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Promat

Tunnel Fire Protection

For Tunnel Structures & Services

www.promat-tunnel.com

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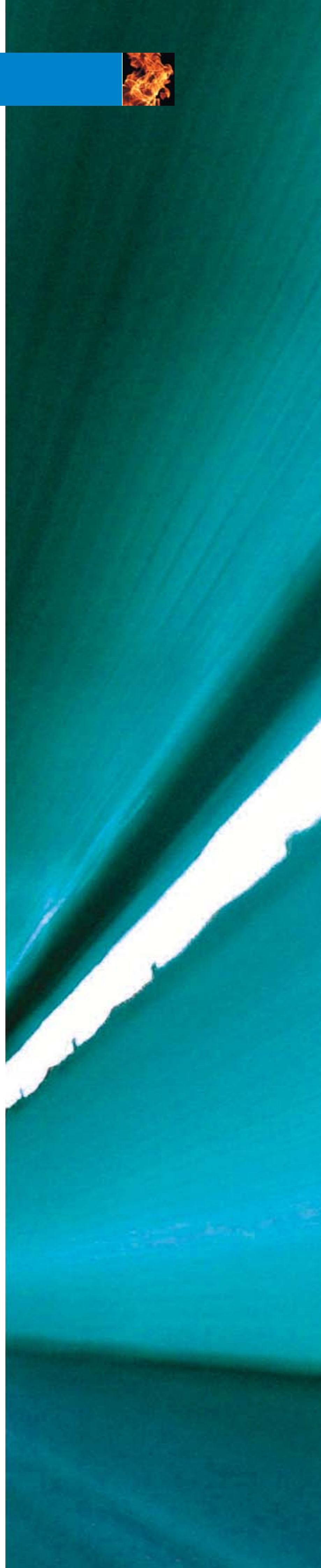
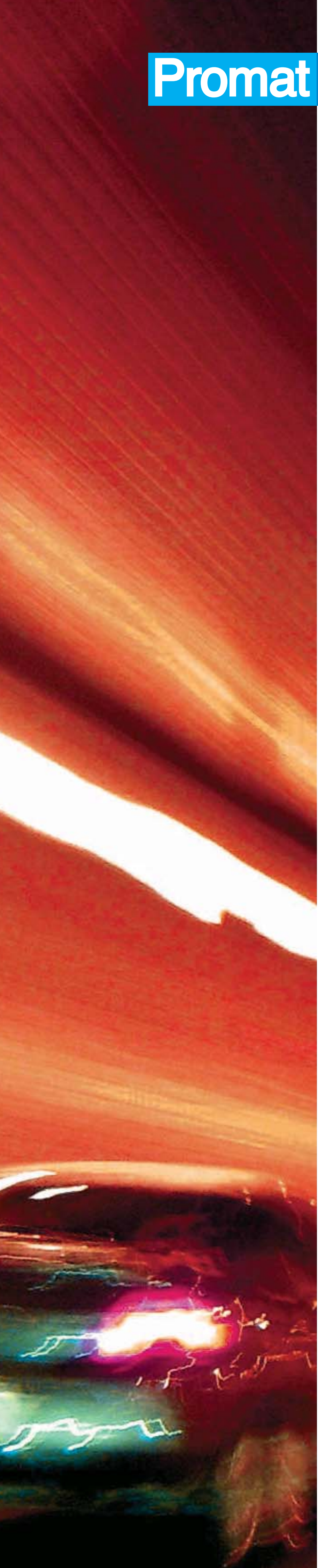




TABLES, GRAPHS & DIAGRAMS

1. INTRODUCTION

Fires in tunnels are a major hazard to human life. Tunnel fires also cause costly damage to surrounding infrastructure. Limited escape facilities and difficulties encountered by intervention forces in gaining access to the tunnel fire call for extensive safety arrangements which must be complementary and mutually coordinated.

Tunnels and underground transport facilities are important means of communication, not only in terms of shorter journey times but increasingly out of consideration for the local population and the environment. Generally speaking, important underground transport links are expected to be available without any restrictions and to operate smoothly round the clock. Interruptions due to accidents, technical malfunctions or maintenance work quickly cause traffic jams and delays, and figure in transport policy statistics as economic losses.

Rising traffic densities and the growing demand for underground communication links result in a higher probability of accidents, injuries and damage. Added to this are other factors which increase the potential hazards of traffic tunnels:

- the increasing length of modern tunnels
- the transportation of hazardous materials
- two-way traffic (with undivided carriageways)
- higher fire loads due to growing traffic volumes and higher loading capacities
- mechanical defects in motor vehicles

When considering tunnels, it is usually in relation to road and rail infrastructure. However, use of the word tunnels can be slightly misleading, as the following information can apply equally to pedestrian walkways, underground rail stations, underground car parks etc...in fact to any concrete structure. Although this document refers to tunnels throughout, all information also applies to underground spaces of any description.

It is usually assumed that because a structure is constructed using concrete, that it is inherently fire resistant, and therefore requires no additional fire protection measures to be taken. Unfortunately, experience over the years has shown that this is not necessarily the case and consideration must be given to the performance and behaviour of concrete structures under fire conditions. In addition, where tunnels and underground spaces are concerned, consideration must also be given to the provision of services protection, e.g. smoke extraction systems, protection to cables and wiring providing power to emergency equipment.

This handbook is intended to provide some background into the behaviour of concrete under fire conditions, to show proven methods of protecting structures against fire, and of providing protection to services within tunnels and underground spaces.

2. WHY PROTECT TUNNELS?

There are three reasons for providing protection against fire within tunnels. First, there is the matter of life safety. This is not necessarily a function of structural performance under fire – although a collapsing structure would not enable people to exit a structure in safety – but more to do with the function of services such as emergency lighting, smoke extraction systems and so on.

Within Europe alone, in the past decade or so, there have occurred within road and rail tunnels at least 10 major fires, and countless minor fire situations. These fires have resulted in a major loss of life (221 dead in four fires that took place over a period of just two years) and in all cases significant structural damage occurred, not to mention substantial economic costs to the community.

As an example, outlined below are some of the tunnel fires which have occurred during the 1990's and earlier this decade, and the resultant death toll. TABLE 2 on pages 16-23 gives an extensive overview of tunnel fire history.

TABLE 1: CASUALTIES IN TUNNEL FIRES

Location	Casualties	Location	Casualties
Bosnia	35	Hokuriku Tunnel, Japan	34
Mont Blanc, France	39	Pecorile Tunnel	8
Tauern Tunnel, Austria	12	O'Shimizu Tunnel	16
Vierzy Tunnel, France	108	Salang Tunnel, Afghanistan	700
Pfänder Tunnel, Austria	3	Kings Cross, England	31
Huguenot Tunnel	3	Isola delle Femmine, Italy	5
Nihonzaka, Japan	7	Velsen, Netherlands	5
St Gottard Tunnel, Switzerland	11	Kaprun, Austria	155

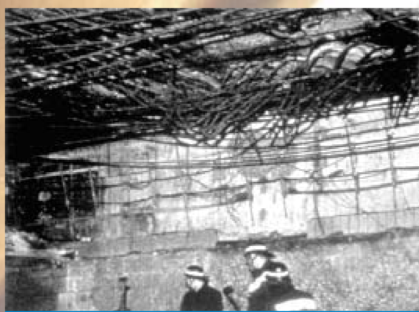
Second, there is the performance of the structure itself. Will it remain in-situ? Will it collapse, possibly causing collateral damage to other parts of the structure and injuries to people passing by? In the Mont-Blanc-Tunnel fire, there was severe spalling of the structural concrete. During the fire 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 both these tunnels pass through rock, localised collapse or spalling although potentially costly and inconvenient, did not endanger persons located away from the damaged areas. If these tunnels had been of the immersed type, the structural damage could have resulted in flooding of the tunnels, with all the associated implications.

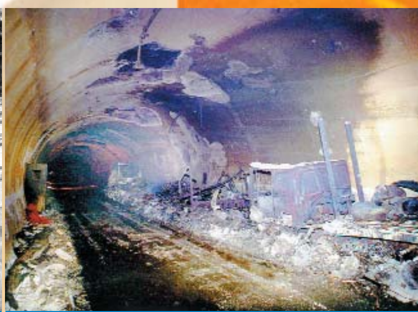
It should be noted that after the fire in the Channel Tunnel, the only thing standing between total loss and a situation where effective repair could be carried out was the thin grout layer between the concrete structure and the water bearing rock layer, so severe was the spalling of the concrete. A 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.

Thirdly, there is the economic damage caused as a result of the failure of a tunnel. This 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 and traffic diversions etc. which result in the largest costs.

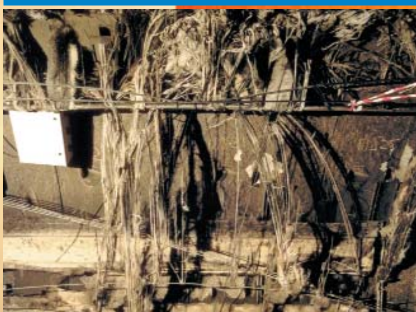
A prime example is the Channel Tunnel fire. Economic damage was estimated to be over twice the cost of the actual tunnel repairs. The direct repairs to the tunnel cost an estimated €87 million while the additional costs in lost business, replacement of infrastructure, materials (e.g. lorries, train carriages etc) together with the impact of the tunnel closure on other, unrelated businesses brought the economic loss alone to some €215 million.

FIGURE 1: EXAMPLES OF FIRE DAMAGE


Example 1 – Moorfleet Tunnel, Germany


Example 2 – Mont Blanc Tunnel, Italy

Example 3 – Velsen Tunnel, Netherlands


Example 4 – Channel Tunnel, UK

Using Mont Blanc Tunnel as a comparison for a simple road tunnel, the differences are not so marked, with the cost of repair being estimated at approximately €206 million and the economic cost at some €250 million. However, the socioeconomic 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.

In terms of fire protection within tunnel and underground systems, the following items should require some consideration.

- Enhancing the fire resistance of the structure
- Air supply systems
- Smoke extract systems
- The provision of fire and smoke resistant safe havens in long tunnels
- Active and passive detection systems
- Fire extinguishing systems
- Fire doors
- Warning and alarm systems

2. WHY PROTECT TUNNELS?

2.1 IMPLICATIONS OF THE EU DIRECTIVE ON STRUCTURAL REQUIREMENTS FOR ROAD TUNNEL

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. 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

The document presents 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 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 EU 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

OBJECTIVE OF THE EU 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 the EU Directive was primarily to make tunnel stakeholders more "risk averse" in generic operational risks with particular reference to the consequences of fire.

2. WHY PROTECT TUNNELS? *Continued from page 9*

2.2 IMPLICATIONS OF THE EU DIRECTIVE TO TUNNEL STRUCTURES

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.

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

2.2.1 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 EU Directive, as explained above, refers to Risk Management techniques and makes specific reference to risk analysis but 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 International in joint partnership with leading consultants in the field of Risk Management of structures has developed a suite of tools which allows the tunnel stakeholders to make key decisions to ensure compliance with the EU 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 EU 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.

2.2.2 RISK ANALYSIS

Almost all risk assessment tools use the explicit risk assessment formula

$$\text{RISK} = \sum \text{FREQUENCY x CONSEQUENCE}$$

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. We know the 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 HRR, the heat release rate).

Promat International with its partnering consultant IEB Consulting Ltd have 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 EU Directive, has been used widely throughout the world to derive design fire sizes for structural resistance in tunnels.

Output from this Qualitative Risk Analysis (QRA) model results in a "Probability – Fire Size Matrix" (see at right).

HRR (MW)	Probability	Years
5	0.325	3.08
15	0.056	17.92
25	0.056	17.79
50	0.068	14.60
100	0.023	42.92

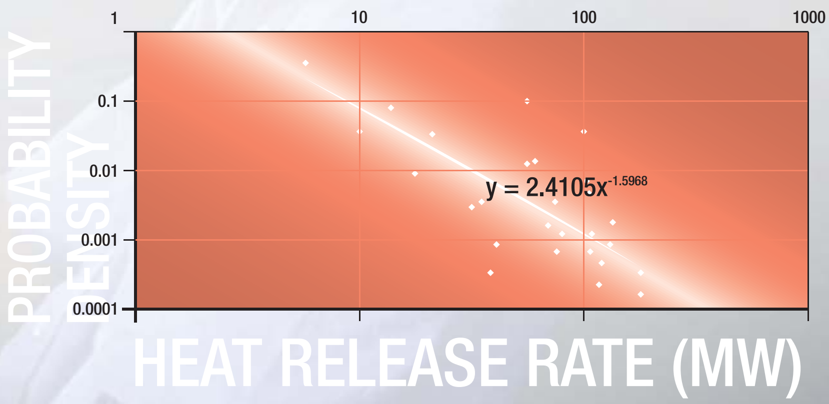


FIGURE 2: HEAT RELEASE RATE (MW)/PROBABILITY DENSITY

Using a balanced approach, analysis of the matrix determines the "design fire size" and as shown in FIGURE 2 sets the Structural Design Criteria in the consequential analysis using Computational Fluid Dynamics (CFD) & Finite Element Analysis (FEA) tools to assess the need or otherwise for Risk Reduction Measures.

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 the above case it was concluded that the probability of the 100MW fire lay within the design life of the tunnel. CFD & FEA was then used to assess the structural performance from such a fire load.

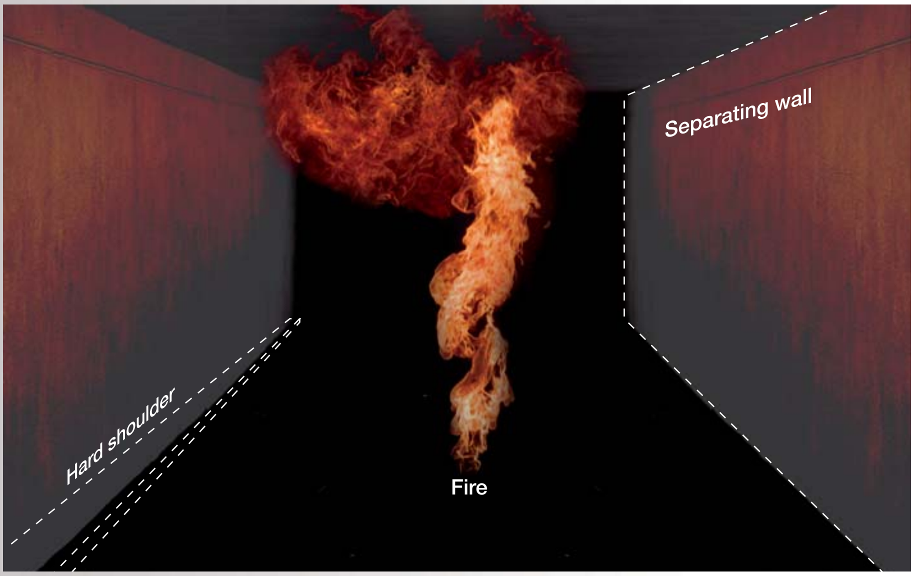
2. WHY PROTECT TUNNELS? *Continued from page 11*

2.2.3 COMPUTATIONAL FLUID DYNAMICS (CFD) AND FINITE ELEMENT ANALYSIS (FEA)

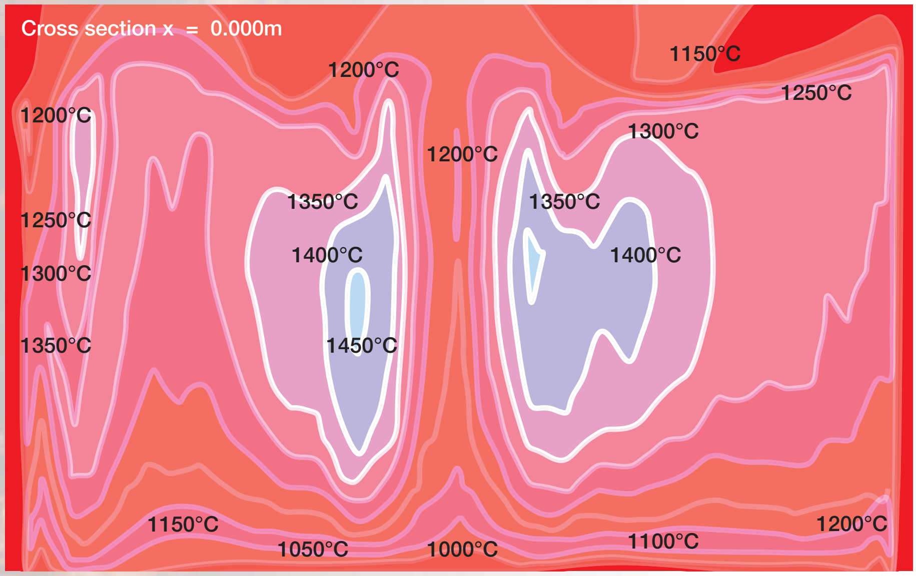
Following risk analysis, if it is concluded that the probability and magnitude of the fire risk may result in consequential structural damage, an assessment of this consequential damage needs to be undertaken. IEB Consulting Ltd and TNO/Efectis have pioneered the coupling of Computational Fluid Dynamics (CFD) and Finite Element Analysis (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 3: 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.

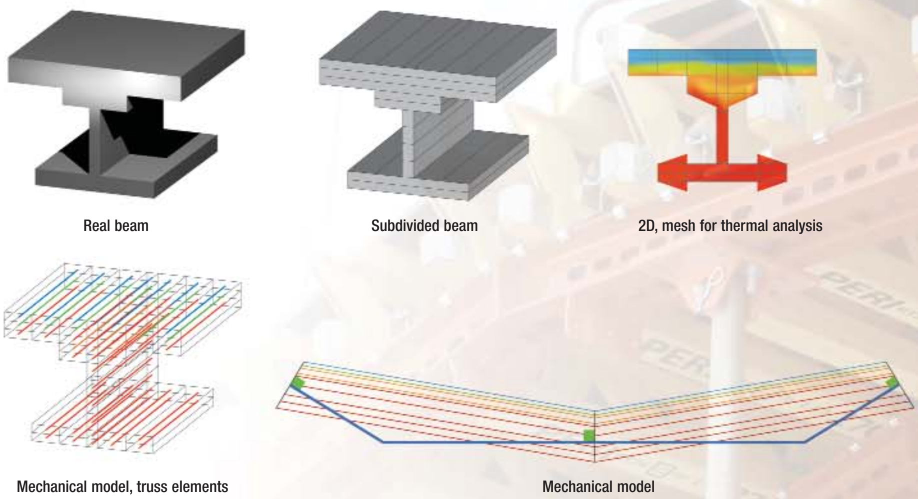


The FEA component allows detailed time dependent failure analysis to be assessed for all components forming the structure and allows detailed assessment up to the point at which the structure is no longer self supporting and failure mechanism begins. For complex structures such as cut & cover tunnels,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

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

This CFD & FEA approach has recently been accepted by the European tunnel community as current best practice in assessing structural resilience of tunnels and was recently presented at a symposium on catastrophic fires in tunnels.

FIGURE 4: STRUCTURAL BEAM FOR TUNNEL SYSTEM



UPTUN WP4 TUNNEL SYSTEM STRUCTURAL RESPONSE

Objectives and results:

- Insight into the structural performance of load bearing elements,
- Define structural procedures to reduce critical behaviour,
- Investigate damage mitigation of the load bearing structures,
- Preserve the functional characteristics of structures,
- Optimise repair and recovery procedures.

Please contact Promat for more information on this analysis by TNO Building & Construction Research in collaboration with Uptun.

