to specific cases, such as:

- Zones of tunnel curvature, which requires cutting the short side to the board with an angle. For practical reason, a maximum offset to theoretical line should not be more than 50mm. Location of the joint can be drawn and determined by using a rotating laser.
- The last board in a ring must be cut to the exact width in order to leave a gap of not more than 25mm measured from the precast barrier in order to allow the drainage of leaks on top of the jersey barrier and walkways according to the tunnel roadway plans.
- Offsets between rings or segments may require shortening of the board length to create an offset in the middle of the following board in order to prevent cracking or damaging the board from bending.

Figure 50 Example of faceted boards lining in a tunnel

6.4 Fixings

6.4.1 Lost formwork method

Fixings used for lost formwork are 50mm x 5mm with countersunk heads. These ones shall be stainless steel and installed at the rate of 12 per m² typically. These screws shall not be installed closer than 50mm from the edge of the board. Please refer to page 33 (Section 6.1) for details.

6.4.2 Post cladding method

When installing PROMATECT® boards using the post clad method, care should be taken to use only those fixings tested and approved. They shall be stainless steel 316 using a stainless steel washer of 30mm diameter. They shall have a minimum embedment depth of 30mm into the concrete. Approximately 5 fixings per m², but this will increase where the boards are cut to size. Fixings shall not be within 100mm of the edge. Please see drawing layout showing typical fixing pattern on a full-sized board.

Previously tested fixings suitable for post clad systems are available from the following manufacturers:

- Fischer
- Hilti
- Würth
- Kunkel

Please refer to page 37 (Section 6.2) for details.

6.4.3 Faceted lining method

Where tunnel designers use boards for circular tunnels, PROMATECT® boards can be provided to follow the radius of the tunnel. Promat is also able to supply a faceted lining system. This system uses backer strips at the joints of the board so that there is an air gap between the board and the concrete. In this case, it is also important to use the actual tested fixings for the system. These are the same as for post clad, however will need to be longer to allow for embedment of 30mm.

With faceted systems, the possible array of fixing types is wide. The length and type may vary with the specification and diameter of the tunnel. Please refer to page 45 (Section 6.3) for details or consult the local Regional Tunnel Manager.

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In any tunnel construction, applying a protective material to enhance the fire resistance of the structure is only part of the story. On its own, this is not going to prevent the loss of life which might occur if there is a fire in a tunnel. Additional systems need to be incorporated into the design. These would include the following:

- Enhancing the fire resistance of the structure
- Air supply systems
- Smoke extract duct systems
- The provision of fire and smoke resistant safe havens in long tunnels
- Detection systems
- Fixed firefighting systems

The active systems within tunnels should consist of lighting, signal systems, surveillance CCTV cameras, fire and smoke alarms, PA systems, antenna (for two way radio communication), hydrants, pumpsets, escape routes, air supply and smoke extracting systems.

This document is concerned only with systems pertinent to passive fire protection, e.g. air supply and smoke extract ducts, escape and cross tunnel fire doors, provision of safe havens and systems for the protection of cables supplying critical services.

7.1 Air supply and smoke extraction systems

As has been shown by many case studies into the cause of death resulting from fire in tunnels, the majority of these casualties are a result of inhalation of smoke particulates.

Smoke can have wide ranging debilitating effects on people:

a) The atmospheres may be hot; temperature near the seat of the fire may exceed 1000°C. Inhalation of hot gases may cause serious burn injuries to the respiratory tract.

b) Toxic and narcotic gases, such as carbon monoxide and hydrogen cyanide, will be present. At high concentrations, carbon monoxide will cause rapid death; lower concentrations may bring about a loss of coordination, particularly on exertion, preventing people reaching escape exits.

c) The atmosphere will contain a low concentration of oxygen; this in itself can bring about unconsciousness and death but normally the effects of toxic gases predominate.

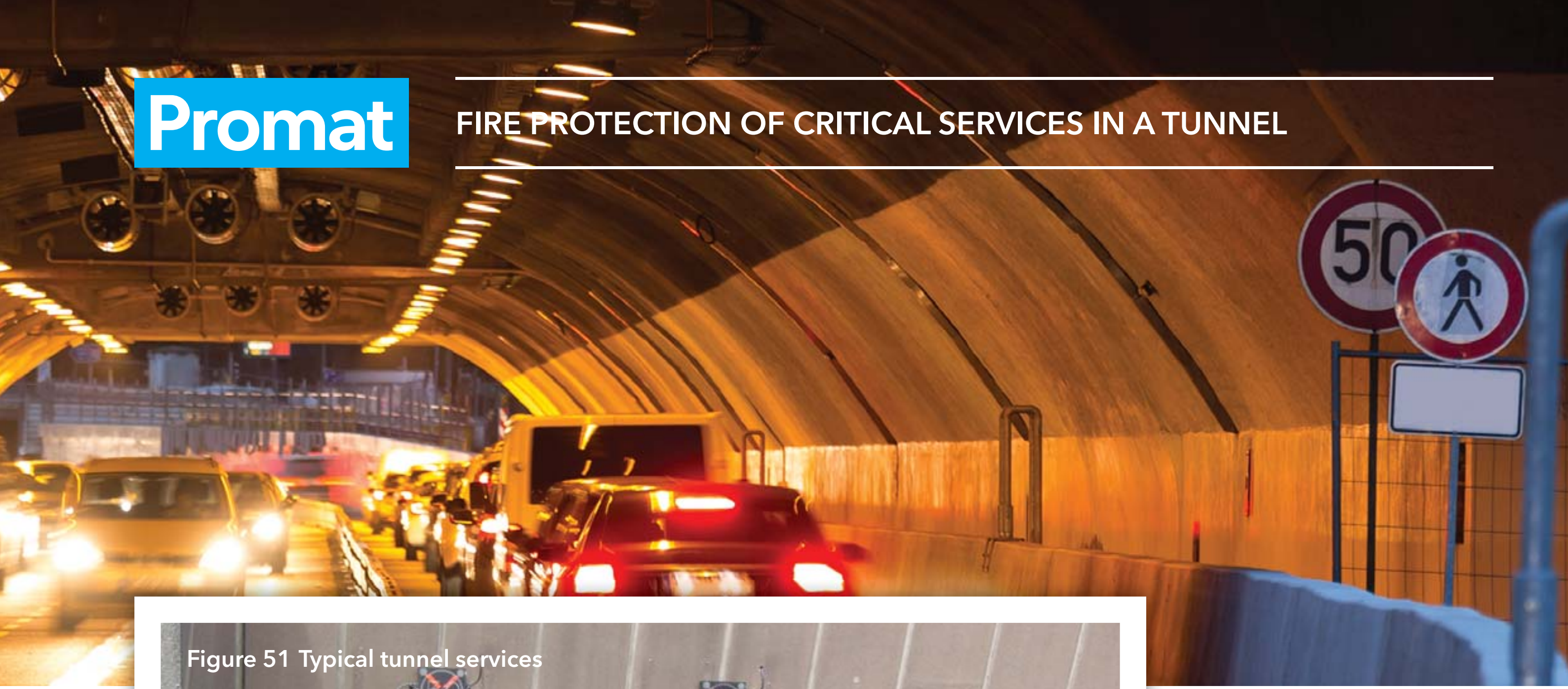
d) There may be many small particles in the atmosphere that restrict vision thus effect tenability.

e) The effects of irritants to the upper respiratory tracts and eyes may impede escape.