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

2. WHY PROTECT TUNNELS? *Continued from page 13*

2.2.4 ECONOMIC AND ENVIRONMENTAL IMPACT

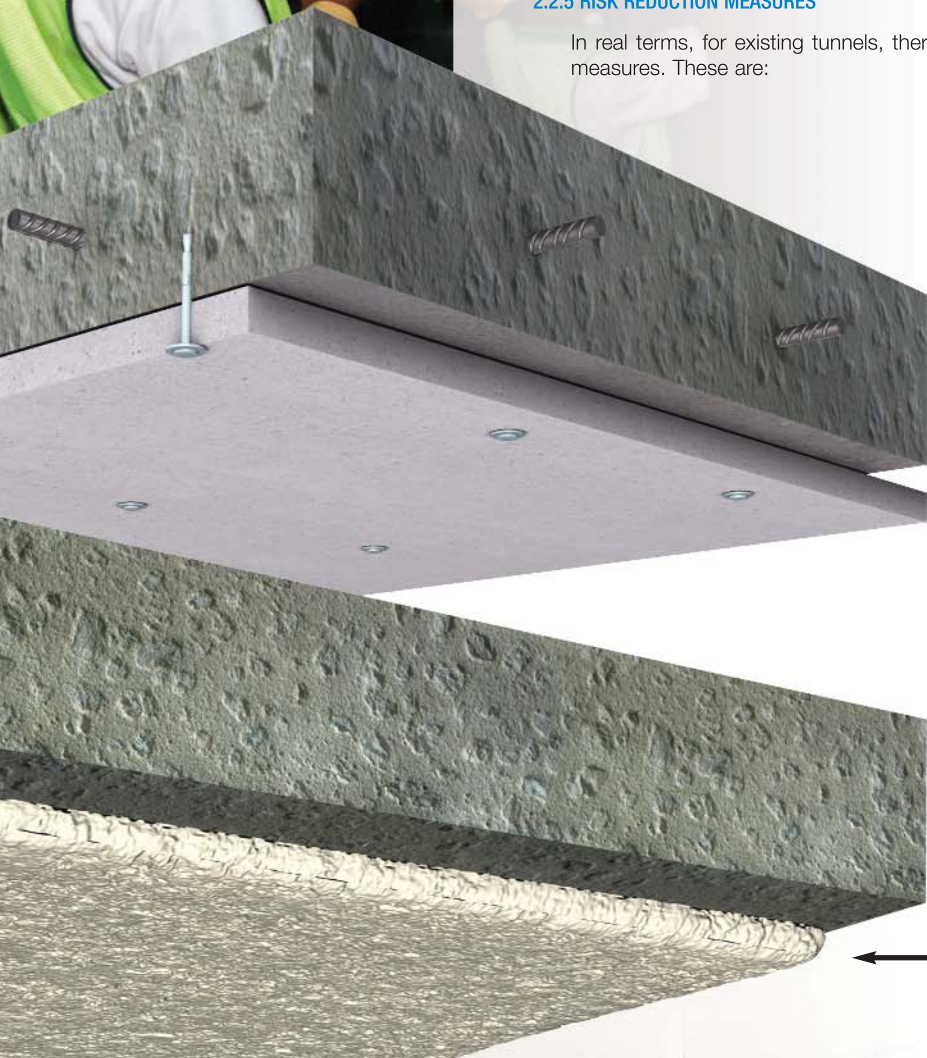
Another factor in assessing the need for structural resilience of tunnels is the need to assess the economic & environmental impact following failure due to fire.

As described on pages 6 and 7, the loss of tunnel operations due to structural collapse can have severe economic and environmental impact on local and national communities.

IEB Consulting Ltd, partners with Promat International have developed an Excel 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 CFD & 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.

2.2.5 RISK REDUCTION MEASURES

In real terms, for existing tunnels, there are two main approaches to introducing Risk Reduction measures. These are:



THE BOARD SOLUTION

and

THE SPRAY APPLIED SOLUTION

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 tunnel. The recent acquisition of Cafco International by Promat assures flexibility in achieving the best solution.

CONCLUSION

Existing EU Legislation & 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 IEB Consulting Ltd and TNO/Efectis, allows Promat International to assist stakeholders to appreciate their obligations regarding Legislative Requirements & Best Practice.

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.

These Design Tools include:

- Quantified Risk Assessments,
- CFD & FEA Analysis,
- Economic & Environmental Impact Analysis, and
- Design of Risk Reduction Solutions.

They will enable stakeholders to fully assess, through a Risk Management process, compliance with the EU Directive and engage in current best practice.

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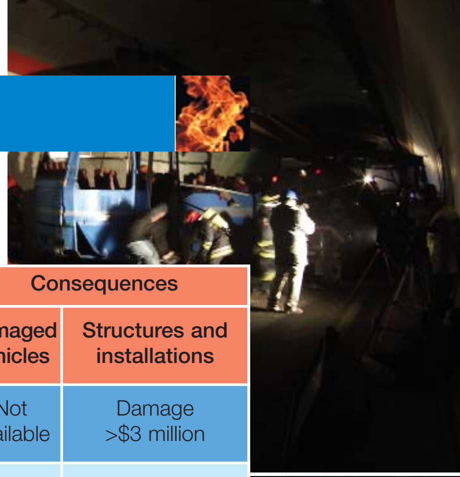
TABLE 2: TUNNEL FIRE HISTORY

Country	Year	Tunnel	Length	Vehicle where fire occurred	Most possible cause of fire	Duration of fire	Consequences	
							Damaged vehicles	Structures and installations
Afghanistan	1982	Mazar-e-Sharif-Kabul – Salang	2,700m	Soviet Military column, at least one petrol truck	Gas tanker explosion	Not available	Not available	Severe damage to structure
Australia	2007	Burnley Melbourne	3,400m	Car/truck collision	Fire due to collision	1 hour	Cars and trucks	Not available
Austria	2002	Tauern – Salzburg	6,400m	Lorry	Faulty engine	Not available	Not available	Severe smoke production
Austria	2001	Gleinalm – A 9 near Graz	8,320m	Coach	Short circuit	>1 hour	1 coach	Severe smoke production over 3km
Austria	2001	Gleinalm – A 9 near Graz	8,320m	Swedish tourist coach	Not available	Not available	Not available	Not available
Austria	2001	Gleinalm – A 9 near Graz	8,320m	Coach	Not available	Not available	Not available	Not available
Austria	2001	Gleinalm – A 9 near Graz	8,320m	Car	Front collision lorry-car	Not available	Not available	Not available
Austria	2001	Tauern – Salzburg	6,400m	Cars	Head on collision of two cars	Not available	2 cars	Not available
Austria	2000	Kitzsteinhorn – Kaprun funicular tunnel	3,300m	Passenger train	Hydraulic oil leak onto heater	Not available	1 train	Line closed for over 1 year
Austria	2000	Tauern – Salzburg	6,400m	HGV	Not available	½ hour	1 HGV	Not available
Austria	1999	Tauern – A10 Salzburg – Spittal	6,400m	Lorry loaded with paint	Front-rear collision 4 cars and 2 lorries	15 hours	16 lorries, 24 cars	Serious damage
Austria	1995	Pfander	6,719m	Lorry with trailer	Collision	1 hour	1 lorry, 1 van, 1 car	Serious damage
Austria	1989	Brenner	200m	Dangerous goods exploded during construction	Dangerous goods	7 hours	Not available	Not available
Austria	1987	Tanzenberg	2,400m	Car	Suicidal car driver	Not available	1 car	Significant damage to tunnel structure and dense smoke
Austria	1986	Herzogberg	2,000m	HGV	Overheated brakes	Not available	1 HGV	1 HGV
Austria	1984	Felbertauern	5,000m	Coach	Overheated brakes	>1 hour	1 coach	Damage to tunnel lining >100m
Azerbaijan	1995	Baku	Not available	Railway/metro train	Electrical fault at rail car	Not available	1 train	Severe smoke production
Belgium	2004	Kinkempois	600m	HGV	Not available	Not available	1 HGV	Closed for several days
Belgium	1987	Brussels Underground	Not available	Station fire	Not available	Not available	Not available	Dense smoke
Canada	2000	Montreal Metro	Not available	Cable fire	Cable	6 hours	Not available	Electrical system, severe smoke production
Canada	2000	Toronto Metro	Not available	Railway/metro train	Not available	Not available	1 train	Line closed for 24 hours
Canada	1997	Toronto Metro	Not available	Train	Rubber matting under the track caught fire	Not available	Rubber matting	Severe smoke production



Country	Year	Tunnel	Length	Vehicle where fire occurred	Most possible cause of fire	Duration of fire	Consequences	
							Damaged vehicles	Structures and installations
Canada	1976	Christie Street Metro Montreal	Not available	Station fire	Arson attack	Not available	Not available	Damage >$3 million
Canada	1974	Rosemont Metro Montreal	Not available	Train fire	Short circuit	Not available	1 train	Not available
Canada	1971	Henri Bourassa Montreal	Not available	Train fire	Collision with end of the tunnel	Not available	1 train	Not available
China	1998	Gueizhou – Guiyang/ Chansha	800m	Train	Exploding gas canisters	Not available	1 train	Tunnel collapsed
Denmark	1994	Great Belt – Korsor during construction	Not available	Tunnel boring machine	Explosion at TBM due to leaking hydraulic oil	Not available	1 TBM	Severe damage to tunnel lining
France	2004	Dullin – Chambery	1,500m	Coach	Engine compartment	1 hour	1 coach	Not available
France	2003	Cret d'Eau	4,000m	Train	Sleeper carriage	Not available	1 train	Not available
France	2003	Mornay	2,600m	Train	Passenger carriage	5 hours	1 train multiple cars	Not available
France	2002	A86 – Versailles Under construction	Not available	Cargo train	Engine exploded	6 hours	1 cargo train	Not available
France	2000	Toulon	1,850m	Construction vehicle	Collision of two construction vehicles	4 hours	2 construction vehicles	Not available
France	1994	Castellar	570m	HGV carrying waste paper	Tyre caught fire	Not available	1 HGV	Not available
France	1986	L'Arme – Nice	1,105m	Lorry with trailer	Braking after high speed	Not available	1 lorry, 4 cars	Equipment destroyed
France	1985	Paris Metro	Not available	Station fire	Rubbish fire	Not available	Not available	Not available
France	1983	Frejus	12,900m	HGV loaded with plastics	Gearbox fire	2 hours	1 HGV	Severe damage to tunnel lining over 200m
France	1979	Paris Metro	Not available	Train fire	Short circuit	Not available	1 train	Heavy smoke
France	1977	Paris Metro	Not available	Station fire	Not available	Not available	Not available	Not available
France	1976	Crossing BP-A6 Paris	430m	Lorry with drums of 16 tons polyester film	High Speed	4 hours	1 lorry	Serious damage over 150m
France	1976	Porte d'Italie B6	430m	HGV carrying 16 tons polyester plastic	Engine fire	1 hour	Not available	Tunnel lining destroyed over 150m
France	1975	Château de Vincennes Metro	Not available	Train	Short circuit under car fire	Not available	1 train	Not available
France	1973	Porte d'Italie Metro	430m	Railway carriage	Arson attack	Not available	1 carriage	Not available
France	1972	Vierzy	Not available	Passenger train	Tunnel collapse	Not available	1 train	Not available
France	1971	Crozet	Not available	Goods train and hydrcarbon fuel train	Collision and derailment	Not available	2 trains	Not available

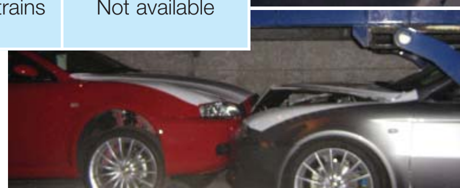


TABLE 2: TUNNEL FIRE HISTORY *Continued from page 17*

Country	Year	Tunnel	Length	Vehicle where fire occurred	Most possible cause of fire	Duration of fire	Consequences	
							Damaged vehicles	Structures and installations
France	1971	Paris Metro	Not available	Train fire	Arson attack	Not available	1 train	Not available
France	1921	Batignolles	1,000m	Passenger train	Collision with stationary train	Not available	2 trains	Not available
France	1903	Couronnes Metro Paris	Not available	Train fire	Electrical fault	Not available	2 trains	Not available
France	1842	Mendon	Not available	Train fire	Not available	Not available	Not available	Not available
France/Italy	2004	Frejus	12,900m	HGV	Breaks caught fire	2½ hours	1 HGV	Not available
France/Italy	1999	Mont Blanc	11,600m	Lorry with 12 tons flour and 9 tons margarine	Oil leakage motor, overheating	>53 hours	23 lorries, 10 cars, 1 motor-cycle etc	Serious damage, tunnel reopens
France/Italy	1990	Mont Blanc	11,600m	Lorry with 20 tons cotton	Motor	Not available	1 lorry	Equipment destroyed
France/Italy	1988	Mont Blanc	11,600m	HGV	Not available	Not available	1 HGV	Not available
France/Italy	1981	Mont Blanc	11,600m	HGV	Engine fire	Not available	1 HGV	Not available
France/Italy	1978	Mont Blanc	11,600m	HGV	Not available	Not available	1 HGV	Dense smoke
France/Italy	1974	Mont Blanc	11,600m	Lorry	Motor	15 minutes	Not available	Dense smoke
France/UK	1996	Channel Tunnel	51,000m	HGV carrier	Polystyrene boxes	7 hours	1 HGV carrier, 10 HGV's	Explosive spalling of concrete lining
Germany	2001	Dusseldorf U Bahn	Not available	Railway/metro train	Train roof caught fire	Not available	1 train	Not available
Germany	2001	Kurt Schu-macher Platz station – Berlin	Not available	Train	Arc lamp	Not available	Not available	Severe smoke production
Germany	2000	Berlin U Bahn	Not available	Train	Not available	Not available	1 train	Not available
Germany	2000	Saukopf – Weinheim	2,700m	Car	Not available	Not available	1 car	Not available
Germany	1999	Candid – Munchen	252m	Car	Car engine	Not available	1 car	Not available
Germany	1999	Leinebush – Göttingen	Not available	High speed cargo train	Ball bearings overheated and train derailed	>12 hours	1 train	Not available
Germany	1991	Bonn U Bahn	Not available	Train	Electrical fire broke out on a train in a station	Not available	1 train	Not available
Germany	1984	Landungs-bruken U Bahn	Not available	Station fire	Arson attack	Not available	Not available	Severe damage $3 million
Germany	1983	Hauptbahnhof U Bahn Munich	Not available	Train	Electrical fire	Not available	Not available	Damage >$2 million
Germany	1981	Ramersdorf U Bahn Bonn	Not available	Station fire	Technical fault	Not available	Not available	Damage $0.5 million

Country	Year	Tunnel	Length	Vehicle where fire occurred	Most possible cause of fire	Duration of fire	Consequences	
							Damaged vehicles	Structures and installations
Germany	1980	Altora U Bahn Hamburg	Not available	Train	Arson attack	Not available	Not available	Damage $5 million
Germany	1978	Hansaring U Bahn Cologne	Not available	Train fire	Not available	Not available	1 train	Damage $1.2 million
Germany	1977	Berlin U Bahn	Not available	Station fire	Fire during construction	Not available	Not available	Not available
Germany	1972	Alexanderplatz U Bahn East Berlin	Not available	Train fire	Derailment	Not available	1 train	Not available
Germany	1968	Moorfleet Hamburg	243m	HGV carrying 14 tons polyethylene bags	Overheated brakes	1 hour 30 min	Not available	Severe concrete spalling over 34m
Hong Kong	2000	Cross Harbour	1,800m	Car	Not available	½ hour	1 car	Not available
Italy	2001	Prapontin – A32 Torino-Bardonecchia	4,409m	Romanian truck, loaded with beets	Mechanical problem	Not available	Not available	Closed until 6 June in westerly direction
Italy	1999	Salerno Railway	9,000m	Passenger train	Smoke bomb set off by football fans	Not available	1 train	Not available
Italy	1997	Exilles rail – Susa	2,100m	Train transporting cars	A cars door swung open hitting electrical wiring causing fire	5 hours	13 freight wagons, 156 cars	Concrete spalling
Italy	1997	Prapontin – A32 Torino-Bardonecchia	4,409m	HGV	Overheated brakes	4 hours	1 HGV	Explosive spalling of concrete lining
Italy	1996	Isola Delle Femmine – Palermo	148m	1 tanker with liquid gas, 1 mini small bus	Front-rear collision	Not available	1 tanker, 1 bus, 18 cars	Serious damage, tunnel closed for 2½ days
Italy	1993	Serra Ripoli Bologne-Florence	442m	1 car/lorry with rolls of paper	Collision	2 hours 30 min	5 lorries, 11 cars	Little damage
Italy	1984	San Benedetto	18,500m	Cars	Bomb attack	>2 hours	Cars	Severe damage to structure
Italy	1983	Pecorile Galleria – Gênes – Savone	662m	Lorry with fish	Front-rear collision	Not available	10 cars	Little damage
Japan	1980	Kajiwara	740m	1 truck with 3600 litres of paint in 200 cans	Gearbox fire, collision with side wall and overturning	1 hour 30 min	One 4 ton truck, one 10 ton truck	Serious damage over 280m
Japan	1980	Sakai	459m	Truck	Collision	3 hours	1 truck, 10 vehicles	Not available
Japan	1979	Shitzuoka – Nihonzaka	2,045m	4 lorries, 2 cars	Front-rear collision	168 hours	127 lorries, 46 cars	Serious damage over 1100m
Japan	1972	Hokoriku Fukui	Not available	Passenger train	Restaurant car fire	Not available	2 carriages	Not available
Japan	1967	Suzaka	244m	Truck carrying 600 polystyrene boxes	Engine fire	>11 hours	13 trucks	Not available
Mexico	1985	Mexico City Underground	Not available	Metro car	Not available	Not available	1 metro car	Not available
Mexico	1975	Mexico City Underground	Not available	Train	Train collision	Not available	Not available	Not available
Netherlands	2001	Schiphol Airport	Not available	Not available	Electrical connection box	Not available	Not available	Not available