Studies on the causes of deaths due to fire indicate that carbon monoxide (CO) poisoning accounts for roughly one-half of total fatalities. The remaining half is accounted for by direct burns, explosive pressures, and various other toxic gases. Although the analysis of blood cyanide (which would come from exposure to hydrogen cyanide) in fire victims is sometimes reported in autopsy data, blood carboxyhemoglobin saturation, resulting from exposure to CO, is often the only fact provided.

It is therefore imperative for long tunnels to include some form of smoke extraction system in the design. Due to the very nature of the hot gases and particulates any system is required to remove from the location, a duct or extraction system will need to be constructed in such a manner that it too is resistant to fire.

However, it is not a simple matter of installing ventilation or extract fans and assuming these will perform the necessary services. Significant research (some 98 tests) carried out in the early 1990s in the Memorial Tunnel, USA provided some valuable data on the performance of ventilation systems. These included natural, semi transverse, fully transverse and longitudinal ventilation systems. Similarly, fire loads ranged through 10, 20, 50 to 100MW in severity. A few sprinkler/deluge systems were also tested during this programme.



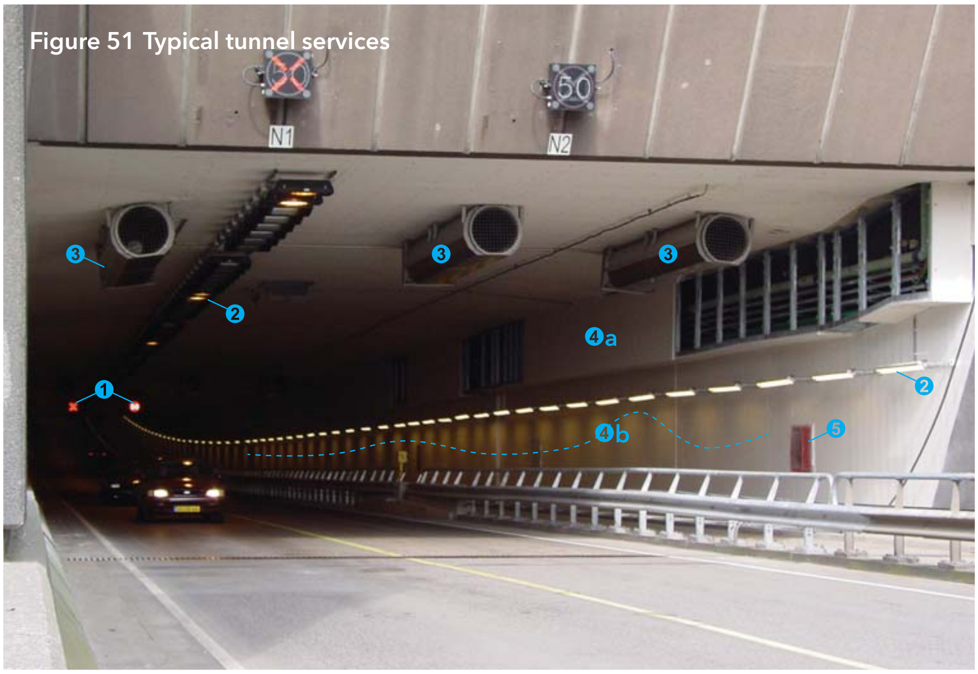


Figure 51 Typical tunnel services

1. Signal systems
2. Lighting
3. Ventilation or extraction system, i.e. jet-fans
4. a Passive protection system, i.e. services enclosure
   b Passive protection system, i.e. fire resistant spray applied coating
5. Fire extinguisher

More recently, a series of tests carried out in the Benelux Tunnel in the Netherlands also focused on the effects of ventilation on smoke layering and sprinklers water dispersion.

In tunnels with longitudinal ventilation systems, the ventilation can have a marked effect on the Heat Release Rate (HRR) of the fire. Investigation and experimentation have shown that longitudinal ventilation within a tunnel can cause different types of fire to behave in very different ways.

The HRR of fires in heavy goods vehicles in particular can be greatly enhanced, even with low rates of ventilation, whereas the HRR of a car under the exact same conditions could be greatly reduced. There is no simple method of calculating the complex relationships between ventilation speeds and increases in the HRR.

Ventilation can also affect the spread of fire along a tunnel. For example, during the Mont Blanc disaster, fire spread rapidly from the source of the fire to cars situated some 290m away.

As shown at the right figure, the effect of the ventilation results in the fire moving horizontally instead of mainly vertically. As a result of this action, any vehicles positioned down wind of the fire could possibly catch alight themselves. The ventilation speed is 2m per second.

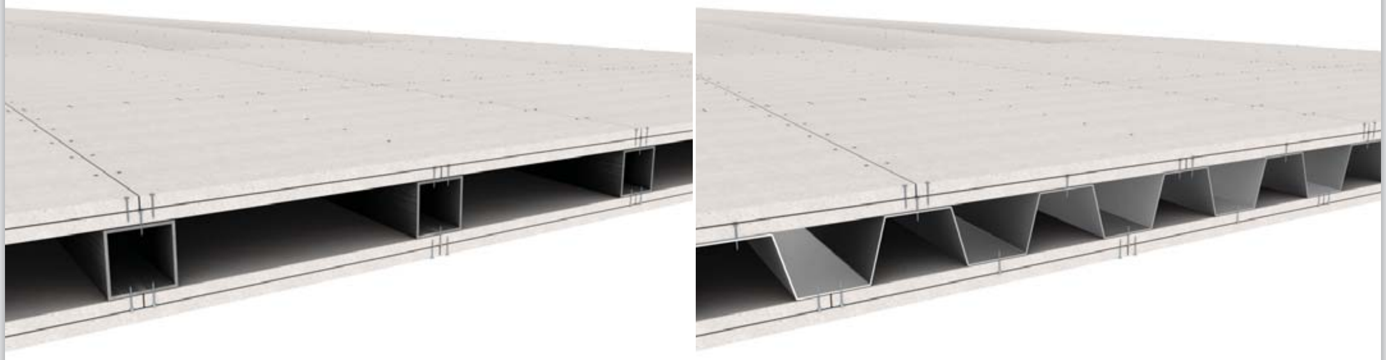
While the effects of natural and longitudinal ventilation in tunnels has been subject to some experimentation, the effects on tunnel fires from semi or fully transverse ventilation is at present less well known.

Figure 52 Effects of air flow on car fire in Mont Blanc Tunnel

In tunnels, there are a number of ways for providing the extract systems. In general however, these can be categorised in two basic concepts. The first is the construction of a plenum within the tunnel roof space, either from concrete, or by building a soffit from PROMATECT® boards. See page 52 (Figure 53) for example.

7.2 Suspended ceilings, smoke extraction plenums

Figure 53 Examples of smoke extraction plenums



A common way of providing smoke extraction systems in tunnels is the construction of a smoke extraction plenum in the tunnel roof space. This is the transverse ventilation system. In an emergency the smoke and hot gases will be extracted into the plenum through smoke inlets or hatches. Above figure shows two typical examples.

Such a plenum can either be constructed out of concrete or steel. Regardless of the selected construction method, the structural integrity of this plenum during fire is of utmost importance as the ventilation philosophy is depending on it. In case the plenum (or part of it) collapses during the event of fire, the intended smoke management approach will be lost. All possible major implications are the usual result, not to mention the hampering effect they would have on emergency response teams.