TABLE 2: TUNNEL FIRE HISTORY *Continued from page 19*

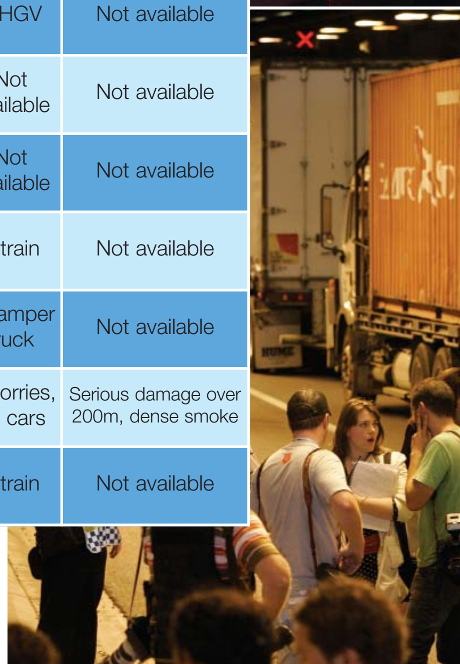
Country	Year	Tunnel	Length	Vehicle where fire occurred	Most possible cause of fire	Duration of fire	Consequences	
							Damaged vehicles	Structures and installations
Netherlands	1999	Amsterdam Underground	Not available	Railway/metro train	Train section	Not available	1 train	Not available
Netherlands	1978	Velsen	770m	2 HGVs and 4 cars	Front-rear collision	1 hour 30 min	4 lorries, 2 cars	Serious damage over 30m
New Zealand	2002	Homer – Milford	1,200m	Coach	Engine compartment	Not available	1 coach	Not available
Norway	2003	Floyfjell – Bergen	3,100m	Car	Car crash, burst into flames on impact	Not available	1 car	Tunnel lining ignited
Norway	2000	Laerdal	24,500m	Coach	Not available	Not available	1 coach	Not available
Norway	2000	Oslofjord	Not available	Truck	Not available	Not available	1 truck	Not available
Norway	2000	Rotsethhorn	1,200m	Car	Collision	Not available	Not available	Not available
Norway	2000	Seljestad – E134 Drammen-Haugesund	1,272m	The trailer truck that caused the multiple collision had a diesel fire in the engine room before collision	Front-rear collision	45 minutes	1 lorry, 6 cars, 1 motorcycle	Serious damage over 1600m, tunnel closed for ½ day
Norway	1999	Oslofjord	Not available	Not available	Explosion during construction started fire	Not available	Not available	Not available
Norway	1996	Ekeberg	1,500m	Bus	Engine fire	2 hours	1 bus	Not available
Norway	1995	Hitra	5,600m	Mobile crane	Overheated engine	2 hours	1 crane	Not available
Norway	1993	Hovden – Høyanger	1,290m	Motorcycle, 2 cars	Front-rear collision	½ hour	1 motor-cycle, 2 cars	111m insulation material destroyed
Norway	1993	Vardo	Not available	Car	Minor fire incident	Not available	Not available	Not available
Norway	1990	Røldal	4,656m	VW transporter with trailer	Engine fire	50 minutes	Not available	Little damage
Portugal	1976	Lisbon Underground	Not available	Train	Electrical fire	Not available	1 train	Damage over $1.8 million
Russia	1991	Moscow Underground	Not available	Train	Electrical fire under train	Not available	1 train	Not available
Russia	1987	Moscow Underground	Not available	Train	Train	Not available	1 train	Not available
Russia	1981	Okyabrskaya Underground Moscow	Not available	Station fire	Short circuit	Not available	Not available	Damage $250,000
Russia	1974	Moscow Underground	Not available	Station fire	Electrical fault	Not available	Not available	Not available
Slovenia	2004	Trojane	2,900m	Not available	Diesel powered air compressor	Not available	Not available	Not available
Slovenia	2003	Golovec – Ljubljana	700m	Coach	Not available	Not available	1 coach	Not available
Slovenia	2003	Locica	800m	HGV	Not available	Not available	1 HGV	Not available

Country	Year	Tunnel	Length	Vehicle where fire occurred	Most possible cause of fire	Duration of fire	Consequences	
							Damaged vehicles	Structures and installations
South Africa	1994	Huguenot	3,914m	Bus with 45 passengers	Electrical fault in gearbox	1 hour	1 coach	Serious damage closed for 4 days
South Korea	2003	Daegu Jungangno Underground Station	400m	Train	Attack using petrol	24 hours	6 carriage trains	Severe damage to concrete
Spain	2003	Guadarrama Rail	30,000m	Train	Train accident	5 hours	1 train	Not available
Spain	1975	Guadarrama	3,300m	Tanker of pine resin	Tanker caught fire	2 hours 45 min	1 tanker	Severe damage to tunnel structure and toxic smoke
Spain	1944	Torre	Not available	Train fire	Multi train collision	>24 hours	Multiple trains	Not available
Sweden	1960	Stockholm Underground	Not available	Train fire	Short circuit	Not available	1 train carriage	Not available
Sweden	1955	Not available	Not available	Train fire	Overheating	Not available	1 train carriage	Not available
Switzerland	2001	St. Gotthard – A2	16,918m	Lorry	Front collision of 2 lorries	>48 hours	13 lorries, 4 vans, 6 cars	Collapse of over 250m of tunnel lining, closed for 2 months
Switzerland	1997	St. Gotthard – A2	16,918m	Car transporter	Overheated engine	3 hours	1 car transporter, 8 cars	Slight damage
Switzerland	1997	St. Gotthard – A2	16,918m	Bus	Overheated engine	20 minutes	1 bus	Not available
Switzerland	1994	St. Gotthard – A2	16,918m	HGV	Tyre caught fire	2 hours	1 HGV carrying 750 bicycles in carton boxes	Severe damage over 50m to tunnel lining
Switzerland	1991	Hirschengraben – Zurich	1,300m	Train	Train car	Not available	1 train	Not available
Switzerland	1987	Gumefens – Berne	343m	1 lorry	Front-rear collision	2 hours	2 lorries, 1 van	Slight damage
Switzerland	1984	St. Gotthard – A2	16,900m	HGV	Rolls of plastic	½ hour	1 HGV	Damage to tunnel facilities
Switzerland	1976	San Bernardino	6,600m	Bus	Bus caught fire	Not available	1 bus	Not available
Switzerland	1972	Lötschberg	Not available	Fire during construction work	Not available	Not available	Not available	Not available
Switzerland	1941	St. Gotthard Giorinco	Not available	Train fire	Derailment	Not available	1 train	Not available
Switzerland	1932	Gütschtunnel	Not available	Train fire	Train collision	Not available	2 trains	Not available
Switzerland	1926	Riekentunnel	Not available	Goods train	Caught fire and stopped in tunnel	Not available	1 goods train	Dense smoke
Switzerland	1969	Simplon	19,800m	Passenger train	Rear carriage caught fire	Not available	1 train	Not available
UK	1994	Kingsway – Liverpool	2,000m	Bus	Bus caught fire	1 hour	1 bus	Minor damage to tunnel
UK	1987	Kings Cross Underground Station	Not available	Wooden escalator	Grease and fibres under escalator floor	6 hours	Not available	Train station

TABLE 2: TUNNEL FIRE HISTORY *Continued from page 21*

Country	Year	Tunnel	Length	Vehicle where fire occurred	Most possible cause of fire	Duration of fire	Consequences	
							Damaged vehicles	Structures and installations
UK	1984	Oxford Circus Underground	Not available	Equipment	Equipment in maintenance tunnel	Not available	Not available	Equipment destroyed
UK	1984	Summit	2,600m	Train with 13 tankers of petroleum spirit	Derailment	72 hours	1 diesel locomotive, 13 tankers	Severe damage to structure
UK	1982	Picadilly Line London Underground	Not available	Cable fire	Electrical cable fire	Not available	Not available	Not available
UK	1981	London Underground	Not available	Station fire	Not available	Not available	Not available	Severe damage
UK	1976	Finsbury Park Underground	Not available	Train	Cable fire	Not available	1 train	Not available
UK	1975	Goodge Street London Underground	Not available	Cross passage	Not available	Not available	Not available	Not available
UK	1975	Moorgate London Underground	Not available	Train	Derailment, train hitting wall	Not available	1 train	Not available
UK	1960	Redbridge London Underground	Not available	Train fire	Arcing in receptacle box	Not available	1 train	Dense smoke
UK	1958	Holland Park London Underground	Not available	Train fire	Arcing in receptacle box	Not available	1 train	Dense smoke
UK	1949	Penmanshiel	Not available	Train fire	Not available	Not available	1 train	Not available
UK	1945	London Underground	Not available	Train fire	Collision	Not available	2 trains	Not available
UK	1905	London Underground	Not available	Train fire	Not available	Not available	1 train	Not available
UK	1866	Welwyn North	Not available	Goods train	Collision	Not available	3 trains	Not available
USA	2007	San Francisco McArthur bridge	Not available	Petrol tanker	Caught fire	Not available	1 tanker	Bridge deck collapsed
USA	2002	Ted Williams	2,600m	Coach	Electrical compartment	Not available	1 coach	Severe smoke production
USA	2001	Howard street – Baltimore	2,253m	Cargo train	Emergency brakes	12 hours	60 train cars, 8 carrying hydro-chloric acid	Not available
USA	2000	New York City Subway	Not available	Train	Electrical supply	>2 hours	1 train	Not available
USA	1999	New York City Subway	Not available	Rubbish fire	Electrical cabling	Not available	Not available	Not available
USA	1996	Washington DC Subway	Not available	Railway/metro train	Short circuit on a carriage led to explosion and fire	Not available	1 train	Not available
USA	1992	New York City Subway	Not available	Not available	Electrical fire on the track	Not available	Not available	Dense smoke
USA	1992	New York City Subway	Not available	Metro car	Under car fire	Not available	1 metro car	Not available
USA	1990	Los Angeles Subway	Not available	Timber supports during construction	Timber supports	Not available	Not available	45m of tunnel collapsed

Country	Year	Tunnel	Length	Vehicle where fire occurred	Most possible cause of fire	Duration of fire	Consequences	
							Damaged vehicles	Structures and installations
USA	1990	New York City Subway	Not available	Cable fire	Cable	Not available	1 train	Dense smoke
USA	1985	Grand Central Station New York	Not available	Station fire	Arson attack	Not available	Not available	Severe damage to station, $3 million
USA	1984	New York City Subway	Not available	Subway car	Under car fire	Not available	1 metro car	Not available
USA	1984	New York City Subway	Not available	Subway car	Cable fire	Not available	2 trains	Dense smoke
USA	1982	Caldecott	1,028m	1 car, 1 coach, 1 lorry with 33000 litres of petrol	Front-rear collision	2 h 40min	3 lorries, 1 coach, 4 cars	Serious damage over 580m
USA	1982	New York City Subway	Not available	Train	Not available	6 hours	4 carriages	Not available
USA	1982	Washington DC Subway	Not available	Train	Derailment	Not available	1 train	Not available
USA	1981	New York City Subway	Not available	Train	Fault in current collectors led to explosion	½ hour	1 train	Not available
USA	1979	Eric Street Subway Philadelphia	Not available	Train fire	Transformer fire	Not available	1 train	Not available
USA	1979	New York City Subway	Not available	Station fire	Discarded cigarette ignited oil spillage on the track	Not available	Not available	Dense smoke
USA	1979	San Francisco Subway	Not available	Train fire	Short circuit	Not available	1 train	Severe smoke production
USA	1978	Baltimore Harbour Freeway	Not available	Truck and fuel tanker	Collision	Not available	1 truck, 1 fuel tanker, 1 HGV	Not available
USA	1975	Blue Mountain	1,300m	Truck carrying fish oil	Engine fire	Not available	1 truck	Not available
USA	1975	Boston Subway	Not available	Subway car	Broken catenary led to a fire	Not available	1 metro car	Not available
USA	1975	New York City Subway	Not available	Subway rail system	Technical fault	Not available	Not available	Not available
USA	1974	Chesapeake Bay	Not available	HGV carrying 190 litre fuel tank	Exploding tyre	4 hours	1 HGV	Not available
USA	1974	Congress New York	Not available	Goods train	Derailment	Not available	Not available	Not available
USA	1971	Sylmar	8,000m	Gas explosion during construction	Not available	Not available	Not available	Not available
USA	1970	New York City Subway	Not available	Train fire	Not available	Not available	1 train	Not available
USA	1970	Wallace	1,000m	Truck fire	Engine caught fire	Not available	1 camper truck	Not available
USA	1949	Holland tunnel New York	2,550m	Lorry with 11 tons of carbondisulfide	Load falling off lorry, explosion	4 hours	10 lorries, 13 cars	Serious damage over 200m, dense smoke
Yugoslavia	1971	Wranduk Zenica	1,500m	Train fire	Engine fire	Not available	1 train	Not available



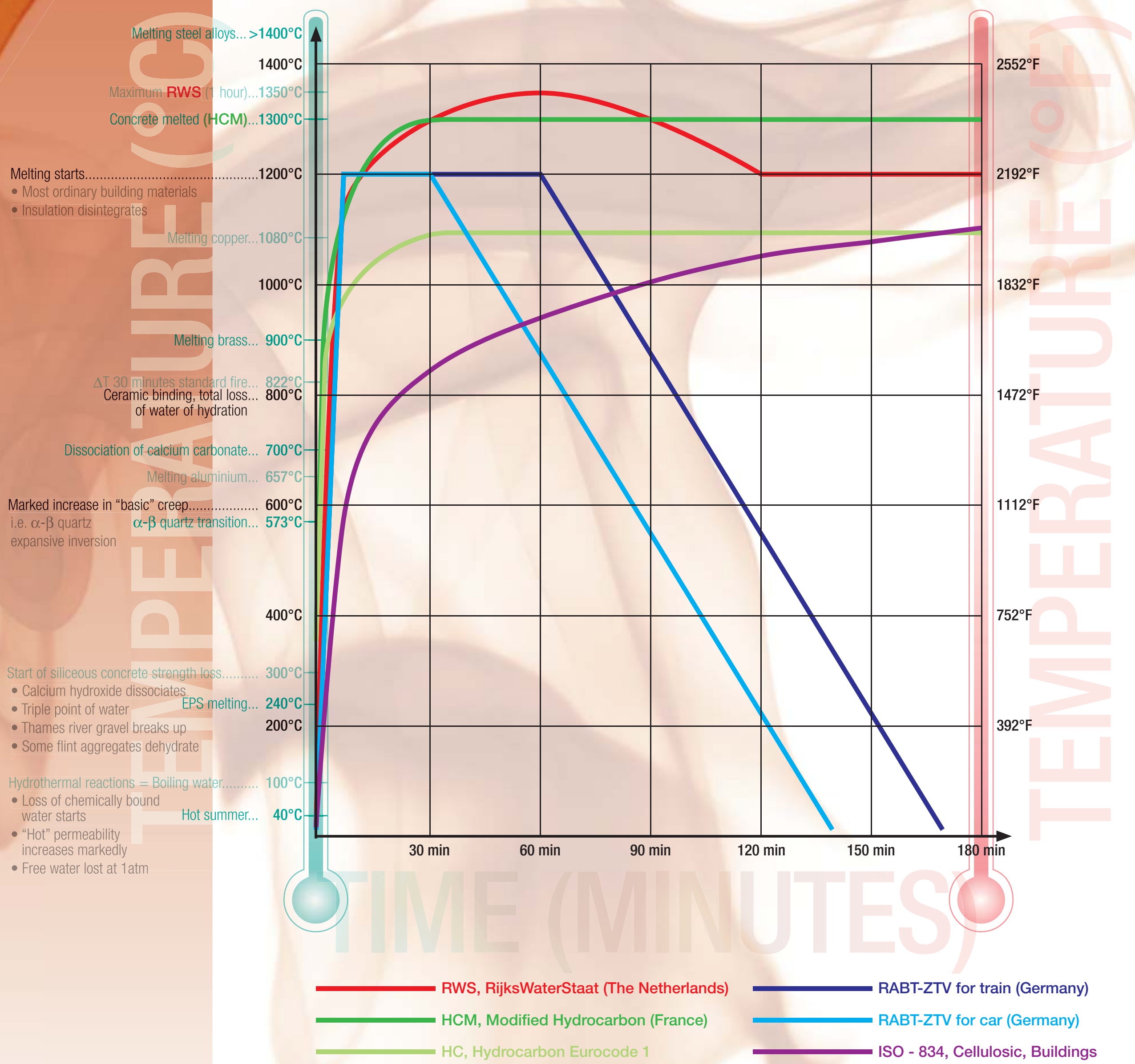
3. TYPES OF FIRE EXPOSURE

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 below.

Whilst research in tunnel fire phenomena continues, it should be noted that that existing data indicates that fires within tunnels show the severity to be much higher than would be experienced under open air conditions. 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 has been arrived at 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.

FIGURE 5: TIME/TEMPERATURE CURVES



3.1 CELLULOSIC 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. ISO834, ASTM119, BS476: Part 20, DIN4102 and AS1530. Although there are other types of fire test curves, e.g. BS7436, 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. In itself, the Cellulosic curve is based upon research dating back to the very early 20th century but it is recognised that with the use of thermoplastic and other modern materials, the Cellulosic curve could be considered less onerous than it should be when applied to modern building design and contents.

TABLE 3: CELLULOSIC FIRE CURVE

Time (minutes)	Furnace temperature (°C)	Time (minutes)	Furnace temperature (°C)
0	20	90	1006
5	576	120	1049
10	678	150	1082
15	738	180	1110
20	781	210	1133
30	842	240	1153
45	902	300	1186
60	945	360	1214

As will be seen from TABLE 3, and the following tables, 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 HYDROCARBON CURVE

Although the Cellulosic 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 curve was developed. Initially, this time/temperature curve was developed separately by various gas and oil companies. All had slight differences.However, today, the curve as detailed in FIGURE 5 reflects the relationship between time and temperature generally used in contemporary testing.

The hydrocarbon curve is applicable where small petroleum type fires might occur, e.g. car fuel tanks, petrol or oil tankers, certain chemical tankers. In fact, although the hydrocarbon 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. a 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.

JET/SPRAY FIRE A turbulent diffusion flame resulting from the combustion of a fuel continuously released with some significant momentum in a particular direction.

TABLE 4: POTENTIAL FIRE DURATION

Fire types	Potential duration
Cellulosic fire	Hours
Hydrocarbon fires	
Cloud fire	Seconds
Fireball/BLEVE	Seconds
Pool fire	Hours
Running fire	Hours
Spray fire	Hours
Jet fire	Hours

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. However, it should be noted that the peak temperature of a hydrocarbon curve can be below that of the cellulosic fire. Again, it should be reiterated that 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:

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

3. TYPES OF FIRE EXPOSURE Continued from page 25

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

TABLE 5: HYDROCARBON FIRE CURVE

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

TABLE 6: HCM FIRE CURVE

The figures given in TABLE 5 referring to hydrocarbon fire temperatures should not be confused with those relating to the modified hydrocarbon curve (TABLE 6) which is now in use in some countries. This modified hydrocarbon curve 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 then part way between RWS and RABT requirements and is much more severe than exposure to the standard hydrocarbon curve detailed within such standards as UL1709, BS476: Part 20: Appendix D etc.

The temperature development of the modified hydrocarbon fire curve is described by the following equation:

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

3.3 RABT ZTV CURVE

The RABT curve was developed in Germany as a result of a series of tunnel fire test programmes such as the Eureka project. In the RABT curve, the temperature rise is very rapid up to 1200°C within 5 minutes, faster than the Hydrocarbon curve which rises only to 1100°C after 60 minutes. 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 FIGURE 5 on page 24.

The RABT test 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.

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

TABLE 7: RABT FIRE CURVE

3.4 RWS (RIJKSWATERSTAAT) CURVE

The RWS 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 curve was based on the results of testing carried out by TNO in the Netherlands in 1979. The difference between the RWS and the Hydrocarbon curve, 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 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 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 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 in their attempts to extinguish the fire. However, in Switzerland, where tunnels through mountains tend to be far longer in length and more remote in their location, the RWS 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 high strength concrete, the interface temperature is often reduced to a maximum of 250°C.

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 recent fires in the Mont-Blanc-Tunnel (France/Italy) and St. Gotthard Tunnel (Switzerland), were a particular consideration. The Runehamar tests were conducted by the Swedish National Testing and Research Institute (SP) in collaboration with their UPTUN partners: TNO Building and Construction Research from the Netherlands and the Norwegian Fire Research Laboratory (SINTEF/NBL).

TABLE 8: RWS FIRE CURVE

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

TESTS & GAS TEMPERATURES – AN UPTUN PROJECT

Taken from "Large scale fire test in Runehamar Tunnel in 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 mass ratio was approximately 80% cellulose to 20% plastic. A polyester tarpaulin covered the cargo. The commodities are described in more detail below.

TABLE 9: COMMODITIES USED AS FUEL IN THE FOUR TESTS

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 the Runehamar tests and the EUREKA tests.

The commodities were placed on particle board in a storage rack system (see FIGURES 6, 7 and 8 below) to simulate a semi-trailer measuring 10450mm by 2900mm. The total height was 4500mm. The height of the platform from the floor was 1100mm.

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

FIGURE 6: SET-UP FOR TEST #1 (WOOD AND PLASTIC PALLETS)

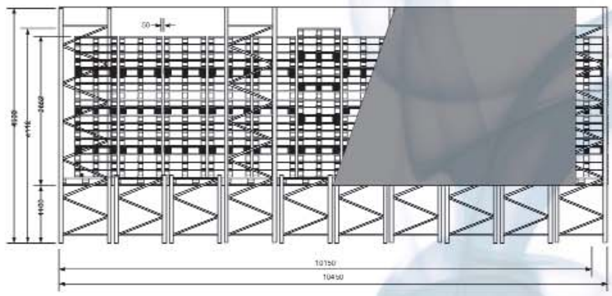


FIGURE 7: SET-UP FOR TEST #2 (WOOD PALLETS AND PUR MATTRESSES)

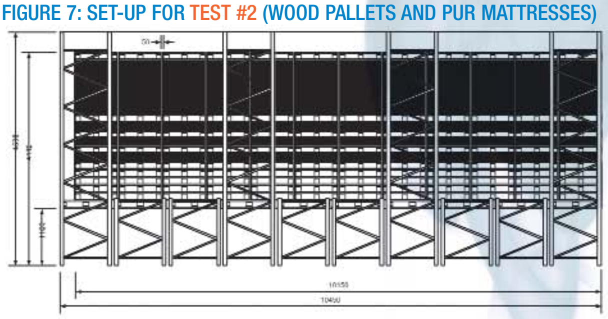


FIGURE 8: SET-UP FOR TEST #3 (WOOD FLAT PACK FURNITURE AND PLASTIC TOYS)

3. TYPES OF FIRE EXPOSURE *Continued from page 27*

TESTS & GAS TEMPERATURES – AN UPTUN PROJECT

Taken from "Large scale fire test in Runehamar Tunnel in Norway"

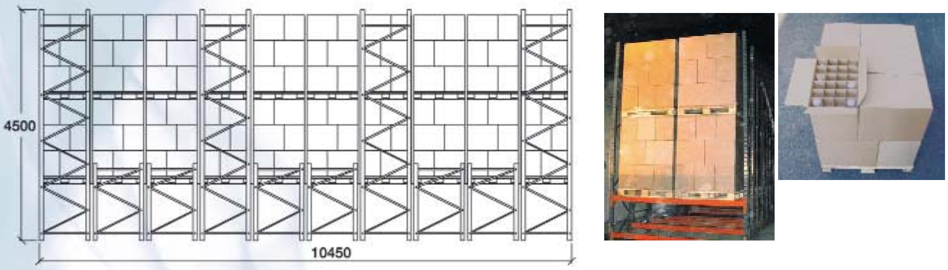
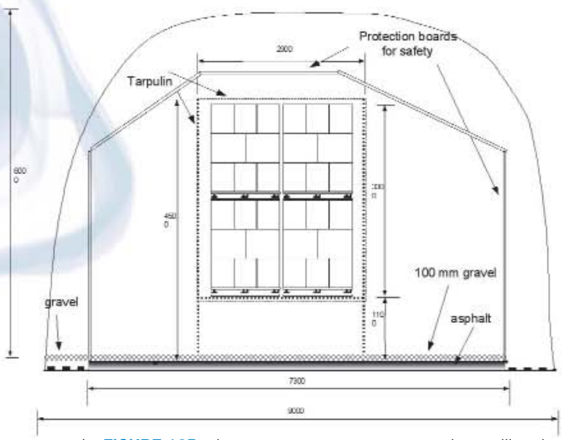


FIGURE 9: SET-UP FOR TEST #4 (PLASTIC CUPS IN CARDBOARD BOXES ON WOOD PALLETS)

FIGURE 11 *(above)*: OVERVIEW OF FIRE DEVELOPMENT AFTER FIVE MINUTES

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 FIGURE 10. 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 10: CROSS SECTION OF THE TUNNEL AT THE TEST LOCATION



The materials used in the tests (see FIGURE 11) were chosen to give different fire development and maximum heat release rates. TEST #1 with wood pallets and plastic pallets had the highest total energy content and gave the highest maximum heat release rate (see FIGURE 12A). The large amount of combustible material also gave a longer period of elevated gas temperatures, with the highest maximum temperature of 1365°C.

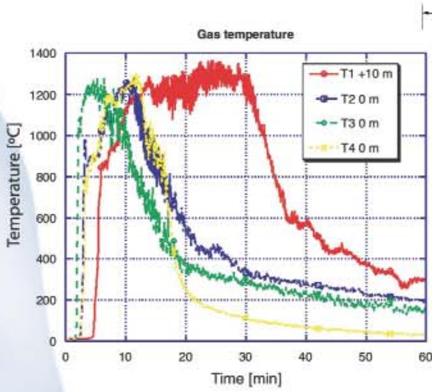


FIGURE 12A: MEASURED GAS TEMPERATURES CLOSE TO THE FIRE DURING THE FOUR TESTS

In FIGURE 12B 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-curve for about three minutes. The temperature then increases even further and more rapidly than the hydrocarbon curve. It instead follows the RWS 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 curve which is 1350°C.

The RWS curve was developed on the assumption that a tanker fire with petrol or fuel oil lasting for 120 minutes would give a heat release rate of 300MW. The heat release rate in the tests in the Runehamar tunnel did not reach 300MW, but the temperatures recorded still followed the RWS curve closely.

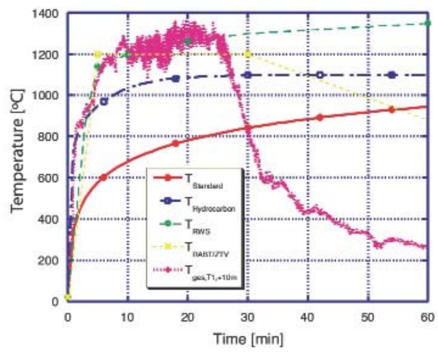


FIGURE 12B: GAS TEMPERATURES IN TEST #1 COMPARED WITH FOUR DIFFERENT STANDARD FIRE CURVES

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.

3.5 HEAT RELEASE RATE vs TIME-TEMPERATURE CURVE

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

Passive fire protection systems are first of all based on a design fire curve in terms of temperature development over time as the thermal attack to the system. Also, 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 specification, without any guidance as to time–temperature development.

This raises the question of how to convert a HRR figure to a design fire curve? For example, which fire curve represents 100MW for 4 hours?

In fact, there is no physical relation between HRR and time-temperature. Therefore the question can not be answered, due to following reasons:

Traffic type	Fire exposure period	Representative nominal fire curve
Pedestrian	None	None (negligible)
Bicycle	2 minutes	None (negligible)
Hay wagon	90-120 minutes	Hydrocarbon
Car (5-10MW)	30-60 minutes	Cellulosic/Hydrocarbon
Container/shuttle	120 (+) minutes	Hydrocarbon/RABT
HGV/lorry (200MW)	120 (+) minutes	RWS
Tanker (300MW)	120 minutes	RWS and/or Hydrocarbon
	240 minutes	
Bus (50MW)	90-120 minutes	Hydrocarbon
MTR/light rail (40MW)	120 minutes	RWS/Hydrocarbon
Train	120 minutes	RWS
	240 minutes	Hydrocarbon

TABLE 10: FIRE LOAD/FIRE CURVES

3.5.1 LOCATION OF FIRE IN THE TUNNEL

If the fire is located near the entrance or exit of the tunnel, the heat can escape from the tunnel and dissipate into the surrounding atmosphere. Should the fire be located in the centre of the tunnel, the heat is trapped and will start to warm the walls and ceiling, which in turn will radiate heat back into the tunnel.

This is also related to the length of the tunnel. In a short tunnel the heat will quickly find its way to one of the exits, decreasing the temperature in the tunnel, conversely in longer tunnels this is not the case.

3.5.2 VENTILATION SPEED

Ventilation systems in tunnels are an important part of a holistic fire safety concept. Full scale fire tests have shown that an increased ventilation speed in the tunnel will most likely increase the fire size and can potentially induce fire spread from one vehicle to the other. By increasing the ventilation speed additional oxygen is fed to the fire source, again increasing the fire size and accelerating the consumption of the fuel, thus decreasing the duration of the fire. A slower ventilation speed reduces the fire size but the duration of the fire will be prolonged.

Depending on the ventilation approach, the fire size and fire duration will be influenced.

Ventilation speed also influences the gas temperature in the tunnel. For a given fire size and fire duration, increasing the ventilation speed will decrease the gas temperature away from the seat of the fire. In this case the overall effect of increasing the ventilation speed may be a lower thermal attack to the structure.

However, increasing the ventilation speed can result in the spread of fire from one vehicle to another. For example, see FIGURE 53 on page 54.

It is therefore very difficult to ascertain whether or not high or low ventilation speeds will increase or decrease temperatures and adversely effect fire spread.

3. TYPES OF FIRE EXPOSURE Continued from page 29

3.5.3 GRADIENT

A 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. Where a low ventilation speed exists, the heat will build up at the location of the fire, leading to an increase in temperature.

With a gradient of 5%, for example, the heat and smoke will climb upwards. If the ventilation goes in the same direction, the heat will be taken from the fire location more rapidly, reducing temperature development at the fire source.

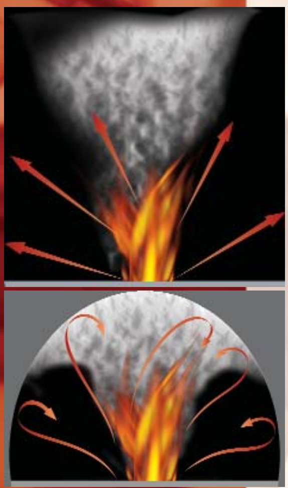
3.5.4 CROSS SECTIONAL AREA

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

3.5.5 TIME/DURATION OF THE FIRE

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

The illustrations at left depict the major difference between fires where heat can dissipate, as in most buildings, and those in tunnels where the heat is trapped and creates a chimney effect.



Top:
HEAT IN A BUILDING DISSIPATES

Bottom:
HEAT TRAPPED IN A TUNNEL CREATES A CHIMNEY EFFECT

If all the above parameters are known, a Computational Fluid Dynamics (CFD) calculation can be made, demonstrating an understanding of temperature development in certain fire scenarios. This can be combined with a finite element analysis (FEA) in order to ascertain temperatures on elements of the structure.

However, tunnels are designed to cope with several fire scenarios which makes it unfeasible to derive a time-temperature curve from each fire scenario.

The above implies that the Heat Release Rate is an important parameter for fire safety design in tunnels, in fact, amongst other items, ventilation systems are designed using Heat Release Rate data.

For the design of passive fire protection systems such as the protection of the structural lining, however, the Heat Release Rate data cannot and should not be utilised as the sole determining factor.

3.6 FIRE PROTECTION REQUIREMENTS OVERVIEW

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 goes for 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, TABLE 11 (on opposite page) 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 conduct in this respect.

TABLE 11: OVERVIEW OF FIRE PROTECTION REQUIREMENTS

Country	Code/Standard	Traffic type	Fire curve	Construction method	Concrete type	Temperature criteria
Netherlands	RWS 1998-CVB-R1161 (rev. 1)	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
France	CETU	Road	• N0: none • N1: ISO 2hours • N2: HCM 2 hours • N3: ISO 4 hours and HCM 2 hours	Any	Any	• T interface <380°C • T rebar <250°C • T unexposed face <60°C
Germany	RABT	Road	RABT-30+110 cooling down	Any	Any	T rebar <300°C
	ZTV/EBA	Rail	RABT-60/90+110	Any	Any	T rebar <300°C
Italy	UNI 11076	All	RWS	Any	Any	• T1: T rebar average <200°C, max. <250°C • T1: T interface average <330°C, max. <380°C • T2: T rebar average <250°C, max. <290°C • T2: T interface average <380°C, max. <420°C • T3: T rebar average <300°C, max. <350°C • T3: T interface average <430°C, max. <460°C
Austria	OVBB	Any	RWS, 3 hours	Any	Any	• T interface <350°C • T rebar <250°C at 40mm concrete cover
Singapore	LTAS	Road, KPE Tunnel	RWS	Immersed	Cast in place	• T interface <380°C • T rebar <250°C
China	GB 50016	Hazardous goods	• L > 1500m; RABT 120+110 • L > 500 but ≤ 1500m; RABT 90+110 • L ≤ 500m; HC, 2 hours	Any	Any	• 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
	GB 50016	Non-hazardous goods	• L > 3000m; RABT 120+110 • L > 1500 but ≤ 3000m; RABT 90+110 • L > 500 but ≤ 1500m; HC, 2 hours	Any	Any	• 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
UAE, Dubai	–	Road, Palm Jumeirah Tunnel	RWS	Cut and cover (C&C)	Cast in place	• T interface <380°C • T rebar <250°C

4. SPALLING CONCRETE *Source: Efectis BV The Netherlands*

Spalling is an umbrella term, covering different damage phenomena that may occur to 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.

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 called into question.

4.1 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, as shown in **FIGURE 5** on page 24. For tunnels many design curves are available. A few of these fire curves are also shown in **FIGURE 5**. 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.

4.2 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:

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.

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.

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, in random order: observation of spalling with slow (1°C/minute) or fast (250ºC/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, and so on. The different observed spalling phenomena are described below, including their relationship to the previously mentioned mechanisms (see also Breunese & Fellinger, 2003).

A summary of these relationships is given in TABLE 12 at right.

	Pose 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
Violent spalling	√	√	√		
Sloughing off			√		√
Corner spalling				√	
Explosive spalling	√	√			
Post-cooling spalling			√		√

TABLE 12:
IMPORTANT RELATIONS BETWEEN MECHANISMS AND SPALLING PHENOMENA

4.2.1 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)

4.2.2 PROGRESSIVE GRADUAL SPALLING (SLOUGHING OFF)

Sloughing off is the form of spalling that is caused by strength loss due to internal cracking (meso-level) 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.

4.2.3 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.

4.2.4 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 cross-section, 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)

4.2.5 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, with an expansion of over 40% occurs after cooling down, when 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.

4. SPALLING CONCRETE *Source: Efectis BV The Netherlands*

4.3 TESTING OF SPALLING BEHAVIOUR

FIGURE 13: TEST SET UP FOR A FULL SIZE TUNNEL SEGMENT

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; 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 FIGURE 13 at left.

4.3.1 GEOMETRY, PRESTRESSING, CONCRETE MIX AND MOISTURE LEVEL

For the concrete it is important to use the concrete mix and geometry as will be used on the project. The case of pre-cast 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 the actual situation. In general, a specimen with higher moisture content is more likely to spall and therefore give a safer test result.

4.3.2 AGE OF THE SPECIMEN

The specimen must be old enough to have a moisture content close to the actual situation as if it had been used for many years. 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 TNO Netherlands, for example, the usual age of specimens at the time of testing is at least 90 days.

4.3.3 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 many insulation materials may melt around 1200°C.

4.3.4 INSULATION MATERIAL

If a protective layer, such as board material or cementitious spray, 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. These details include covering of hollow spaces in the concrete surface, and 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 safe test. The layer thickness should be identical in both tests. Interpolation of layer thicknesses is impossible for spalling tests!

The latest investigations into the fire performance of concrete show that even the addition of polypropylene 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 further be 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. Care should therefore be taken to ensure claims for the performance of PP fibres are substantiated by adequate evidence.

4.4 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 and the exposure of underlying steel can result in rapid deterioration of strength and load capacity. It should 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 (moisture), but also chemically bound within the concrete (hydrated water).

Such spalling may impair performance by exposing the reinforcement or tendons to the fire 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 or steel into concrete will – when added in specific volumes and distributed uniformly – reduce the risk of tensile forces causing explosive failure to the parent concrete when exposed to the most rigorous fire. This is achieved by a series of pressure relief pores occuring upon exposure to heat can reduce the effects of spalling.

The addition of polypropylene or steel 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 both macro synthetic and steel fibre reinforced concrete, the addition of polypropylene or steel fibres, with a recipe adjusted for this addition, spalling caused by fire can be minimised. It was also found that the addition of polypropylene or steel fibres 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 or steel fibres is of great importance.

Based on the opinions of a number of researchers, the use of polypropylene or steel 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.

It should also be noted that 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 curve (1100°C) and the RWS curve (1350°C). In addition consideration must be given to the fact that not all polypropylene or steel fibres can be considered equal. The best fibres are those manufactured to a dimension and tolerance and from new materials specifically for the task at hand. 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.

TABLE 13: FACTORS TO CONSIDER WHEN COMPARING PROMATECT®-H OR PROMATECT®-T BOARDS TO POLYPROPYLENE FIBRES (PPF) FOR FIRE PROTECTION OF CONCRETE STRUCTURES

Item	PROMATECT®-H or PROMATECT®-T boards, cementitious sprays	PP fibres
Insulation of the rebars	Fully insulates pre-set and pre-designed limits of maximum requirements.	No insulation at all.
Bond between steel and concrete	Maximum temperatures not exceeded at reinforcement, maintains bond.	At 300°C the bond between rebars and concrete will be significantly reduced.
Replacement of concrete after fire	Only the boards or sprays must be replaced after severe fires.	All concrete, which was exposed to temperatures exceeding 300°C must be replaced. Even after small fires (T>160°C) repairs are required because the fibres have melted, and therefore can no longer fulfil their intended function.
Long term durability, chlorides	Boards and sprays have 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.
Damaged area after fire	Relatively small damaged area.	Damaged area (T>300°C) bigger than that directly affected by fire.
Avoid spalling	Boards and sprays are designed to reduce temperature increase on and in the concrete structure and therefore prevent spalling occurring.	Until now all tests with PP fibres have shown spalling of the concrete specimen. PPF do not stop structural damage occurring due to high temperatures (micro cracks can occur at 150°C).
Influence on the concrete properties	Boards and sprays have no adverse effect on the properties of concrete structures.	PPF reduces compressive strength leading to brittle failure. PPF will also cause reduced pull out strength of anchors under fire conditions due to melted fibres.
Influence on workability of the concrete	Boards and sprays have no adverse effect on the workability of concrete structures.	Workability decreases with increasing concentration of fibres. 3kg/m³ of fibres dehydrates the concrete mixture severely, making it difficult to pump or pour the concrete.
Being able to withstand all types of fires	Boards and sprays can withstand all types of fires, up to the most severe RWS fire.	A smouldering fire will cause dehydration of the outer layer of concrete, causing even more aggressive spalling when temperatures increase after 20-30 minutes.
Influence on the clearance of the tunnel cross section	Board and spray systems are relatively thin, <40mm depending on the fire requirements.	PPF tunnels require larger cross sections, bigger TBM's, more tubing segments, bigger volumes of excavated soil etc. Sacrificial linings, containing PPF can be over 250mm thick.
Quality control of the fire protective system	Boards and sprays are produced to ISO9001 quality standards.	How controllable is a homogeneous mix made up on site? PP fibres must be evenly distributed throughout a mixture. Impossible to control or to check. Therefore performance under fire is unpredictable.