A smoke extraction plenum of this nature gets exposed to tunnel fire temperatures from both sides, i.e. from below but also from the top because hot gases are pulled into the duct. Temperature exposure will be equally high from both sides, especially at the location of the smoke inlets near the fire source.

Regardless of the selected construction method, such a plenum system therefore requires thermal protection from both sides, not only from below.

Where a plenum is to be constructed out of concrete, please refer to a separate document for board lining solutions for more information of concrete protection.

The other option is to construct the plenum using a steel frame, spanning from wall to wall, with intermediate hanger rods structurally or mechanically required. As prescribed, such a frame requires thermal protection from below and from above. The hanger rods also require thermal protection in order to prevent elongation due to thermal expansion, which has the potential to cause unwanted deflection and sagging of the plenum.

The steel frame should be designed so that it can cope with:

- Dynamic load cycles coming from passing traffic.
- Additional weight of the PROMATECT® boards, taking into account the potential additional weight of water which may be absorbed into the boards.
- Elevated temperatures in case of fire and still retain its function.

Typically the design of such a suspended steel frame is conducted by a local structural engineer. Promat has designed smoke extraction plenum systems for use in tunnels and have fire tested a number of different configurations using PROMATECT® boards.

System components

The smoke extraction plenum system consists of a load bearing steel frame, which can be made out of square hollow sections (SHS) or various other steel framing members. The PROMATECT® boards are screwed to either side of the steel frame, also covering the edges at the framing exposed at the location of hatches.

The amount of steel used in terms of kilograms per square metre surface has an effect on the temperature development within the plenum system. The more kilograms of steel per square metre, the better the heat sink (heat absorption), hence the lower the temperatures will be on the steel. In contrast, if less steel is required for structural reasons it should be noted that the temperature development will increase as a function of time.

The fire tests took this effect into account, varying the heat sink effect, in combination with the selected PROMATECT® board thickness. For example, when exposed from both sides by the RWS fire curve, steel temperatures have been recorded between 285°C and 570°C, depending on the thickness of the PROMATECT® boards and the mass of steel being used.

On the basis of the test data generated by these fire tests reports, the structural engineer can design the loadbearing steel frame, with Promat advising on the required thickness of the PROMATECT® boards.

7.3 Cable protection systems

In the event of a fire it is vital to the safety of tunnel occupants that certain electrical systems remain functioning until people have escaped. Such systems therefore require protection from fire for a specified period of time and include:

- Lighting for means of egress (emergency escape route lighting) and areas of refuge
- Exit signs
- Communications
- Electrically operated extinguishing systems, fire and smoke detection
- Ventilation and smoke extraction systems
- Tunnel drainage and fire pumps

In addition to protection from fire outside the duct, it is normally vital that any fire within the duct is contained, e.g. if cable sheathing ignites due to an electrical overload.

A suitably designed duct will:

i) Prevent the propagation of fire from one compartment to another.

ii) Assist in maintaining escape routes.

iii) Ensure the continuing operation of services.

iv) Reduce damage to localised areas.

v) Contain smoke and toxic fumes from burning cables if the fire was within the cable enclosure.

By enclosing standard cables in the PROMATECT® cable duct systems, all above requirements can be met in providing up to 240 minutes fire protection, depending on the duct construction and the fire exposure curve. This avoids the use of more expensive and bulkier fire-rated cables, which cannot provide performance to the more extreme exposure curves, such as the HCM and RWS fire curves.

Design considerations

The following points are some of the factors which should be considered when determining the correct specification to ensure the cable duct system provides the required fire performance.

i) Applicable time-temperature curve

ii) Maximum allowable temperature on the specific cables
Non fire rated cables can generally operate in temperatures of approximately 130-150°C for short periods of time. However, such increases in cable temperatures do increase the electrical resistance of the cable. The former temperatures are regularly used as the performance design criteria for fire rated cable protection systems in tunnels. It should be noted that the majority of fibre optic cables begin to break down once exposed to temperatures in the range of 50-80°C.

iii) The cross section of the enclosure
The larger the perimeter of the enclosure around the cables, the greater the area exposed to fire and thus more heat enters the duct. In instances where a three sided duct is constructed with the fourth side being the concrete structure, the concrete will act as a heat sink, which will delay the increase in the air temperature inside the duct. This in turn will ensure functionality of the cables for a greater duration as the rise in cable temperature is postponed.

iv) The amount of copper/aluminium within the cable duct
The biggest heat conductor in a cable protection system is the copper/aluminium wire core itself. Although the protection system provides thermal protection to the cables, the heat sink effect into the cables themselves can be rather large as the cables are heated from ambient temperatures to a maximum of approximately 130-150°C.

The greater the volume of copper/aluminium wire within the enclosure, the greater the heat sink effect and the longer functionality can be sustained. If a lower volume of cable is used, thicker fire protection systems may be required.

v) Required fire resistance performance
Generally, the most onerous requirement is to maintain the integrity of the circuit when the system is exposed to external fire. This means the cables must continue to function at full capacity whilst exposed to fire. If this continued functionality is not required, the performance specification may be reduced by the approval authority to provide only stability, integrity and insulation of the duct system itself and/or the wall and floor penetrations.

vi) Supporting structure
The supporting hangers and their fixings should be capable of bearing the load of the complete cable system including any applied insulation material or other services suspended from it. Chemical anchors are not generally suitable. It is usually not advisable to use unprotected hangers if the stress exceeds 6N/mm² for a period of 240 minutes (or 10N/mm² for a period of 120 minutes) and/or if hanger lengths exceed 2000mm. Unprotected hangers are not allowed where they may be exposed to the RWS or HCM fire curve. It should be noted that even stainless steel hangers will not survive such a thermal attack for long, regardless of the stainless steel grade or tension stress level. The use of protected hangers is therefore mandatory for both RWS and HCM fire curves.

Continued on next page

7.3 Cable protection systems

Design considerations

vii) Penetrations through walls and floors
Care should be taken to ensure that movement of the cable system in ambient or in fire conditions does not adversely affect the performance of the wall, soffit or floor or any penetration seal. Also the sagging of the cable duct as a result of the elongation of the hangers must be addressed at the penetration point of the duct through any wall, floor etc.

viii)Other requirements
Acoustic performance, thermal insulation, water tolerance, strength and appearance can be important considerations.

Promat has conducted extensive fire testing on cable protection systems for tunnel applications, using PROMATECT®-H and PROMATECT®-T boards. On the basis of the test data obtained, these systems have been designed to cope with the most severe time-temperature curve applied in tunnel design, the RWS fire curve.

For details of systems exposed to other time/temperature curves, please consult Promat.

Figure 54 Examples of cable protection systems constructed from PROMATECT® boards

7.4 Safe havens

In long tunnels, safe havens should form an integral part of the tunnel design. Recent fires in tunnels have shown that exposure to smoke and toxic fumes from burning vehicles is the main cause of loss of life. Deaths occur even at relatively short distances from the seat of the fire. The provision of safe havens therefore is imperative in long tunnels, both to provide protection for passengers from vehicles until fire and emergency personnel can reach them and also as a place which can provide respite from heat and smoke for firefighters.