4. SPALLING CONCRETE

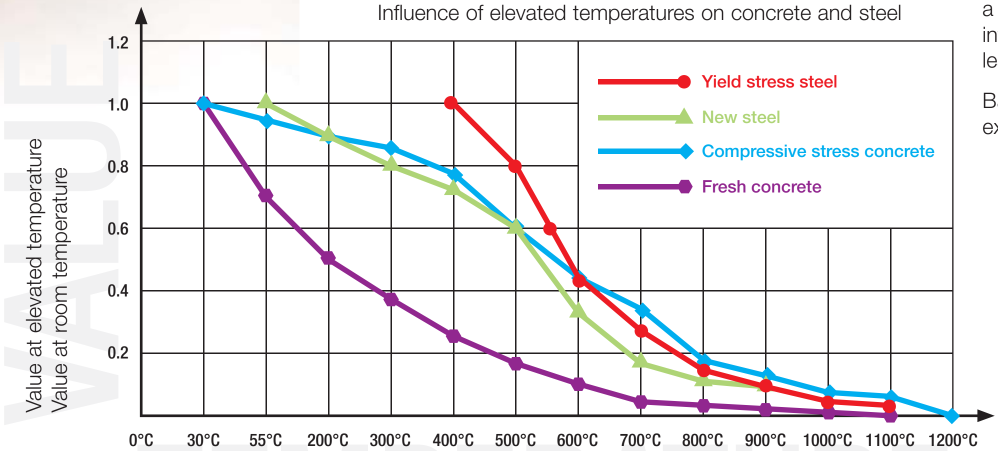
4.5 CRITERIA FOR THE FIRE RESISTANCE OF CONCRETE

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. The Dutch RWS standard suggests that, as a rule of thumb in the case of loadbearing members, account should be taken only of cores whose temperature is less than 500°C. At the tensions at which reinforcing steel is commonly used today, steel starts to flow at 500°C. In statistically determinate structures this leads to failure. In statistically indeterminate structures re-distribution of the moments is often possible, so that a higher temperature of the re-inforcing steel need not necessarily lead to failure.

FIGURE 14: INFLUENCE OF TEMPERATURE ON CONCRETE

Influence of elevated temperatures on concrete and steel



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

- Temperature on the concrete interface should not exceed 380°C (for bored tunnels this limit is 200-250°C).
- Temperature on the reinforcement should not exceed 250°C with a minimum of 25mm concrete cover. (Note: For exposure to RABT, the reinforcement temperature should not exceed 300°C.)

There is a high risk of failure due to the temperature of the steel in the concrete in columns with a high reinforcement level under high loads. For this reason, the (non-normative) tables give a critical steel temperature of 500°C for ordinary concrete and steel and 400°C for tension steel. In the Netherlands, Rijkswaterstaat specifies for tunnels a maximum permissible concrete surface temperature of 380°C. This maximum was set not because of any perception that concrete fails at that temperature but because it is assumed that in practice this is a temperature at which there is only a very small probability of damage to concrete. This requirement also implies that the temperature of the underlying reinforcement remains low, so that its strength is unimpaired.

- The design of the tunnel section has an effect on fire induced collapse.
- Rectangular tunnels were typically constructed using a grade C30/35 concrete. Nowadays 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.
- Rectangular structures suffer from less spalling than circular tunnels and have limited compression loads.
- Circular tunnels were constructed from segmented reinforced concrete sections typically use a C50 grade concrete or higher.
- 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 an average 100% deeper on these types of circular tunnels.

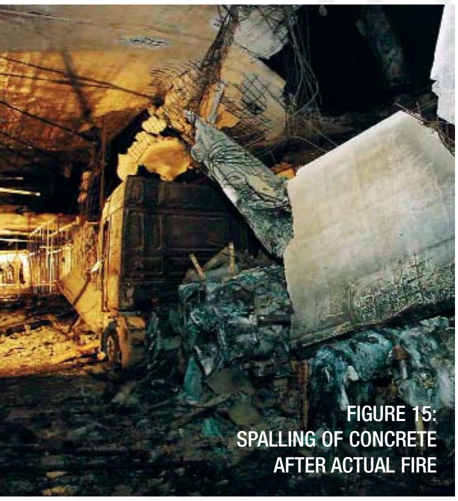


FIGURE 15:
SPALLING OF CONCRETE
AFTER ACTUAL FIRE

FIGURE 16:
REINFORCEMENT
TEMPERATURES

5. CHOOSING FIRE PROTECTION MATERIALS

5.1 CONSIDERATIONS WHEN APPLYING 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 (e.g. time/temperature curve)?
- How long must the protected structure survive (e.g. duration of time/temperature curve)?
- Type of concrete (e.g. cast in place [immersed or cut and cover tunnels], prefabricated, circular tunnels)?
- The moisture content of the concrete?
- The density of the concrete?
- The aggregates used in the concrete mix itself (e.g. silicious or calcegenous)?

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.

5.2 BOARD MATERIALS

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. In addition, being mechanically fixed, suction and wind loading from passing traffic has no adverse effect on boards, with correctly installed products remaining in place without any deformation occurring.

Boards are completely unaffected by combustion by-products of traffic passing through tunnels, and are also unaffected by the ingress of water. In fact, in very wet tunnels, boards can act as a conduit for water, ensuring the excess runs off into the tunnel drainage systems rather than 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.

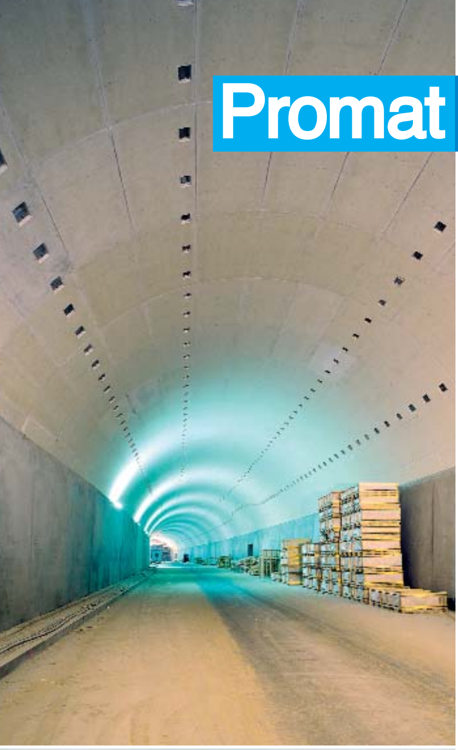
Using a board product such as PROMATECT® ensures that condensation as a result of wet tunnels does not form on the exposed surface of the boards, but rather this small amount of moisture is absorbed by the PROMATECT® and then evaporated into the surrounding air. The absorption of water into PROMATECT®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

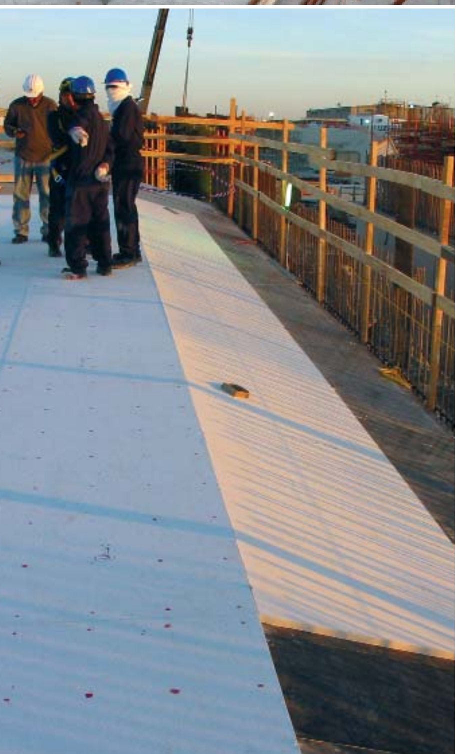
Board systems in general require little maintenance. Where access is required to periodically inspect the concrete substrate, boards can quickly and easily be removed and reinstated, thus maintaining the fire protection layer at all times.

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.





6. TYPES OF TUNNEL

6.1 BORED TUNNELS USING CONCRETE SEGMENTS

A bored tunnel refers to a construction method for tunnels which involves digging a tube-like passage through the earth. It usually refers to tunnelling through rock, as blast tunnelling is not widely used these days. 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.

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. TBMs provide 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.

The use of TBMs 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 the type of rock being bored. Despite these advantages, TBMs have 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 the route, thus the tunnel is simultaneously lined as it is drilled.

6.2 IMMERSED TUNNEL

The immersed tube is a construction method using pre-fabricated tunnel sections. While the ends 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, in which compressed air is used to force water out of the working chamber.

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 sinking, 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.

6.3 CUT AND COVER (C&C) TUNNELS

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.

The cut-and-cover method can also involve digging a trench, building the concrete floor, walls, and ceiling, or installing pre-cast tunnel sections, and then refilling the trench over the tunnel. In built-up areas in cities, use of this method is often not possible. In soft earth or mud, a large diameter pipe-like device can be driven through the ground by jacks or compressed air. Workers remove the earth as the pipe moves forward, its edge cutting into the earth.

7. FIXINGS *Source: Fischer fixing systems*

Where daily use of a road or rail tunnel involves high traffic loads, the demands placed on means of attachment will be more onerous. Traffic passing through a tunnel causes high suction loads on ceilings due to the displacement of air by vehicles. This suction load depends on the type of vehicle (e.g. car, train or tram) and the headroom. The value often taken is 100kg/m^2. The weight of the cladding and the number of attachment points can be determined by means of a load simulation for traffic passing through a tunnel. The manufacturer of the pertinent cladding material should provide reports which show the exact types of fixing methods employed, and the loads from suction etc. that the systems are designed and tested to take. Attention needs also be paid to the material from which the fixings are manufactured (zinc galvanised steel, stainless steel) and the condition of the concrete itself.

Therefore, before any choice of fixing can be made, consideration has to be given to three important elements. The likely corrosion to which the anchors may be subject, the crack width if any, and the compressive strength of the concrete.

7.1 LOCALISED CORROSION AND PITTING IN TUNNEL CONSTRUCTION

7.1.1 LONG SERVICE LIFE OF STAINLESS STEEL GRADES USED FOR ANCHORS

Due to their excellent long-term corrosion resistance in naturally occurring ambient conditions, stainless steel grades are used more and more in fixing engineering.[1 and 2] Although they tend to be more expensive, the extra costs are compensated relatively quickly by their longer service life and lower maintenance and repair costs.

Besides the economic aspects, safety reasons have meant that stainless steel grades used in fixing engineering have gained tremendously in importance, particularly in complex applications such as road tunnels.[3, 4, 5, 6, 7, 8 and 9] Stainless steel grades are used more frequently for conventional architectural applications such as claddings, the reason being environmental impact factors, improved safety standards and aesthetics.

7.1.2 "STAINLESS" STEEL THAT RUSTS

When exposed to extreme ambient conditions,however, it has been seen that even "stainless" or non rusting steel grades can "rust" or corrode, with a relatively minor tension existing, for instance, as intrinsic tension in the actual material, normally sufficient to trigger tension crack corrosion. Ambient atmospheres with corrosion-inducing pollutant are often seen in industrial surroundings, in the chemical industry, in multi-storey car parks, indoor swimming pools, in chimneys and in tunnels. In indoor swimming pools, it is mainly the high chloride concentration,[10 and 11] while other specialised applications are also exposed to high pollutant concentrations which constitute a substantial corrosion hazard by forming some highly aggressive condensate.[12] Selecting the right kind of material is often difficult for aggressive atmospheres such as these, with planners having to rely on field tests and/or on adapted special tests to determine the expected corrosion behaviour of the various materials in these applications.

Quite a number of results from exposure tests and special tests in pollutant gas atmospheres allow conclusions to be ascertained in terms of the long term life of various stainless steel grades in road tunnels. These findings have also led to a new differentiation in stainless steel grades being introduced in the General Building Supervision Approval DIET Z-30.3-6 on 3 December 2003 (Germany).

According to the new approval, only materials with the highest corrosion resistance class IVY must be used in atmospheres containing chloride and in inaccessible, corrosion-prone places such as road tunnels. TABLE 14 on page 40 shows an extract from the General Building Supervision Approval DIET Z-30.3-6 with the different stainless steel grades used in construction engineering shown in relation to the corrosion resistance classes. FIGURE 17 at right also attempts to classify some of the listed steel grades used in fixing elements in terms of their corrosion resistance and to compare their strengths in their solution-annealed condition.

Using a specific application and the results of long term exposure test and laboratory trials, this section attempts to show how safe and sustained material concepts can be used for fixing engineering in tunnel construction.

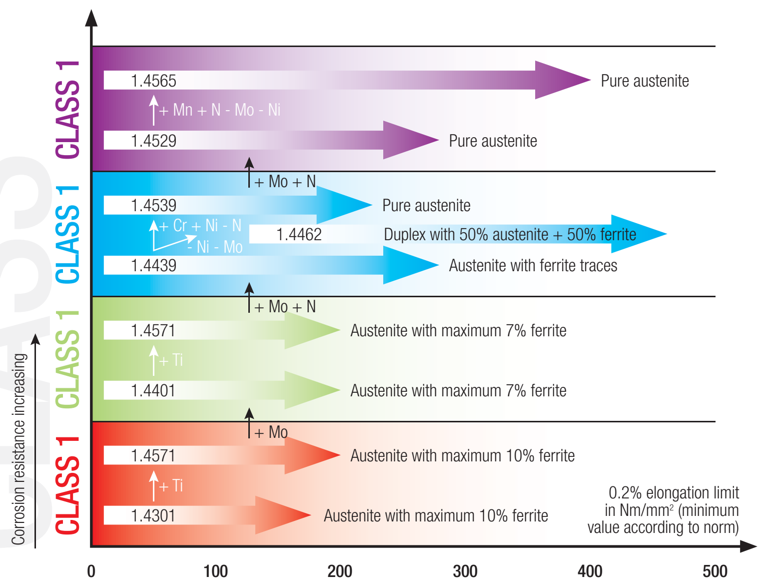


FIGURE 17:
ALLOY STRUCTURE AND STRENGTH PROPERTIES OF STAINLESS STEELS

REFERENCES:

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(2) Gümpel, P. (1996). *Rostfreie Stähle,* expert-ver-lag. Kontakt & Stadium, Bd 493.

(3) Hasemaier, H., Übeleis, A. & Böhni, H. (1993). *Korrosionsbeständige Befestigungen in Straßentunnels – Feldversuche.* Scheweizer Ingenieur und Architekt Nr. 16-17, S. 289-295.

(4) Übeleis, A. & Felder, G. (1993). *Schadstoffe in Straßentunnels – Auswirkungen auf die Beständigkeit met. Werkstoffe.* VDI-Berichte Nr. 1060, S. 69-84, VDI-Verlag, Düsseldorf.

(5) Arnold, N., Arlt, N., Gümpel, P. & Heimann, W. (1996). *Stainless Steels for Fasteners for Architectural Application in Highly Corrosive Environments Proceedings.* 2nd European Congress Stainless Steels, Düsseldorf, 3.–5.6.96, S. 138-142.

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(7) Arnold, N., Gümpel, P., Heitz, T. & Pscheidl, P. (1997). *Chloridinduzierte Korrosion von nicht rostenden Stählen in Schwimmbadhallen-Atmosphären.* Teil 1: Elektrolyt Magnesium-Chlorid Materials and Corrosion 48, S. 679/86.

(8)-(12) *See page 40.*

NOTES:

[1] Under DIN EN 10088-1 or SEW 400.

[2] A = Austenite;
F = Ferrite;
FA = Ferrite-austenite.

[3] Only for blank metallic surfaces. In the event of potential contact corrosion, the less noble metal is at risk.

[4] Constructions are classified as inaccessible if their condition cannot be checked or can be checked only under aggravated conditions and which, if required, can be refurbished only at great effort and expense.

[5] These materials have a high resistance to tension corrosion. The materials 1.4565, 1.4529 and 1.4547 also have a higher resistance to local corrosion manifestations (pitting and/or fissure corro-sion). For components in indoor swimming pool atmospheres without regular cleaning, only the materials 1.4564, 1.4529 and 1.4547 are suitable. In areas with water with a Cl content <250mg/litre (drinking water), material 1.4539 is also permitted.

REFERENCES:

Continued from page 39

[8] Arnold, N., Gümpel, P. & Heitz, T. (1998). *Chloridinduzierte Korrosion von nicht rostenden Stählen in Schwimmbadhallen-Atmosphären.* Teil 2: Einfluss von Hypochloriten Materials and Corrosion 49, S. 482/488.

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7. FIXINGS

Source: Fischer fixing systems

TABLE 14: EXTRACT FROM "GENERAL BUILDING SUPERVISION APPROVAL DIBT Z-30.3-6"

Steel grade[1] Brief designation	W-No.	Micro-structure[2]	Corrosion: Resistance class[3]	Corrosion: Load and typical application
X2CrNi12	1.4003	F	I/low	Interior constructions with the exception of humid rooms.
X6Cr17	1.4016	F		
X5CrNi18-10	1.4301	A	II/moderate	Accessible constructions, with negligible chloride and sulphur dioxide content, no industrial atmosphere.
X2CrNi18-9	1.4307	A		
X3CrNiCu18-9-4	1.4567	A		
X6CrNiTi18-10	1.4541	A		
X2CrNiN18-7	1.4318	A		
X5CrNiMo17-12-2	1.4401	A	III/medium	Constructions with moderate chloride and sulphur dioxide exposure and inaccessible constructions.[4]
X2CrNiMo17-12-2	1.4404	A		
X3CrNiCuMo17-11-3-2	1.4578	A		
X6CrNiMoTi17-12-2	1.4571	A		
X2CrNiMoN17-13-5	1.4439	A		
X2CrNiMoN22-5-3	1.4462	FA	IV/strong	High corrosion load[5] caused by chloride and/or chloride or sulphur dioxide and high air humidity, rising concentrations of pollutants.
X1NiCrMoCu25-20-5	1.4539	A		
X2CrNiMnMoNbN25-18-5-4	1.4565	A		
X1NiCrMoCuN25-20-7	1.4529	A		
X1CrNiMoCuN20-18-7	1.4547	A		

7.1.3 DUST ATTACKS ANCHORS

One of the most significant factors is the dust load acting on the fixing element. Tunnel dust not only includes soot, but also mineral substances, abrasive particles from tyres and wearing parts as well as several percentages per weight of water-soluble chloride originating from salt spraying the road during winter months. This salt, bound in dirt and snow residues, is normally carried into the tunnel by the vehicles and more or less spreads evenly throughout the tunnel. Empirical data shows that the chloride load in the dust can be lowered at certain points by regular cleaning, but that the chloride content is still 1% by weight at these points.

7.1.4 SALT FILM ON MATERIALS

The salt crystals carried in dust form a highly concentrated salt film on the surface of the materials, particularly under the condensate conditions usually found in tunnel atmospheres. Some data is available on the impact of unadulterated salt load on stainless steel grades, with laboratory tests examining the effect of dehydrated salt droplets from various chloride solutions, such as $MgCl^2$, NaClO and $Ca(ClO)^2$ solutions on various stainless steel grades exposed to mechanical tension when stored in humid air at a temperature of 40°C.