Ideally, any safe haven should have a minimum fire resistance period to match that of the main structural protection, and should be constructed in such a manner that is resistant to both heat (insulation) and ingress of smoke into the chamber.

In recent fires, some personnel who have managed to reach a safe haven but have then succumbed through exposure to the effects of heat and smoke ingress into the chamber. Consideration should therefore be given to providing a separate air supply for these areas.

Promat can offer the designs and systems required to construct such safe areas for all types and durations of fire exposure.

7.5 Fire doors

Figure 55 Examples of steel framed fire doors in tunnel

Fire resistant doors within tunnels are installed to provide a means of egress and to prevent the spread of fire, hot gases and smoke from the tunnel to the surrounding compartments. Fire doors are installed:

- at cross connections between two tunnel tubes,
- to allow emergency services to use as a base for first attack fire fighting,
- to provide access to an escape route, and/or
- to protect people who have entered safe havens.

In view of the smoke emissions from vehicles, and the high toxicity of this smoke as a result of the types of materials used in modern car manufacture, it is also imperative that doors provide a high degree of resistance to the passage of smoke. Ideally, where used as access to safe havens, doors should provide a high degree of thermal insulation to reduce the affects of heat on the occupants of the chambers.

Any fire door situated within a tunnel should be capable of providing the same degree of corrosion resistance to the aggressive and polluted environment of a tunnel as any other services.

In the design phase of a fire door, it should be noted that elongation of steel members will cause gaps around the perimeter of the door, potentially introducing failure of the system. In addition to elongation, steel members also tend to curve as a result of heating on one side only.

A tunnel fire door should be fire tested in two configurations:

a) The door leaf opening away from the heat source

b) The door leaf opening into the heat source

A lot of research has been conducted, mainly under the auspices of the European Union. The results of this research will eventually translate is being translated into directives, guidelines and standards for tunnel fire safety around the world. One such example is NFPA 502 Standard For Road Tunnels, Bridges & Other Limited Access Highways 2017 Edition USA.

8.1 FIT

FIT (European Thematic Network on fire in tunnels) provides a European platform for dissemination of information of up-to-date knowledge and research on fire and tunnels. FIT represents 33 members from 12 European countries.

To optimise, when possible, benefits of the knowledge throughout Europe – from real fire accidents, testing and research – there are many benefits to using all available information via a European Thematic Network. The main objectives have been identified for the FIT Thematic Network as follows:

i) The network dissemination of RTD and design results obtained in European and National RTD projects. The aim is to optimise research efforts, to reach critical mass and to enhance impact at a European level by combining the results of the different projects.

ii) FIT will establish a set of consultable databases with essential knowledge on fire in tunnels.

iii) Realise recommendations on design fires for tunnels.

iv) To develop European consensus for fire safe design on the basis of existing national regulation, guidelines, codes of practice and safety requirements.

v) Define best practices for tunnel authorities and fire emergency services on prevention and training, accident management and fire emergency operations.

8.2 DARTS

DARTS (Durable And Reliable Tunnel Structures) is an RTD project. It was conducted during 2001-2004 by a partnership of eight European companies and is performed with financial support of European Communities under the Fifth Framework Programme, Competitive and Sustainable Growth Programme (GROWTH 2000).

The objective of this DARTS-project is to develop operational methods and supporting practical tools for the best passive decision-making process for selecting in each individual case, the cost optimal tunnel type and construction procedures regarding environmental conditions, technical qualities, safety precautions and long service life.

DARTS is developed for the main current types of tunnels: rock tunnels, bored tunnels, NATM tunnels, immersed tunnels and cut and cover tunnels.

8.3 UPTUN

UPTUN is the acronym for cost effective, sustainable and innovative upgrading methods for fire safety in existing tunnels, a European RTD-project funded by the European Commission in FP5.

The main UPTUN project objectives are:

a) To develop innovative technologies where appropriate and relevant, comparing to and assessing existing technologies for tunnel application. Focus is on technologies in areas of detection and monitoring, mitigating measures, influencing human response, and protection against structural damage.

b) To develop, demonstrate and promote procedures for rational safety level evaluation, including decision support models and knowledge transfer.

In order to achieve these objectives overall, a strong European consortium was needed, covering all relevant expertise, with sufficient mass and impact to ensure adoption of UPTUN deliverables throughout Europe. The consortium was built around prominent tunnel safety institutes in Europe, balancing owners, industry, research and other stakeholders on the one hand, with the (tunnel) member states on the other.

The UPTUN consortium consists of 41 members from 13 different EU member states, 1 EEA member state and 3 accession countries. The distribution of the input to the project was well balanced over the eastern, northern, southern and western EU member states.

The project was specifically targeted at ensuring a pan European approach towards improvement of fire safety in European tunnels. This will enable European tunnel operators and regulators to benefit from economies of scale resulting from a European approach and also create additional added-value for the community.

Among others, a full scale fire test in the Runehamar Tunnel in Norway was conducted in the framework of UPTUN.

8.4 SIRTAKI

SIRTAKI (Safety Improvement in Road and Rail Tunnels using Advanced ICT and Knowledge Intensive DSS) is an IST project supported by the Commission of The European Communities in the framework of the "Key Action I of IST Programme".

The strategic goal of SIRTAKI is the development and assessment of an advanced tunnel management system that specifically tackles safety issues and emergencies and integration within overall network management.

A multidisciplinary consortium with representation from all participating members, including local authorities, system providers and research institutions from eight different European countries, has implemented numerous SIRTAKI initiatives over 36 months from September 2001.

PROMATECT®-H RWS-HCM board – product properties

PROMATECT®-H RWS-HCM board is a non combustible matrix engineered mineral board reinforced with selected fibres and fillers. It does not contain formaldehyde or Magnesium Oxy-Chlorides.

Material properties

Generic description	PROMATECT®-H RWS-HCM board
Surface condition	Front face: smooth Back face: sanded
Alkalinity	pH 12
Coefficient of expansion	-6.4 x 10^{-6} m/mk
Water vapour diffusion resistance factor, μ	5
Thickness tolerance	From ±0.5mm (standard thickness boards)
Dimension tolerance	±3mm (standard dimension boards)

Physical performance

Property	Test method	Test results
Density	BS EN 323	Dry 105°C: 870kg/m³ ± 15% 23°C, 50% RH: 940kg/m³ ± 15%
Modulus of elasticity, E	BS EN 310	Longitudinal 4995N/mm² Transverse 4389N/mm²
Flexural strength, $F_{rupture}$	BS EN 310	Longitudinal 10N/mm² Transverse 6N/mm²
Tensile strength, $T_{rupture}$	BS 5669: Part 1	Longitudinal 7.14N/mm² Transverse 4.94N/mm²
Compressive strength	BS 5669: Part 1	11.36N/mm²
Combustibility	AS 1530: Part 1 DIN 4102: Part 1 EN 13501-1 (A1)	Non combustible
Surface burning	BS 476: Part 7 AS 1530: Part 3	Class 1 Class 0,0,0,0
Thermal conductivity	ASTM C518	0.242W/m°K
Moisture content	BS EN 322	6%

Fixing

Screw pull out resistance	RAMPA (Type B 3815) screw inserts Screw depth of 15mm on board face: 330N

Standard dimension

Thickness	Length x Width
8mm ± 0.5	2440mm x 1220mm, 2500mm x 1250mm
10mm ± 0.5	2440mm x 1220mm, 3000mm or 2500mm x 1250mm
12mm ± 1.0	2440mm x 1220mm, 3000mm or 2500mm x 1250mm
15mm ± 1.0	2440mm x 1220mm, 3000mm or 2500mm x 1250mm
18mm ± 1.0	2440mm x 1220mm, 3000mm or 2500mm x 1250mm
20mm ± 1.0	2440mm x 1220mm, 3000mm or 2500mm x 1250mm
25mm ± 1.5	2440mm x 1220mm, 3000mm or 2500mm x 1250mm
27.5mm ± 1.5	2440mm x 1220mm, 3000mm or 2500mm x 1250mm

PROMATECT®-H RWS-HCM board is off-white in colour. The front face is smooth and is suitable for any forms of architectural/finishing treatment; the reverse face is sanded.