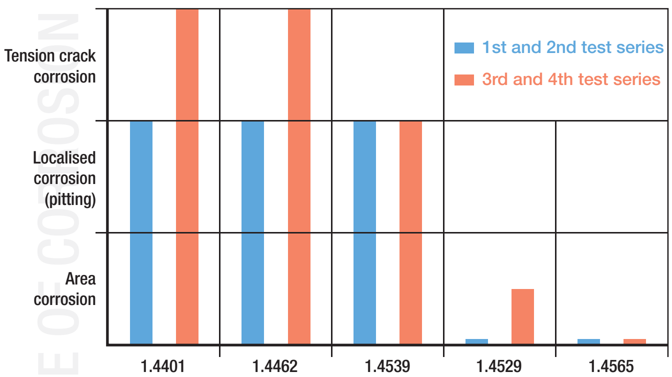


FIGURE 18: TYPES OF CORROSION FOUND DURING EXPOSURE OF STAINLESS STEEL SPECIMENS WITH SALT DROPLETS IN HUMID AIR

1st and 2nd test series in 70% relative humidity,
3rd and 4th test series in 35% relative humidity

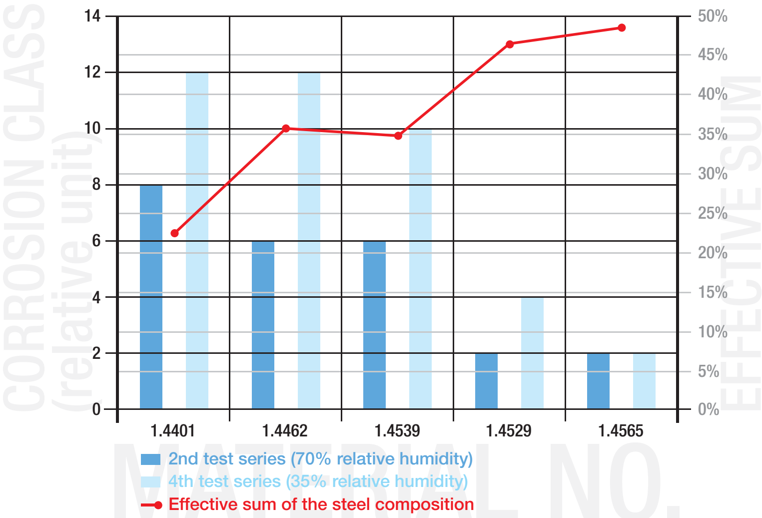
FIGURE 18 at left shows clearly that the resistance of the materials rises in line with the corrosion class (FIGURE 17 on page 39). These tests also showed a good correlation between the corrosion behaviour and the so-called effective sum which can be calculated from the composition of the alloy using the following equatio:

$W = \%Cr + 3.3 \cdot \%Mo + 30 \cdot \%N$

A purely qualitative classification of the corrosive intensity judged by the appearance of the specimen after long-term exposure clearly shows the correlation between the effective sum of the steel and its corrosion resistance (FIGURE 19, below right). The relative classification between no corrosion attack (stage 0 in FIGURE 19) and a very strong corrosion attack (stage 12 in FIGURE 19) demonstrates that the attack with higher effective sum is a great deal lower.

The use in tunnel atmospheres with deposits containing chloride requires the appropriate resistance to the highly dangerous localised corrosion (pitting) and tension crack corrosion. For the materials 1.4462 and 1.4539, classed in the General Building Supervision Approval DIBT Z-30.3-6 as conditionally corrosion resistant in the highest corrosion resistance class IV, these requirements are not met, with the effect that these materials should not be used at points exposed to the highest loads. FIGURES 20-25 at right below show examples of the specimens of the various stainless steel grades prepared with dried salt droplets and stored in humid air at longer periods. Of the steel grades examined, it should be noted that it is only the materials with the highest effective sum, i.e., steel grade 1.4529 with 6% molybdenum and steel with high nitrogen content 1.4565, that show an adequate corrosion resistance to exposure of this description. The situation can be exacerbated further by porous particles of soot because this will enlarge the cathode surface.

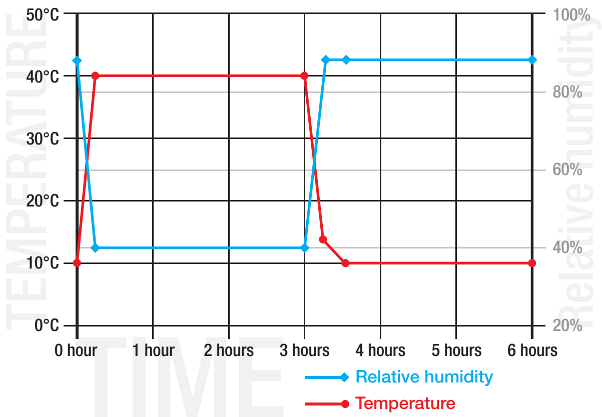
FIGURE 19:
RELATIVE CLASSIFICATION OF THE CORROSION AFTER LONG-TERM EXPOSURE AS FACTOR OF THE EFFECTIVE SUM OF THE STEEL GRADES



7.1.5 CORROSION CAUSED BY POLLUTANT GASES

The resistance of materials has been tested in numerous test series using climate and pollutant gas test chambers. The pollutant gas concentrations used in these tests are shown in TABLE 15 on page 42. The climate cycles used in the tests are shown in FIGURE 26 below.

FIGURE 26: CLIMATE CYCLES OF THE 4TH TEST SERIES



Following the tests, which were carried out both with round specimens and in pre-stressed bow type specimens, the surfaces of the material were checked visually and the degree of corrosion was classified according to a guideline series. FIGURES 27 A-D on page 42 show the classification of the corrosion of the various stainless steel grades. It also demonstrated that it is only the high-alloy steels 1.4529 and 1.4565 which show a high resistance to tunnel atmospheric pollution.

To quantify the corrosion, the round material specimens were cleaned in a light pickling solution which removed the loose, porous and flaky corrosion layers, such that only the attack of the localised corrosion (pitting) remained. The depth of corrosion was then measured using a measuring microscope, with the median value of 5 different pitting points (if available) in the round specimens determined. The results of these measurements are shown in FIGURE 27 for all materials tested.

The high-alloy materials 1.4529 and 1.4565 also remain corrosion-immune in this test and therefore showed the highest resistance under exposure to pollutant gases in road tunnels. All of the results correlate well in total with the results of the exposure tests in road tunnels and with empirical data. Among the alpine tunnels, the strongest corrosive effects were found in the Mont Blanc and the Gotthard tunnel where the resistance of the materials 1.4529 and 1.4565 was also demonstrated, whereas the other high-alloy steels such as duplex 1.4462 showed localised corrosion.

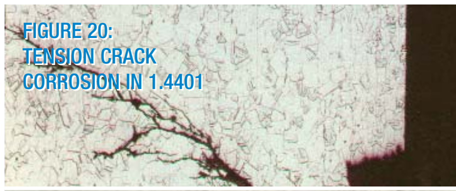


FIGURE 20:
TENSION CRACK CORROSION IN 1.4401


FIGURE 21:
SELECTIVE CORROSION IN 1.4462

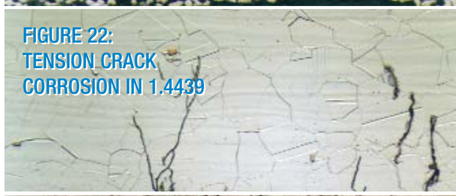


FIGURE 22:
TENSION CRACK CORROSION IN 1.4439


FIGURE 23:
LOCALISED PITTING CORROSION IN 1.4539

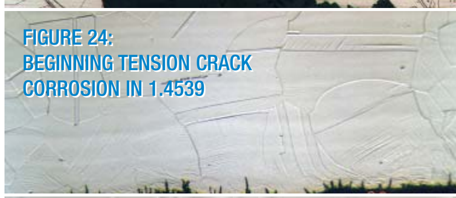


FIGURE 24:
BEGINNING TENSION CRACK CORROSION IN 1.4539

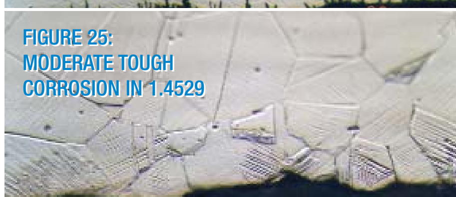


FIGURE 25:
MODERATE TOUGH CORROSION IN 1.4529

FIGURE 27 A

FIGURE 27 B

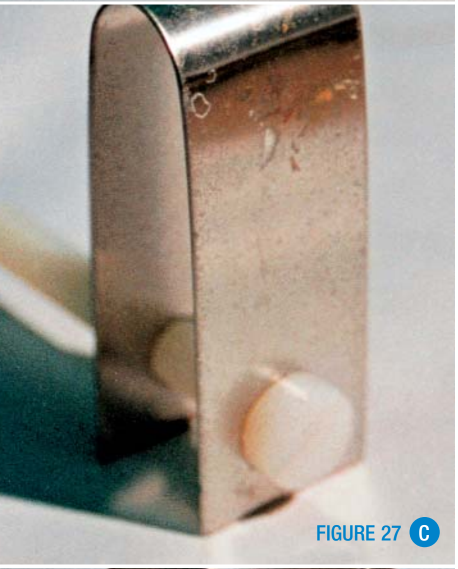


FIGURE 27 C

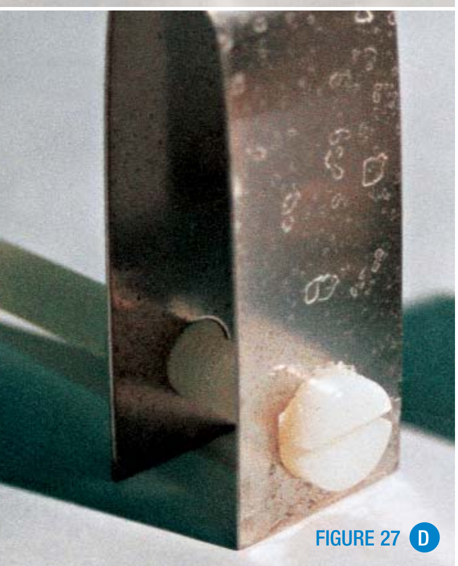


FIGURE 27 D

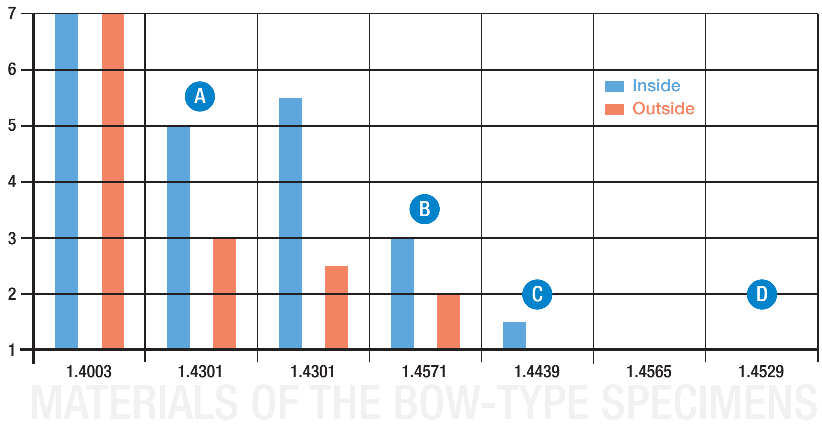
7. FIXINGS

Source: Fischer fixing systems / Continued from page 41

TABLE 15: EXTREME VALUES OF ATMOSPHERIC COMPONENTS IN ST. GOTTHARD TUNNEL AND IN POLLUTANT CONCENTRATIONS IN TEST SERIES

Atmospheric components	S_2 (ppm) max.	NO (ppm) max.	NO (ppm) max.	H_2S (ppm) max.	Chloride content
St. Gotthard Tunnel	>20	14	2.0	6	Max. 2.5%
1st test series	45	30	7	13	5%
2nd test series	45	30	7	13	5%
3rd test series	22	14	2.3	6	2.5%
4th test series	43	30	5	11	–

FIGURE 27: BEHAVIOUR OF STAINLESS STEELS IN THE POLLUTANT GAS TEST

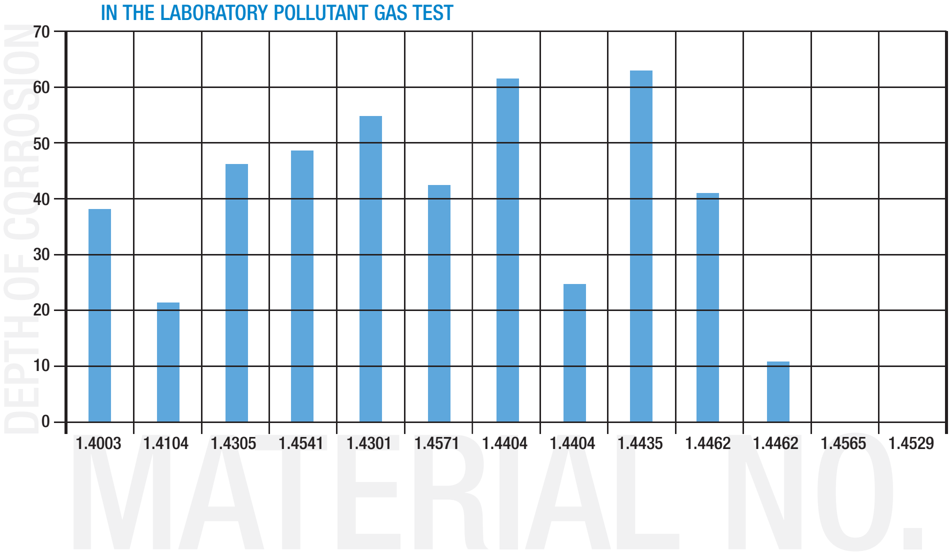


See indicative figures at right of the page

SUMMARY

In principle, stainless steel should be used for fixing elements only if it has the appropriate corrosion resistance. The long service life of such stainless steel grades can help prevent major financial losses caused by corrosion. The corrosion resistance of stainless steels is a typical and system-inherent property and depends to a large extent on the various system parameters. The system parameters coming to bear in the corrosive effects acting in road tunnels (FIGURE 28 below) are subject to wide-ranging scatter, which is certainly one reason why the empirical values of the various tunnels differ so widely. Consequently, the views regarding the use of material grades and qualities in road tunnels differ equally widely. Unlike in structural steel, the process of corrosion in stainless steel does not show as "rusting off" with the resulting reduction in the cross section, but by way of a selective corrosion occurring after a short period of time. Stainless steel for fixing elements in road tunnels should therefore always be selected in compliance with the regulations in the German General Building Supervision Approval Z-30.3-6 which will ensure that the requirements involving the use of these high grade materials are met.

FIGURE 28: MAXIMUM DEPTH OF PITTING CORROSION IN "μm" OF THE ROUND MATERIAL SPECIMENS IN THE LABORATORY POLLUTANT GAS TEST



7.2 CRACK WIDTH IN CONCRETE

In accordance with many international standards (e.g. BS, DIN, Euro codes), the maximum acceptable crack width in reinforced concrete is limited to wk=0.3mm under semi permanent loadbearing conditions. If structures are subject to exceptional loading, e.g. seismic, then there is a possibility that wider cracks could occur. Recent analysis shows that the cracks in reinforced concrete structures could be as wide as 1.5mm after being subjected to earthquakes to the maximum design load.

Anchors might be situated near to, or even within cracks in the concrete, and as worst case, could even be positioned at the intersection point of two cracks. Tests have confirmed that in the event of concrete cracking, there is a high probability that at some point, these cracks would radiate into contact with the fixings. This is particularly true of expansion bolts because there are local tensile stresses in the area surrounding the fastening due to the expansion forces of the bolts.

The type of bolt to be used should be chosen with due consideration of the possibility of the concrete cracking, and an appropriate type of fixing utilised.

7.3 COMPRESSIVE STRENGTH OF CONCRETE

If a tunnel is constructed using high strength concrete, the nominal compressive strength of the concrete would be approximately 60N/mm^2. However, it is often the case that the compressive strength is far higher than this, at around 90 to 100N/mm^2.

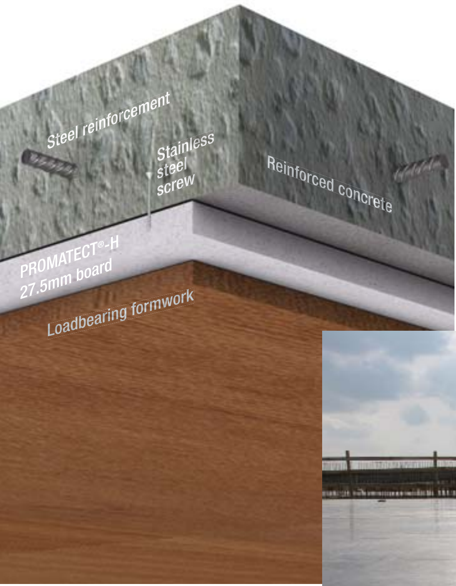
Anchors in which the fastening is by means of torque control or displacement controlled friction locking are not suitable for use in this type of high strength concrete. Torque controlled anchors are not capable of creating the deformation in the concrete which is required for the bolt head to expand into. Thus the load would be held by friction of the bolt within the drilled aperture only. A drilled hole tends to be smooth, the friction between the anchor and the hole is minimal and the loading which can successfully be applied is unacceptably low.

For fixing into high strength concrete, undercut anchors should be used, as these do not rely on the compressive strength of the concrete, nor the smoothness of any drilled hole.

With the research that has taken place over the last ten years or so, both by fixing manufacturers and independent research bodies, it has been determined that the optimum material for fixings in tunnels should consist of stainless steel of grade 1.4529. This material is resistant to all types of corrosion, surface pitting and corrosion induced stress cracking.

8. METHODS OF APPLYING BOARD PROTECTION

FIGURE 29:
BOARDS LAID WITH THE SMOOTH FACE DOWN USING LOST FORMWORK
(as illustrated below)



8.1 AS LOST SHUTTERING

8.1.1 PROMATECT®-H CEILING SYSTEM, LOST FORMWORK METHOD

Essentially this system consists of the following installation steps:

A) THE BOARDS ARE LAID ON THE LOADBEARING FORMWORK

The PROMATECT®-H boards will be laid with the smooth face down (FIGURE 29) 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 30). 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 31).

The dimensions of each tunnel section in the ceiling area are approximately 16m x 25m on a typical Dutch cut and cover or immersed tunnel. If the dimensional and squareness tolerances on the PROMATECT® 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, PROMATECT® boards are cut to tight tolerances in the factory, such that gaps in between the boards will be minimised.

FIGURE 30:
FIXED STRIP OF PLYWOOD SERVES AS A DATUM FOR THE FIRST ROW OF BOARDS

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 32).

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 (for example, 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 32:
BOARDS CUT TO AN ANGLE AT THE HAUNCHES

FIGURE 31:
BOARD JOINTS ARE SIMPLY ABUTTED, NO SPECIAL TREATMENT REQUIRED

The locations of the screws are marked on the boards, using a template and a spray can of paint (FIGURE 33).

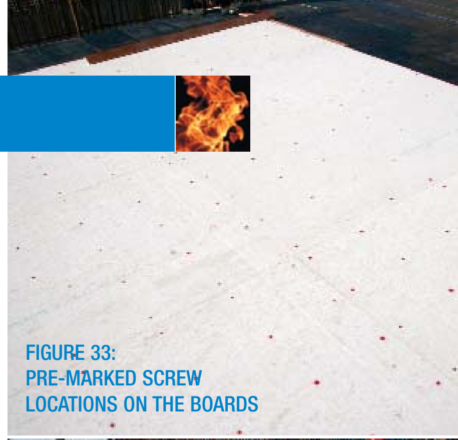


FIGURE 33:
PRE-MARKED SCREW LOCATIONS ON THE BOARDS

B) THE FIRST LAYER OF REINFORCEMENT IS INSTALLED

Prior to the installation of the stainless steel screws, the first layer of reinforcement is installed on the stools (spacer blocks creating concrete cover thickness). In this way the screws are always protected from foot traffic (FIGURE 34).

FIGURE 34:
FIRST LAYER ON REINFORCEMENT INSTALLED, PRIOR TO SCREW INSERTION

C) STAINLESS STEEL SCREWS ARE PARTLY INSERTED IN THE PROMATECT®-H BOARDS

The 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 35).

FIGURE 35:
PRINCIPLES OF SCREW INSERTION

Several methods are available on the market to ease the installation of the stainless steel screws (FIGURES 36 & 37):

- Battery-powered screwdrivers can be equipped with depth guiding devices to ensure the correct depth of 20mm.
- Screws can be supplied on a plastic strip, which is fed into the screwing machine, increasing installation speed.
- Battery-driven drilling machines can be equipped with a tube through which the screw can be dropped down onto the surface of the board. The installer remains standing upright while installing the screws.