PROMATECT®-H RWS-HCM board is resistant to effects of moisture and will not physically deteriorate in a damp or humid environment. Whilst its performance characteristics are not degraded by moisture or aging under normal tunnel operating conditions, PROMATECT®-H RWS-HCM board is not designed for application in areas subject to continual damp or high temperatures.

Application

- Lining for tunnel structure fire protection
- Cladding to steel ducts, self-supporting ducts
- Cable and services enclosure
- Fire exit door

Health and safety

When machining the PROMATECT®-H RWS-HCM product, airborne dust may be released, which may be hazardous to health. Do not inhale the dust. Avoid contact with skin and eyes. Use dust extraction equipment. Respect regulatory occupational exposure limits for total inhalable and respirable dust. Safety data sheet is available from Promat and, as with any other material, should be read before working with the product.

PROMATECT®-H RWS-HCM product is not classified as a dangerous substance so no special provisions are required regarding the transportation and the disposal of the product to landfill. The product can be placed in on-site rubbish skips with other general building waste which should then be disposed by a registered contractor in the appropriate and approved manner.

Disclaimer

PROMATECT®-H RWS-HCM board is used in the higher temperature tunnel fire curves such as RWS and HCM. Where the specification calls for lower temperature fire curves, e.g. RABT, HC and ISO, the board used is standard grade PROMATECT®-H.

All properties herein are mean values given for information and guidance only. If certain properties are critical for a particular application, it is advisable to consult Promat. PROMATECT®-H RWS-HCM board is manufactured under a quality management system certified in accordance with ISO 9001: 2008. The product has passed the site audit in accordance with the environmental standards of ISO 14001: 2004 and occupational health and safety requirements of OHSAS 18001: 2007.

PROMATECT®-T matrix engineered calcium silicate-aluminate board – product properties

PROMATECT®-T matrix engineered calcium silicate-aluminate board is a non combustible matrix engineered mineral board reinforced with selected fibres and fillers. It does not contain formaldehyde and Magnesium Oxy-Chlorides.

Material properties

Generic description	PROMATECT®-T matrix engineered calcium silicate-aluminate board
Surface condition	Front face: smooth, sanded Back face: lightly honeycombed textured
Alkalinity	pH 10
Coefficient of expansion	-8.3×10^{-6} m/mk
Thermal shrinkage	1.7 (3 hours at 950°C) 4.0 (3 hours at 1250°C)
Water vapour diffusion resistance factor, µ	5
Thickness tolerance	±0.5mm (standard thickness boards)
Dimension tolerance	±3mm (standard dimension boards)

Physical performance

Property	Test method	Test results
Density	BS EN 323	Dry 105°C: 900kg/m^3 ± 10% 23°C, 50% RH: 940kg/m^3 ± 10%
Flexural strength,	BS EN 310	Longitudinal 4.5N/mm^2
Tensile strength,	BS 5669: Part 1	Longitudinal 1.2N/mm^2
Compressive strength	BS 5669: Part 1	1.2N/mm^2 (1% deformation) 7.8N/mm^2 (10% deformation)
Combustibility	EN 13501-1 (A1)	Non combustible
Surface burning	BS 476: Part 7 AS 1530: Part 3	Class 1 Class 0,0,0,0
Thermal conductivity	ASTM C518	0.212W/m°K (at 20°C)

Fixing

Screw pull out resistance	50mm long quick fix screw 5mm 20mm deep: 657N (air dry), 372N (saturated)
Bolt pull through resistance	M8 bolt, washer diameter 30mm 3.22N (for 25mm thick boards)

Standard dimension

Thickness	Length x Width	Tolerances (length, width)
12mm ± 0.5	2500mm x 1200mm	+3mm, -3mm
15mm ± 0.5	2500mm x 1200mm	+3mm, -3mm
20mm ± 0.5	2500mm x 1200mm	+3mm, -3mm
25mm ± 0.5	2500mm x 1200mm	+3mm, -3mm
30mm ± 0.5	2500mm x 1200mm	+3mm, -3mm
35mm ± 0.5	2500mm x 1200mm	+3mm, -3mm
40mm ± 0.5	2500mm x 1200mm	+3mm, -3mm

Please contact Promat for supply information of squared boards.

PROMATECT®-T board is off-white in colour. The front face is smooth and is suitable for any forms of architectural/finishing treatment; the reverse face is sanded.

PROMATECT®-T board is resistant to effects of moisture and will not physically deteriorate in a damp or humid environment. Whilst its performance characteristics are not degraded by moisture or aging under normal tunnel operating conditions, PROMATECT®-T board is not designed for application in areas subject to continual damp or high temperatures.

Application

Curved lining for tunnel structure fire protection.

Health and safety

When machining the PROMATECT®-T product, airborne dust may be released, which may be hazardous to health. Do not inhale the dust. Avoid contact with skin and eyes. Use dust extraction equipment. Respect regulatory occupational exposure limits for total inhalable and respirable dust. Safety data sheet is available from Promat and, as with any other material, should be read before working with the product.

PROMATECT®-T product is not classified as a dangerous substance so no special provisions are required regarding the transportation and the disposal of the product to landfill. The product can be placed in on-site rubbish skips with other general building waste which should then be disposed by a registered contractor in the appropriate and approved manner.

Disclaimer

All properties herein are mean values given for information and guidance only. If certain properties are critical for a particular application, it is advisable to consult Promat. PROMATECT®-T matrix engineered calcium silicate-aluminate board is manufactured under a quality management system certified in accordance with ISO 9001: 2008. The product has passed the site audit in accordance with the environmental standards of ISO 14001: 2004 and occupational health and safety requirements of OHSAS 18001: 2007.