FIGURE 36: SCREW INSERTION

A combination of the above features can be made and should first be discussed with a local power tool supplier.

The screws for the lost formwork system are 5mm x 50mm chipboard screws, with a countersunk (CSK) head type and a Pozidrive-2 connection.

The design of a screw has major influence on mechanical performance and fire performance, in combination with PROMATECT® boards. Among others, properties like shaft-diameter 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 37:
SCREW INSTALLED AND PROTECTED BY REINFORCEMENT

The number of screws should be in the region of 12 screws per m^2. 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, as detailed in FIGURE 38 for example, has an average of 12.8 screws per m^2.

The majority of the boards are laid on the formwork in their standard full size dimension. Some panels 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 panels are used, the following criteria should be followed:

- The minimum quantity of screws should be 12 screws per m^2.
- The distance from the edge of the boards should be a minimum of 50mm.
- The screws for cut pieces should be evenly distributed over the surface of the panel. In other words, the spacing distances in X and Y direction should be optimised and be as close as possible.

For example, a screw pattern on a cut to size panel of 1675mm x 1090mm in which all criteria are followed, the surface area of the panel is 1.83m^2 which means that the minimum member of screws should be 22.

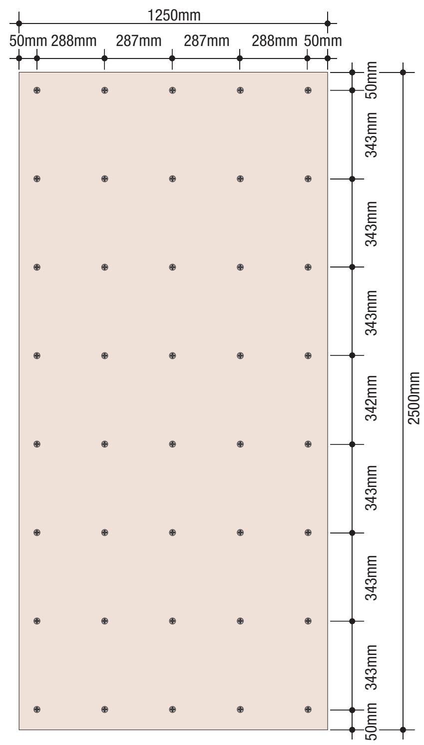


FIGURE 35: EXAMPLE OF SCREW PATTERN OF LOST FORMWORK

8. METHODS OF APPLYING BOARD PROTECTION Continued from page 45

FIGURE 39:
THE POURING OF CONCRETE

FIGURE 40:
EXTRACTED FORMWORK

FIGURE 41:
OPENING OF MANHOLES

FIGURE 42:
ANCHOR SYSTEM
FOR JET-FANS

D) WHEN THE CONCRETE IS POURED

Before the concrete is poured, the PROMATECT® boards should 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 39**).

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

E) AFTER THE CONCRETE IS SUFFICIENTLY CURED, FORMWORK IS EXTRACTED

The following advantages of PROMATECT® as lost formwork system have been reported by contractors over the years:

FORMWORK SAVINGS

- The shuttering material only has to have load-bearing properties. There is no need to apply phenol coated plywood boards as PROMATECT® boards will be laid on top of the formwork. The formwork elements just have to be installed properly (i.e. level and flushed).
- As concrete will not be in direct contact with the formwork, there is no need for demoulding oil (i.e. no slippery surfaces). The plywood sheets will remain clean and can be re-used.
- Formwork can be installed at a distance up to 90mm from the side walls.
- The PROMATECT®-H boards can span the 90mm distance, depending on the expected load. At this location, care should be taken with the vibrating action during pouring of the concrete. Extraction of the formwork is much easier as it will not get jammed between the walls.
- As the PROMATECT® forms a barrier, there is no adhesion between the concrete and the formwork, it is easy to extract the formwork and it remains clean (**FIGURE 40** at left).

EASE OF INSTALLATION

- Joints between boards only have to be butt jointed. No special treatment (e.g. fillers or mastic) is necessary from a fire performance point of view. The cement water will not run through the joints. Where gaps of more than 1mm occur, mastic can be used to seal the gap in order to prevent water from the cement leaking through the gap, causing unsightly stains.
- Vertical wall panels can also 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 in the PROMATECT® lining for manholes (**FIGURE 41** at left) and end-walls can easily be made by installing phenol coated formwork instead. After striking the formwork, standard size PROMATECT® boards will close the opening by post fixing the board into the opening. See **SECTION 8.2** on pages 47 to 53.
- PROMATECT®-H 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. Installation rates for the PROMATECT® boards of 150m^2 per man per day have been reported on European tunnel projects.
- The installation of the system does not interfere with other construction activities.
- Extensive Promat expertise is available with this system in immersed and cut and cover tunnels.

TUNNEL SERVICES AND SPECIAL SHAPES

- Anchor systems for services (e.g. jet-fans, **FIGURE 42** at left) can be fixed onto the 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, 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 installed in the very early stages of the construction of the tunnel, fire protection during the construction phase is provided.
- The PROMATECT® lost formwork system provides a flush finish ceiling.
- No obstacles such as anchor heads on the soffit of the tunnel.

8.1.2 PROMATECT®-T CEILING SYSTEM, LOST FORMWORK METHOD

The lost formwork method can also be applied, utilising PROMATECT®-T boards.

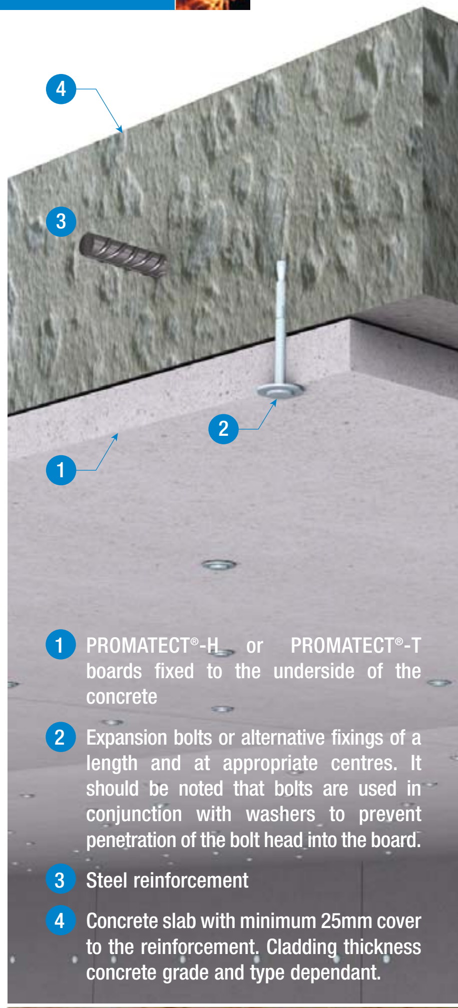
The system and the installation method are similar to the PROMATECT®-H system as described in SECTION 8.1.1, with the following additional advantages:

- The very high thermal performance of PROMATECT®-T boards is unmatched. Therefore the thickness of the fire protective layer can be reduced and the interface temperature on the concrete surface will be even lower, thus providing a higher level of structural safety.
- The PROMATECT®-T boards can be supplied with red coloured X-marks at the location of the insertion of the screws, on the reverse side of the board. For standard board dimensions of 2500mm x 1200mm, the boards can be supplied with 5 rows of eight X-marks. The tolerance on the location of the X-mark is ±10 mm.
- Half size boards of 1250mm x 1200mm can be supplied for the ease of handling.
- PROMATECT®-T boards are cut to tight tolerances in the factory, suitable for application in a lost formwork system.
- The PROMATECT®-T lost formwork system is the most competitive lost formwork system in the market capable of withstanding the Rijkswaterstaat (RWS) fire exposure.

8.2 POST CONSTRUCTION INSTALLATION TO CONCRETE

In many instances, the construction method used to build a tunnel prohibits the installation of the PROMATECT®-H using the lost shuttering method. It is also the case that many older tunnels may simply require upgrading. To this end, Promat has also developed and tested systems for the protection of concrete where the fire protection boards are applied after the structure has been completed.

An example for such a post construction method is the Zeeburg Tunnel in the Netherlands.



1. PROMATECT®-H or PROMATECT®-T boards fixed to the underside of the concrete
2. Expansion bolts or alternative fixings of a length and at appropriate centres. It should be noted that bolts are used in conjunction with washers to prevent penetration of the bolt head into the board.
3. Steel reinforcement
4. Concrete slab with minimum 25mm cover to the reinforcement. Cladding thickness concrete grade and type dependant.

FIGURE 43 *(above)* :
POST INSTALLATION OF
SINGLE LAYER PROMATECT® BOARDS

FIGURE 44: POST CONSTRUCTION METHOD IN
ZEEBURG TUNNEL, NETHERLANDS

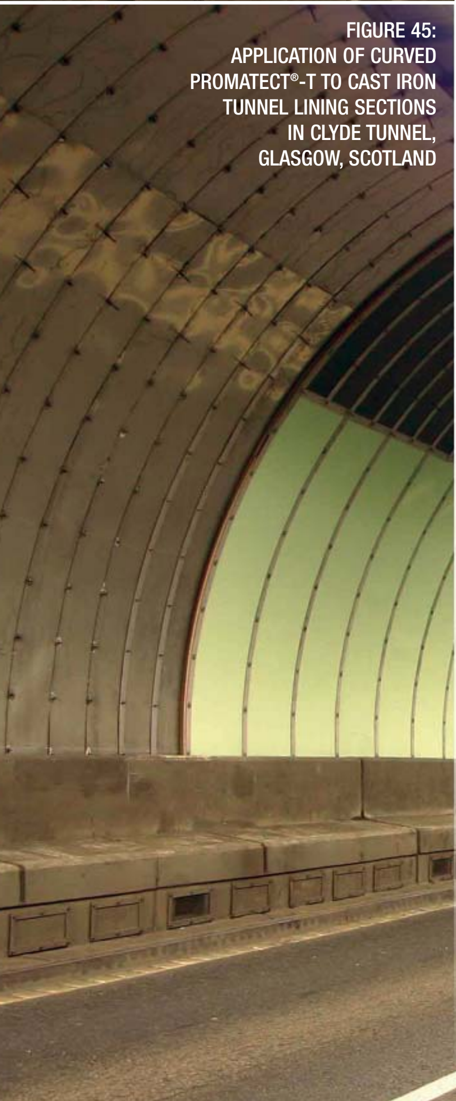


FIGURE 45:
APPLICATION OF CURVED PROMATECT®-T TO CAST IRON TUNNEL LINING SECTIONS IN CLYDE TUNNEL, GLASGOW, SCOTLAND

8. METHODS OF APPLYING BOARD PROTECTION *Continued from page 47*

8.2.1 PROMATECT®-H OR PROMATECT®-T FOR POST CLADDING

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

The PROMATECT® 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. 1200mm x 1200mm x 27mm PROMATECT®-H weighs approximately 36kg, so installation should be considered as a two person operation.

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

An example for curved post cladding method is the Clyde Tunnel (**FIGURE 45** at left) in Glasgow, Scotland, where PROMATECT®-T boards were used to line the cast iron tunnel sections.

8.2.2 FIXINGS

It is likely that the concrete to which the PROMATECT® boards is being fixed would not be completely flat. Therefore care needs 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. Note that washers should be manufactured of the same material type as the bolts to ensure that corrosion does not occur.

Care should be taken when drilling holes into the concrete to avoid the positions of the reinforcement within the concrete. The PROMATECT®-H boards should, as far as is possible, be properly supported when drilling takes place 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.
- Appropriate length to secure the panel thickness (see **SECTION 7** on pages 39-43).
- Minimum 40mm anchor depth penetration into the concrete.
- Expansion action of the anchorage shall be within the concrete and not within the PROMATECT® panel.
- Supplied with a nut and washer head to facilitate removal of the PROMATECT® panels where required.
- Suitable for use in tension zone of concrete (cracked concrete).
- Suitable for use where anchors will be subject to positive and negative pressure fluctuation (dynamic loads).

For corrosion resistance of fixings, please refer to **SECTION 7**.

8.2.3 STEEL FRAMING

Tests have been carried out on systems for both horizontal and vertical applications where the PROMATECT®-H 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, is the frame fixed directly to the concrete structure or is it a free span across the width of the tunnel (see **SECTION 8.2.6** on pages 51 and 52). The frame could consist of either zed sections or top hat (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® board (see above **SECTIONS 7 & 8.2.2**).

Fixing type, centres and depth into the substrate depends upon the type of framing system and is subject to the fire performance requirement 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 performance requirement 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.

8.2.4 INSTALLATION OF PROMATECT®-H OR PROMATECT®-T BOARDS

A) PREPARATION OF BOARDS

Wherever possible, PROMATECT®-H 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 PROMATECT®-H panels to size according to the requirements of the ceiling plan.
- Pre-drilling of holes to make PROMATECT®-H panels ready for securing of impact anchors. The position for holes for various PROMATECT® panels are predetermined according to the anchor layout plan. Suitably prepared templates must be used to drill the anchor layout on each PROMATECT®-H panel.

B) INSTALLATION OF BOARDS

With the smooth face of the PROMATECT® panels facing down, the panels are held in positions flat against the substrate with suitable clamping and lifting equipment, e.g. a panel lifting hoist (**FIGURE 46** at right).

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 panel 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® panel 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 PROMATECT® panel. Place the next PROMATECT® panel tightly abutting the installed panel and repeat the process. Repeat installation of panels outwards from the inner tunnel wall and towards the outer tunnel wall. See **FIGURE 47** at right for examples of a machine drilling the concrete.

Care must be exercised to ensure that the butt joints between panels 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, PROMATECT®-T 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® panels as templates, the template used for off site drilling can be used to facilitate the simultaneous drilling of both the PROMATECT® panels and the anchor positions. Thereafter secure the impact anchors as described above. Pre-cut or cut on site panels shall be prepared to suit site conditions for panels along the junction with tunnel walls.

FIGURE 46:
PANEL LIFTING HOIST

FIGURE 47 *(above and this pictures)* :
DRILLING OF CONCRETE

8. METHODS OF APPLYING BOARD PROTECTION

8.2.5. SUSPENDED CEILINGS, PROTECTIVE MEMBRANE

Many tunnels, especially older city tunnel, were built using a cut and cover 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.

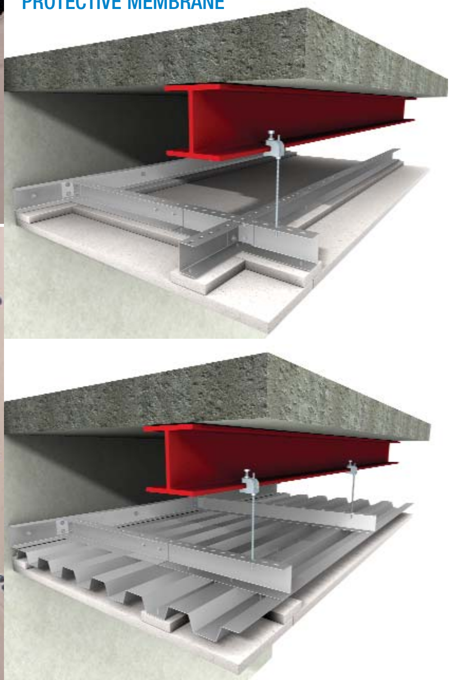
In refurbishing such a tunnel, the protective membrane system is both technically and commercially the most feasible option.

A) SYSTEM COMPONENTS

The protective membrane system consists out of a steel frame which is suspended from the load bearing structure or, depending on the span of the ceiling, can be supported along the walls only (FIGURE 48 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 the 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.

FIGURE 48:
SUSPENDED CEILINGS, PROTECTIVE MEMBRANE



The designer of the suspended steel frame has two options for the horizontal load bearing members:

1) The use of C, Z or omega profiles;
2) The use of a trapezoidal steel decking.

Typically the design of such a suspended steel frame is conducted by a local structural engineer. 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, 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, the advantage is that no intermediate strips are required and the installation rate can be increased.

B) 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 the following locations on and within the system:

1) Reverse side of the PROMATECT® board;
2) Reverse side of the trapezoidal steel sheet or on the C-profiles;
3) HEA 350 I-profile, which was supporting the concrete slab, simulating a large steel beam;
4) Lattice girder, which was supporting the concrete slab, simulating a light weight steel support member;
5) The surface of the concrete;
6) Air temperature in the cavity of the system.

The temperature development on these individual members are available from the Promat Technical Department. The elevated temperatures on the steel members, as mentioned under 2, 3 and 4 are of particular interest to the structural engineer designing the suspended steel frame. Based on the mechanical load, the span, the loading system, the required safety factor and the maximum temperature, the required steel dimensions can be calculated.

The temperature on the concrete surface, as mentioned in 5 (above), is of interest to address the reaction of the concrete when exposed to these elevated temperatures. In accordance with the RWS 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 in a particular project the temperature on the concrete 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 electrical cables for example, are regularly installed behind the protective membrane. Such cables 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 rated cables however can only take some 130-160°C. It could therefore be a more economical option to design the fire resistance of the protective membrane such that the suspended steel frame, the steel or concrete beams and the concrete slab are sufficiently protected and to protect the cable trays separately.

8.2.6 SUSPENDED CEILINGS, ESCAPE ROUTES

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 ceiling 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.

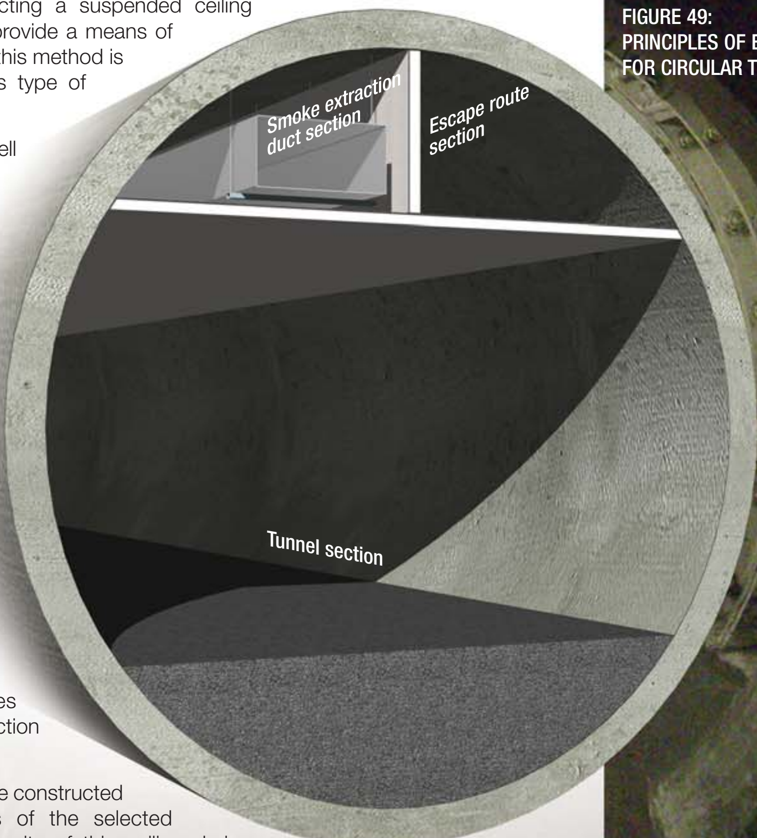


FIGURE 49:
PRINCIPLES OF ESCAPE ROUTE FOR CIRCULAR TUNNELS

The escape door leading to the stairwell should be fire resistant to prevent fire spreading into the escape route. The spread of smoke and toxic gases into the escape route will also be prevented. 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 refer to SECTION 8 in this manual outlining concrete protection.