Fire incidents in road tunnels worldwide

Year	Tunnel @ length	Location	Vehicle(s) of which the fire occurred	Most possible cause of fire	Duration of fire	Consequences		
						Injuries and/ or casualties	Damage of vehicles	Damage of structure
1949	Holland @ 2,550m	New York, USA	1 lorry with 11 tons of carbondisulfide	Load fell off, exploded	240 minutes	66 injured of smoke inhalation	10 lorries + 13 cars	Serious damage over 200m
1974	Mont Blanc @ 11,600m	France and Italy	1 lorry	Motor problem	15 minutes	1 injured	Unknown	Unknown
1976	Crossing BP-A6 @ 430m	Paris, France	1 lorry with 16 tons of polyester film in drums	High speed	60 minutes	12 injured of smoke inhalation	1 lorry	Serious damage over 150m
1978	Velsen @ 770m	Velsen, The Netherlands	4 lorries + 2 cars	Front-rear collision	80 minutes	5 injured + 5 dead	4 lorries + 2 cars	Serious damage over 30m
1979	Nihonzaka @ 2,045m	Shitzuoka, Japan	4 lorries + 2 cars	Front-rear collision	9540 minutes	1 injured + 7 dead	127 lorries + 46 cars	Serious damage over 1,100m
1980	Kajiwara @ 740m	Kajiwara, Japan	1 truck with 3600 litres of paint in 200 cans	Collided with side wall and overturned	Unknown	1 dead	2 trucks	Serious damage over 280m
1982	Caldecott @ 1,028m	Oakland, CA, USA	1 lorry with 33000 litres of petrol + 1 coach + 1 car	Front-rear collision	160 minutes	2 injured + 7 dead	3 lorries + 1 coach + 4 cars	Serious damage over 580m
1982	Salng @ 2,700m	Mazar-e-Sharif-Kabul, Afghanistan	Soviet Military column, at least 1 petrol truck	Suspected mine explosion	Unknown	>200 dead	Unknown	Unknown
1983	Pecorila Galleria @ 662m	Gênes Savone, Italy	1 lorry with fishes	Front-rear collision	Unknown	22 injured + 9 dead	10 cars	Minor damage
1986	L'Arme @ 1,105m	Nice, France	1 lorry with trailer	Braking after high speed	Unknown	5 injured + 3 dead	1 lorry + 4 cars	Equipment destroyed
1987	Gumefens @ 343m	Berne, Switzerland	1 lorry	Front-rear collision	120 minutes	2 dead	2 lorries + 1 van	Slight damage
1990	Røldal @ 4,656m	Røldal, Norway	1 transporter with trailer	Unknown	50 minutes	1 injured	Unknown	Minor damage
1990	Mont Blanc @ 11,600m	France and Italy	1 lorry with 20 tons of cotton	Motor problem	Unknown	2 injured	1 lorry	Equipment destroyed
1993	Serra Ripoli @ 442m	Bologne and Florence, Italy	1 lorry with rolls of paper + 1 car	Collision	150 minutes	4 injured + 4 dead	5 lorries + 11 cars	Minor damage
1993	Hovden @ 1,290m	Høyanger, Norway	2 cars + 1 motorcycle	Front-rear collision	60 minutes	5 injured	2 cars + 1 motorcycle	111m of insulation material destroyed
1994	Huguenot @ 3,914m	Western Cape, South Africa	1 coach with 45 passengers	Electrical fault	60 minutes	28 injured + 1 dead	1 coach	Serious damage
1995	Pfänder @ 6,719m	Lochau, Austria	1 lorry with trailer	Collision	60 minutes	4 injured + 3 dead	1 lorry + 1 van + 1 car	Serious damage

Above details are up to date of this publication.
Source from *ITA Working Group 6 – Structural fire protection for road tunnels, Report No. 18. April 2017.*

Continued on next page

Fire incidents in road tunnels worldwide

Year	Tunnel @ length	Location	Vehicle(s) of which the fire occurred	Most possible cause of fire	Duration of fire	Consequences		
						Injuries and/ or casualties	Damage of vehicles	Damage of structure
1996	Isola Delle Femmine @ 148m	Palermo, Italy	1 tanker with liquid gas + 1 bus	Front-rear collision	Unknown	20 injured + 5 dead	1 tanker + 1 bus + 18 cars	Serious damage, tunnel closed for 2½ days
1999	Mont Blanc @ 11,600m	France and Italy	1 lorry with flour and margarine	Oil leakage in the motor	Unknown	39 dead	23 lorries + 10 cars + 1 motorcycle	Serious damage, tunnel reopened on 22nd Dec 2001
1999	Tauern @ 6,401m	A10 Salzburg-Spittal, Austria	1 lorry with paint	Front-rear collision	Unknown	49 injured + 12 dead	14 lorries + 26 cars	Serious damage
2000	Seljestad @ 1,272m	E134 Drammen-Haugesund, Norway	1 trailer truck with a diesel fire in the engine room + 1 lorry + 5 cars	Multiple collision	45 minutes	6 injured	1 truck + 1 lorry + 5 cars + 1 motorcycle	Serious damage, NOK 1 mill, tunnel closed for 1½ days
2001	Prapontin @ 4,409m	A32 Torino-Bardonecchia, Italy	1 truck with beets	Mechanical problem	Unknown	19 injured of smoke inhalation	Unknown	Closed until 6th June 2001 in westerly direction
2001	Gleinalm @ 8,320m	A9 near Graz, Austria	1 car	Front collision	Unknown	4 injured + 5 dead	Unknown	Unknown
2001	St. Gotthard @ 16,918m	A2, Switzerland	1 lorry	Front collision	48 minutes	11 dead	13 lorries + 4 vans + 6 cars	Serious damage, tunnel closed for 2 months

Above bove details are up to date of this publication.
Source from *ITA Working Group 6 – Structural fire protection for road tunnels, Report No. 18. April 2017.*

Runehamar tests and gas temperatures in collaboration with UPTUN: Large scale fire test in Runehamar Tunnel, Norway

In total, four tests were performed on a fire in a semi-trailer set-up. In three tests mixtures of different cellulose and plastic materials were used to simulate the fire load, and in one test a "real" commodity consisting of furniture and fixtures was used. In all tests the ratio of mass was approximately 80% cellulose to 20% plastic. A polyester tarpaulin covered the cargo.

The commodities used as fuel are detailed in below table and the following:

Test	Description of fire load	Target	Total weight	Theoretical calorific energy	Mass ratio of plastic
Test #1	• 360 wood pallets, measuring 1200mm x 800mm x 150mm • 20 wood pallets, measuring 1200mm x 1000mm x 150mm • 74 PE plastic pallets, measuring 1200mm x 800mm x 150mm	• 32 wood pallets • 6 plastic pallets	10,911kg	240GJ	18%
Test #2	• 216 wood pallets + 240 PUR mattresses, measuring 1200mm x 800mm x 150mm	• 20 wood pallets • 20 PUR mattresses	6,853kg	129GJ	18%
Test #3	• Furniture and fixtures (tightly packed plastic and wood cabinet doors) • Upholstered PUR arm rest and sofas • Stuffed animals • Potted (plastic) plant • Toy house of wood, plastic toys • 10 large rubber tyres @ 800kg	• Upholstered PUR arm rest and sofas	8,500kg	152GJ	18% (not in including tyres)
Test #4	• 600 corrugated paper cartons with interiors, measuring 600mm x 400mm x 500mm • 15% of total mass of 18,000 unexpanded polystyrene cups • 40 wood pallets, measuring 1200mm x 1000mm x 150mm	• 4 wood pallets • 40 cartons with 1,800 PS cups	3,120kg	67GJ	19%

Overview of fire development after five minutes

The reason for using furniture is that in the past a test was carried out (e.g. EUREKA 499 project) with similar materials and a very high ventilation rate of 6m/s at the start of the test. This particular test provides a good point of comparison between the data from both Runehamar and EUREKA tests.

The commodities were placed on particle board in a storage rack system (see figures on page 62 to simulate a semi-trailer, measuring 10450mm by 2900mm. The total height was 4500mm. The height of the platform from the floor was 1100mm.

Continued on next page

Runehamar tests and gas temperatures in collaboration with UPTUN: Large scale fire test in Runehamar Tunnel, Norway

The test fire was located 560m from the west entrance and the wind direction in the tunnel was from east to west. The cross-section of the tunnel at the site of the test fire is shown in below Figure 59. Two small ignition sources, consisting of fibreboard cubes soaked with heptane, were placed within the lowest wood pallets (adjacent to the flue between the two pallets) on the upstream end of the semi-trailer set-up. The tarpaulin was lifted away during the ignition process. Directly after ignition the tarpaulin was replaced. At a distance of 15m from the downstream side of the test site there was a target consisting of one stack of the same materials combination as used in the main test. This target was used to ascertain fire spread due to radiation and convection.

Figure 56 Set-up for Test #1 (wood and plastic pallets)

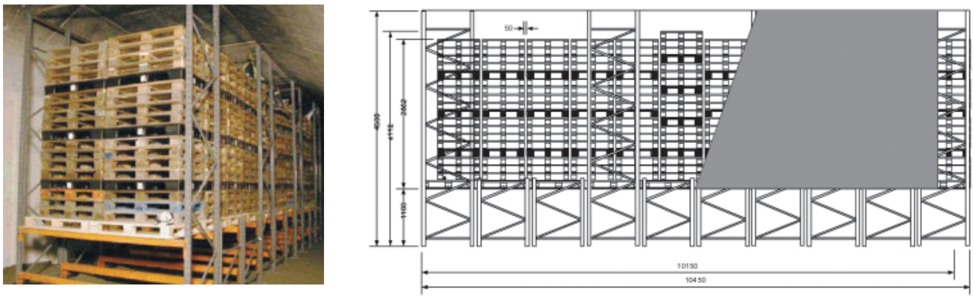


Figure 57 Set-up for Test #2 (wood pallets and FUR mattresses)

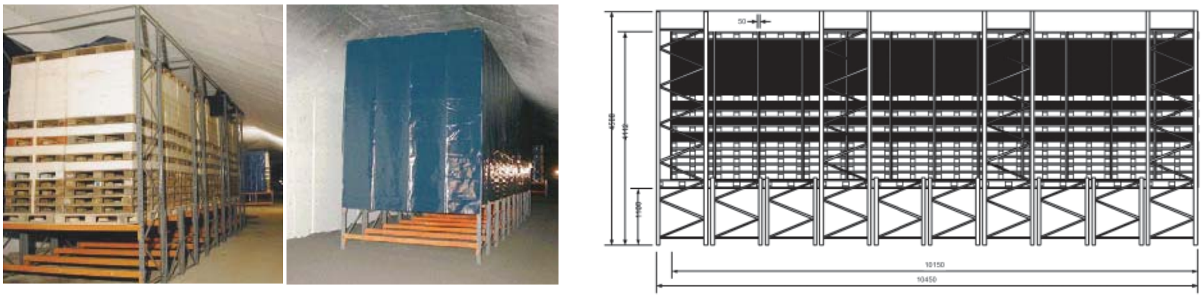
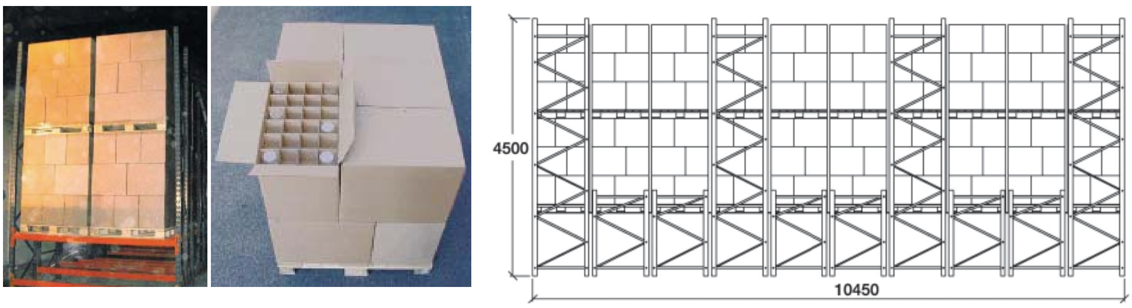


Figure 58 Set-up for Test #3 (wood flat pack furniture and plastic toys)

Figure 59 Set-up for Test #4 (plastic cups in cardboard boxes on wood pallets)



Runehamar tests and gas temperatures in collaboration with UPTUN: Large scale fire test in Runehamar Tunnel, Norway

The materials used in the tests (see Figure 60) were chosen to give different fire development and maximum Heat Release Rates (HRR). Test #1 with wood pallets and plastic pallets had the highest total energy content and gave the highest maximum heat release rate (see Figure 61).

The large amount of combustible material also gave a longer period of elevated gas temperatures, with the highest maximum temperature of 1365°C.

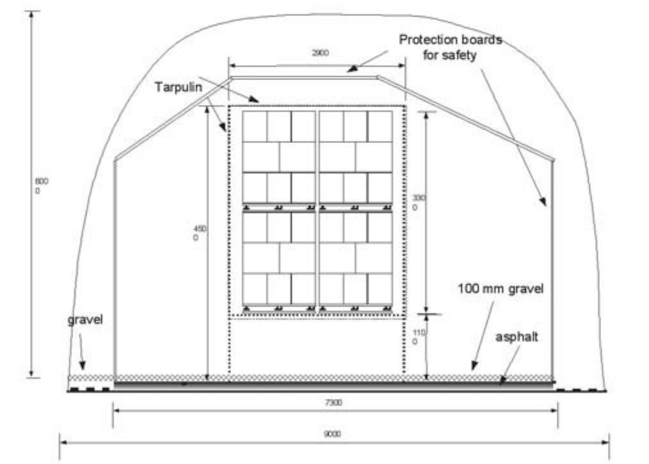


Figure 60 Cross section of the tunnel at the test location

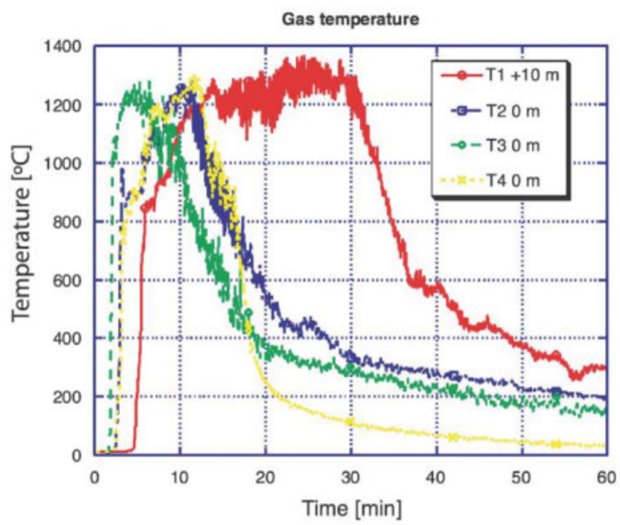


Figure 61 Measured gas temperatures close to the fire during Tests #1–4

In Figure 62 the gas temperature near the ceiling in Test #1 (at 10m from the heat source) is compared to four different standard fire curves. It can be seen that the increase in gas temperature in the test with wood pallets and plastic pallets is very rapid and almost exactly follows the Hydrocarbon fire curve for about three minutes.

The temperature then increases even further and more rapidly than the Hydrocarbon fire curve. It instead follows the RWS fire curve, again almost exactly, apart from the slight time variations and for a period around 20 minutes after ignition where the measured temperature is higher than the peak of the RWS fire curve which is 1350°C.

The RWS fire curve was developed on the assumption that a tanker fire with petrol or fuel oil lasting for 120 minutes would give a HRR of 300MW. The HRR tested in the Runehamat Tunnel did not reach 300MW, but the temperatures recorded still closely followed the RWS fire curve.

In Test #4 only 3120kg of cardboard boxes and polystyrene cups were used, potentially creating the lowest calorific energy output of all tests. However, temperatures were recorded to be in the same magnitude of Test #1, although for a much shorter duration.

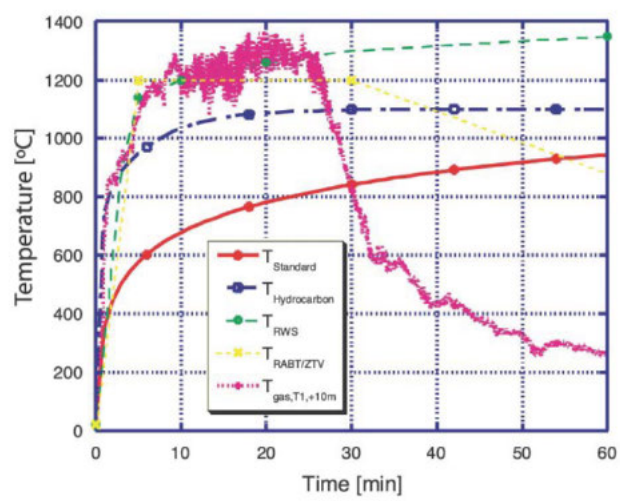


Figure 62 Gas temperatures in Test #1 compared with four different standard fire curves

Frequently asked questions

9.1 Should vertical tunnel walls be protected as well?

This depends on the assessment of the risk by the relevant authorities and fire consultants. In many tunnels up to 1m of the wall down from the tunnel soffit requires fire protection. Research on the Runehamar Tunnel suggests that walls do need some degree of protection.

9.2 Which is the best protection method to minimise servicing requirements after the tunnel is completed? Is post cladding easier to remove while lost shuttering is more difficult?

Promat has up to 40 years of experience detailing and providing fire protection systems to tunnel applications. To date there has not been a requirement to totally remove PROMATECT® boards for servicing. It is true that post cladding facilitates ease in retrieval.

9.3 How are the cracks in the tunnel concrete treated during fixing of protection materials?

Cracks in concrete pose no problem to the PROMATECT® boards. If cracks in the concrete need to be repaired, the boards can be removed, or drilled through to gain access to the concrete for grouting repairs.

9.4 Does protection of PROMATECT® boards inhibit regular inspection and maintenance procedures of the tunnel, especially for water seepage and concrete spalling?

Water seepage is expected especially in sub-sea tunnels. For example, Westerschelde Tunnel has a 12m water column. PROMATECT® can be soaked by water seepage. Wet spots are therefore visible and hence do not inhibit inspection.

9.5 How about rebar carbonisation? How would a PROMATECT® board lining affect treatment of this problem in tunnel?

The concrete cover should be designed for addressing this aspect, although the PROMATECT® board lining shields the concrete from direct contact of aggressive car pollution. An examination of a 9-year old PROMATECT® board cladding to Velser Tunnel in the Netherlands showed negligible loss of strength. No rebar carbonisation was visible in the concrete.

9.6 Can the boards be removed after installation if required?

Yes, for post fixed applications, if there is a perceived need to remove boards at some point in the future. Instead of using flat head anchors, a locking nut/washer combination can be specified.

9.7 How do the protection materials react to alternating pressure from vehicular traffic?

Many tests have been carried out subjecting PROMATECT® board specimens of alternating pressures, 3 times more cycles than normally encountered in vehicular tunnels. No displacement of the system occurred.

9.8 How does installer build in maintenance and service procedure for PROMATECT® boards installed in an operational tunnel?

PROMATECT® boards require little or no maintenance, other than visual inspection.

Frequently asked questions

9.9 How does fixing of services and lighting to a protected concrete soffit affect fire performance of the tunnel concrete?

Drilling through the boards does not adversely affect the performance of the system, assuming of course that the installer does not go too far and drills holes everywhere. Tests have been carried out to both RWS and Hydrocarbon fire curves where services have been bolted through the PROMATECT® boards (simulated in the tests by suspending weights from expansion bolts) and the performance of the system is consistent between these tests and the standard tests where no penetrations have been made. Of course, all services should be supported directly from the concrete and the installer should not rely on fixing any services only to the PROMATECT® boards.

9.10 How does the installer ensure the screws or bolts remain in situ?

If PROMATECT® boards are used as permanent shuttering, screws are embedded within the concrete and thus cannot fall out. Tests have been carried out to show that even without the screws, a section of board used as shuttering has very high adhesion to the concrete and will not fall away. Tests on fully soaked boards have been carried out to simulate the effects on suction and to ascertain whether the bolt heads and washers would pull through the board. Tests were carried out on 15mm, 20mm, 25mm and 30mm thick boards showed that very high loads are required to pull the fixings through the boards. The average pull through strength measured for a 25mm thick board, fully immersed in water for 72 hours prior to test, was a pull through load of 1884N for a 6mm diameter expansion bolt and 1271N for a 5mm diameter screw.

9.11 What happens if there are any post installation gaps between the PROMATECT® boards?

This depends on the size of the gaps. PROMATECT® boards have been tested where gaps of 3mm were deliberately left between the boards in an attempt to simulate poor installation. No adverse affects were recorded in these tests.

9.12 Will these boards contribute to corrosion of metallic objects within the tunnel?

No. Unlike magnesium type boards, PROMATECT®-H calcium silicate boards will not contribute to corrosion.

9.13 Can these boards be used in a circular tunnel?

Depending on the radius, PROMATECT®-T boards can be for post curving to the shape of the tunnel. If the radius is too small, a faceted system can be used such as in the Port of Miami tunnel.

Please consult the local Regional Tunnel Manager.

9.14 What colour & appearance are the boards?

PROMATECT®-H RWS-HCM board is off-white in colour and has a smooth finish on one face with a sanded reverse face.

PROMATECT®-T matrix engineered calcium silicate-aluminate board is smooth on front and sanded on the back with lightly honeycombed texture and greyish white in colour.

9.15 What types of finish are available for board lining in tunnel?

PROMATECT® boards can be left undecorated or easily finished with a water borne 2-pack epoxy coating to enhance light reflection and to aide washability.

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Through its subsidiaries, the group offers an extensive range of products: small and large roofing materials, cladding and building boards, passive fire protection systems and ceramic tiles.

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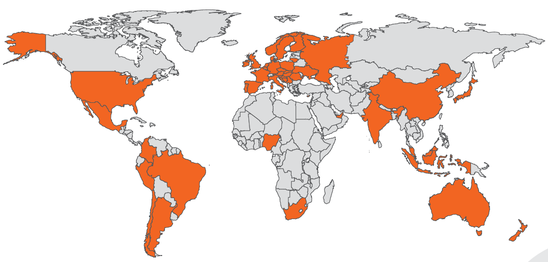

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