The other option is to construct the ceiling 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.

8. METHODS OF APPLYING BOARD PROTECTION *Continued from page 51*

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

- The dynamic load cycles coming from passing traffic.
- The additional weight of the the PROMATECT® boards, 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 load bearing function

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

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 ceiling systems for use in tunnels and have fire tested a number of different configurations, using PROMATECT® boards.

A) SYSTEM COMPONENTS

The escape route ceiling 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 (FIGURE 50 below). The system described above satisfies the thermal requirement of 60°C on the floor surface as mentioned above.

FIGURE 50: LOADBEARING CEILING CONSTRUCTION

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

B) THERMAL DATA

During the fire tests temperature recordings have been taken at the following locations on and within the system:

1) Reverse side of the PROMATECT® board;
2) The Z-profiles;
3) The trapezoidal steel sheet;
4) On top of the metal grid (criterion failure <60°C).

The elevated temperatures on the steel members, as listed under 2 and 3 are of particular interest to the structural engineer when designing the steel frame. Based on the mechanical load, the span, the loading system, the required safety factor and the maximum temperature, the required steel dimensions can be obtained.

The temperature development on these individual members are available from Promat.

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 PROMATECT® boards which are installed with staggered joints. Therefore the cover strips as discussed in the SECTION 8.2.5 on page 50 regarding single layer PROMATECT® protective membranes are not required on double layer PROMATECT® escape route ceiling systems.

8.2.7 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 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.

FIGURE 51 at far right shows 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. fire performance, span, thickness of PROMATECT®-T board and type of concrete. Please consult Promat for further details.

PROMATECT®-T boards can be supplied as flat sheets and can be curved on site. Care should be taken to ensure that the thickness of the PROMATECT®-T board 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.

FIGURE 52 at right shows the PROMATECT®-T boards fixed either directly to the soffit or onto top hat sections of a curved section. The dimensions of the steel sections and the centres of positioning are dependent on a number of factors, e.g. fire performance, span, thickness of Promatect board and type of concrete etc. Please consult Promat for further details.

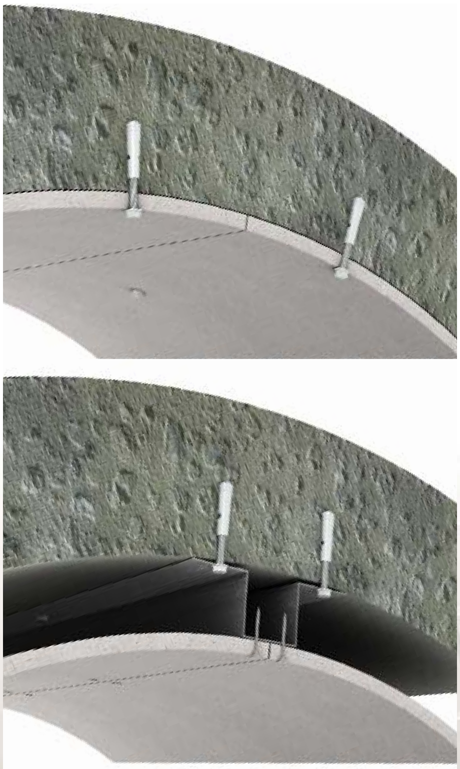
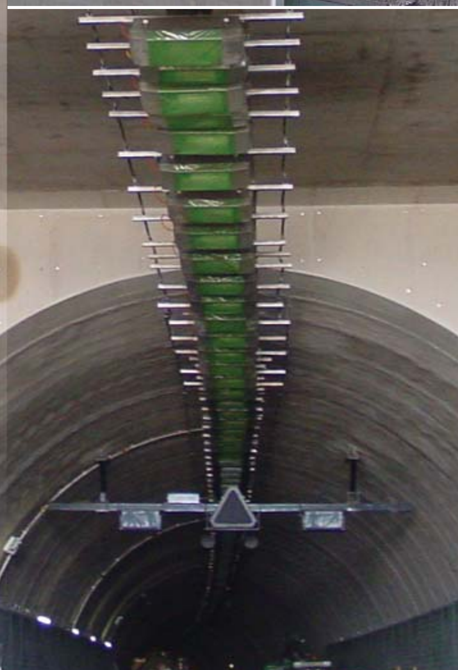


FIGURE 52:
SECTION THROUGH CURVED CONCRETE SECTIONS

FIGURE 51:
SECTION THROUGH
FLAT CONCRETE SLAB



9. FIRE PROTECTION OF ESSENTIAL SERVICES

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 active and passive systems need to be incorporated into the design to ensure optimum life safety systems. 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
- Active and passive detection systems
- Fire extinguishing systems

The active systems within tunnels should consist of lighting, signal systems, monitoring cameras, fire and smoke alarms, loudspeakers, antenna systems (for two way radio communication), hydrants, pump cellars, escape routes, air supply and smoke extracting systems.

This manual 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.

9.1 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:

1) 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.
2) 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.
3) 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.
4) There may be many small particles in the atmosphere that restrict vision.
5) 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.

FIGURE 53: TYPICAL TUNNEL SERVICES SYSTEMS

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 through 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.

More recently, a series of tests carried out in the new 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 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 heat release rates.

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 can be seen from FIGURE 54, 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 top picture shows the effects of a neutral air flow, the lower picture shows the effects of a ventilation speed of 2m/second.

FIGURE 54:
EFFECTS OF AIR FLOW ON CAR FIRE

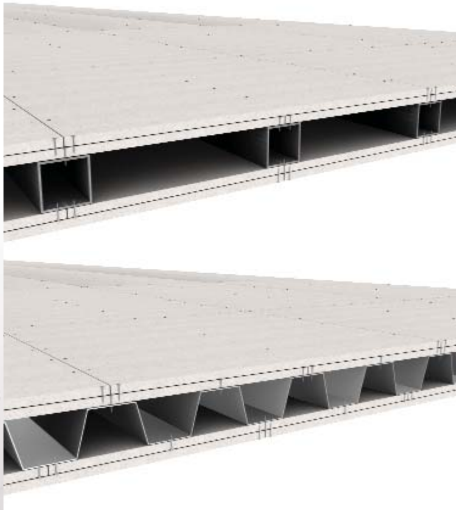
While the effects of natural and longitudinal ventilation in tunnels has been subject to some experimentation, the effects on tunnel fires from semi or fully transverse ventilation is at present less well known.

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 and by far the most common is the construction of a plenum within the tunnel roof space, either from concrete, or by building a soffit from PROMATECT® boards.

9.2 SUSPENDED CEILINGS, 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 gasses will be extracted into the plenum through smoke inlets or hatches. Please refer to FIGURE 55 at right for two typical examples.

FIGURE 55:
SMOKE EXTRACTION PLENUMS



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 hatches 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 SECTION 8 in this manual outlining concrete protection.

The other option is to construct the plenum using a steel frame, spanning from wall to wall, with intermediate hanger rods if mechanically required. As described above, 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.

9. FIRE PROTECTION OF ESSENTIAL SERVICES *Continued from page 55*

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®-T 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 trapezoidal steel decking. The PROMATECT®-T 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®-T thickness. In this way Promat, has developed a design model in which these parameters are fully considered. 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®-T 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®-T boards. Temperature development rates on individual component members are available at Promat offices.

9.3 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,
- Electrically operated fire and smoke alarms,
- 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:

1) Prevent the propagation of fire from one compartment to another;
2) Assist in maintaining escape routes;
3) Ensure the continuing operation of services;
4) Reduce damage to localised areas;
5) Contain smoke and toxic fumes from burning cables if the fire was within the cable enclosure.

By enclosing standard cables in the Promat cable duct systems, all the above requirements can be met, 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.

1) APPLICABLE TIME-TEMPERATURE CURVE

2) MAXIMUM ALLOWABLE TEMPERATURE ON THE SPECIFIC CABLE(S)
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.

3) 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.

4) 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.

5) REQUIRED FIRE PERFORMANCE
Generally, the most onerous requirement is to maintain the integrity of the circuit(s) 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.

6) 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 $6N/mm^2$ 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 advisable.

7) 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.

8) OTHER REQUIREMENTS
Acoustic performance, thermal insulation, water tolerance, strength and appearance can also 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, a design guide has been developed taking the above mentioned parameters into account, thus balancing the requirements to optimise the required PROMATECT® thickness. 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 ISO Cellulosic, Standard Hydrocarbon or RABT time/temperature curves, please consult the nearest local Promat office.

See FIGURE 57 at the right of this page for some examples of cable protection systems constructed from PROMATECT® boards.

FIGURE 56:
SERVICE TUNNEL

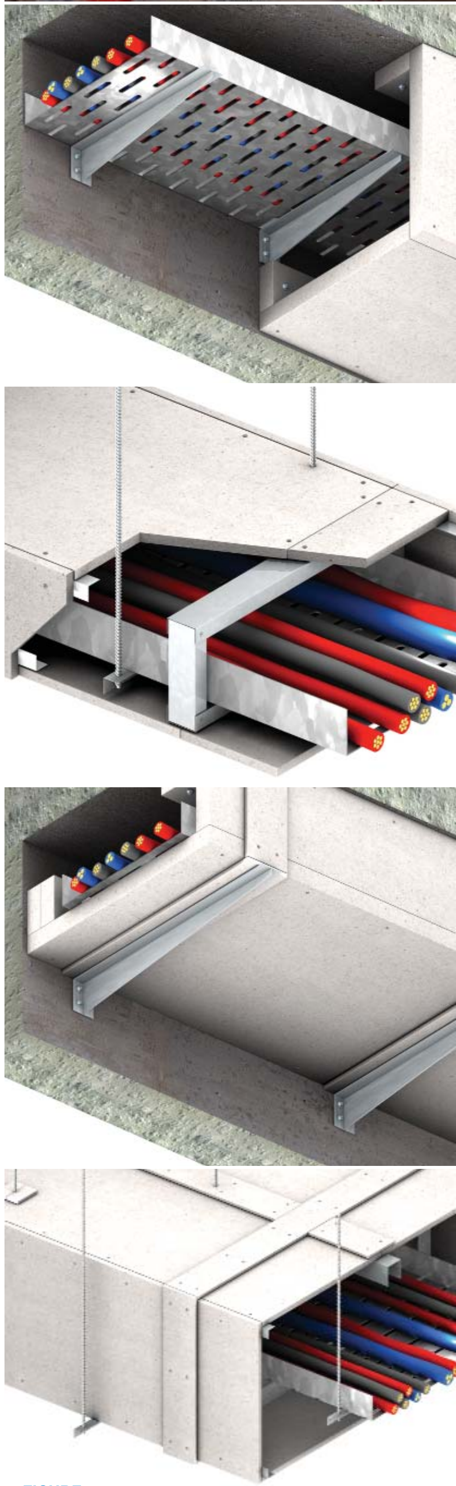


FIGURE 57 *(four examples)* :
PROMAT CABLE PROTECTION SYSTEMS

FIGURE 58 *(three examples)* :
STEEL FIRE DOORS
WITHIN TUNNELS

9. FIRE PROTECTION OF ESSENTIAL SERVICES

9.4 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 fire fighters.

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. Please contact Promat for further details.

9.5 FIRE DOORS

Fire rated 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 provide access to an escape route (mid tunnel channel in an immersed tunnel),
- 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:

1) The door leaf opening away from the heat source;
2) The door leaf opening into the heat source.

Promat has designed a fire rated door suitable for tunnels and fire tested according to the RWS standard. For ease of operation in an emergency situation, the leaf is designed as a sliding door which requires a minimum of force to open. The door provides thermal insulation for the full duration of 120 minutes when exposed to the RWS fire development. It also retains its integrity.

The material used to provide insulation to the door leaf is PROMATECT®-T. The perimeter of the door leaf, as well as some connections to the surrounding walls, are sealed by means of PROMASEAL®-PL intumescent strips.

10. FAQs

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. Recent research (Runehamar) suggests that walls do need some degree of protection.

2) WHICH IS THE BEST PROTECTION METHOD TO MINIMISE SERVICING REQUIREMENTS AFTER THE TUNNEL IS COMPLETED – POST CLADDING IS EASIER TO REMOVE, WHILE LOST SHUTTERING IS MORE DIFFICULT?

Promat has over 32 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.

3) HOW ARE THE CRACKS IN THE CONCRETE DURING FIXING OF PROTECTION MATERIAL TREATED?

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.

4) DOES PROMATECT® PROTECTION 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 such as those in the Netherlands. For example, Westerschelde Tunnel has a 12m water column. PROMATECT® can be soaked by water seepage but the boards are unaffected by water. Wet spots are therefore visible and hence do not inhibit inspection.

5) HOW ABOUT REBAR CARBONISATION? HOW WOULD A PROMATECT® LINING AFFECT TREATMENT OF THIS PROBLEM IN TUNNELS?

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

6) WHAT IS THE EXPERIENCE OF SUCH REPAIRS IN OTHER PROTECTED TUNNELS?

The worst case scenario is the PROMATECT® panel has to be removed to allow access for concrete repair. This is quite easily achieved.

7) HOW WILL PROTECTION MATERIAL REACT TO CHEMICALS IN WATER SEEPAGE?

PROMATECT® boards are inert and will not have adverse reaction to chemicals in the water.

8) HOW WILL PROTECTION MATERIAL REACT TO ALTERNATING PRESSURE FROM VEHICULAR TRAFFIC?

A test has been carried out in Germany's iBMB subjecting PROMATECT® specimens of alternating pressures, three times more cycles than normally encountered in vehicular tunnels. No displacement of the system occurred.

9) HOW DO WE BUILD IN MAINTENANCE AND SERVICE PROCEDURE FOR PROMATECT® AFTER PROTECTED TUNNEL IS OPERATIONAL?

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

10) HOW DOES FIXING OF SERVICES AND LIGHTING TO A PROTECTED CONCRETE SOFFIT AFFECT FIRE PERFORMANCE OF THE CONCRETE?

Drilling through the panels 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 curves where services have been bolted through the PROMATECT® (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.

11) HOW DO WE ENSURE THE SCREWS OR BOLTS REMAIN IN SITU?

If PROMATECT® is used as permanent shuttering, screws are embedded within the concrete and thus cannot fall out. If the bolts used for fixing using the post installation method described in SECTION 8, are not tight, the board will fall as the support is removed.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 showed that very high loads are required to pull the fixings through the boards. The average pull through strength measured for a 25mm 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.

12) WHAT HAPPENS IF THERE ARE ANY POST INSTALLATION GAPS BETWEEN THE PROMATECT® BOARDS?

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

11. TUNNEL FIRE RESEARCH

In recent years a lot of research has been conducted, mainly under the auspices of the European Union.The results of this research will eventually translate into directives, guidelines and standards for tunnel fire safety around the world.

11.1 FIT

FIT is the abbreviation for European Thematic Network on Fire in Tunnels. FIT provides a European platform for dissemination of information of up-to-date knowledge and research on Fire & Tunnels. FIT represents 33 members from 12 European Countries.

To optimise 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 following main objectives have been identified for the FIT Thematic Network:

1) 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.
2) FIT will establish a set of consultable databases with essential knowledge on fire in tunnels.
3) Realise recommendations on design fires for tunnels.
4) To develop European consensus for fire safe design on the basis of existing national regulation, guidelines, code of practices and safety requirements.
5) Define best practices for tunnel authorities and fire emergency services on prevention and training, accident management and fire emergency operations.

11.2 DARTS

DARTS is an RTD-project on Durable and Reliable Tunnel Structures.

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

The objective of the DARTS-project is to develop operational methods and supporting practical tools for the best proactive 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.

11.3 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:

1) 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.
2) 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, one EEA member state and three 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.

11.4 SIRTAKI

SIRTAKI – Safety Improvement in Road & rail Tunnels using Advanced ICT and Knowledge Intensive DSS – is a 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.

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APPENDIX 1: PHYSICAL PROPERTIES

TABLE 16: PROMATECT®-H PHYSICAL PROPERTIES

Properties	Description
Neutral designation	Calcium silicate matrix, asbestos free
Material class	Non combustible in accordance to DIN4102, EN 13501-1 (A1) and BS476: Part 4.
Surface spread of flame	Class 1 in accordance to BS476: Part 7
Building regulations classification	Class 0
Bulk density (air dry)	900kg/m³ (nominal)
Thermal conductivity (λ)	0.17W/m°K at 20°C (typical value)
Alkalinity	Nominal pH 12
Water vapour diffusion resistance factor (μ)	20 (tabulated value)
Moisture content	Air-dried, approximately 7%
Water absorption capacity	Maximum 0.55g/cm³
Dimensions and tolerances (for squared boards)	For sheets of 1220mm x 1220mm: Length x width ± 0.5mm Squareness ± 1mm across diagonals Thickness 27mm ± 0.5mm
Dimensions and tolerances (for standard boards)	For sheets of 1250mm x 2500mm and 1250mm x 3000mm: Length x width ± 3mm Thickness 27mm ± 1.5mm
Surface condition of standard boards	Visible face smooth, opposite face honeycombed.
Biological	Inorganic material that will not rot and not attrack pests.
Flexural strength, F	Longitudinal: 10N/mm² (average production value) Transverse: 5.5N/mm² (average production value)
Tensile strength, T	Longitudinal: 5N/mm² (typical value) Transverse: 4N/mm² (typical value)
Compressive strength (perpendicular to surface of board)	9.3N/mm² (typical value)
Screw pull out resistance	Screw inserts (Type B 3815) RAMPA Screw depth of 15mm on board face: 330N (typical value)

All physical and mechanical property values are averages based on standard production and tested according to internal procedures. The typical values are given for guidance. The figures can change dependent on the test methods used. If a particular value is of prime importance or a specification, please consult Promat Technical Department.

TABLE 17: PROMATECT®-T PHYSICAL PROPERTIES

Properties	Description
Neutral designation	Matrix engineered calcium silicate-aluminate
Material class	Non combustible in accordance to DIN4102, EN 13501-1 (A1), BS476: Part 4.
Surface spread of flame	Class 1 in accordance to BS476: Part 7
Building regulations classification	Class 0
Bulk density (ovendry)	900kg/m^3 (nominal)
Thermal conductivity (λ)	0.21W/m°K at 20°C (typical value)
Alkalinity	Nominal pH 10
Water vapour diffusion resistance factor (μ)	5 (typical value)
Water absorption capacity	Maximum 0.6g/cm^3
Dimensions and tolerances (for squared boards)	For sheets of 1200mm x 1250mm: Length x width ± 0.5mm Squareness ± 1mm across diagonals Thickness 15mm, 20mm, 25mm, 30mm, 35mm and 40mm ± 0.5 mm
Dimensions and tolerances (for standard boards)	For sheets of 1200mm x 2500mm: Length x width ± 3mm Thickness 15mm, 20mm, 25mm, 30mm, 35mm and 40mm ± 0.5 mm
Surface condition of standard boards	Visible face smooth, opposite face honeycombed.
Biological	Inorganic material that will not rot and not attrack pests.
Flexural strength, F	Longitudinal: 4.5N/mm^2 (average production value)
Tensile strength, T	Longitudinal: 1.2N/mm^2 (typical value)
Compressive strength (perpendicular to surface of board)	1% deformation: 1.2N/mm^2 (typical value) 10% deformation: 7.8N/mm^2 (typical value)
Screw pull out resistance	20mm deep air dry: 657N (typical value) 20mm deep saturated: 372N (typical value) (quick fix screw 5mm x 50mm)
Bolt pull through resistance	For 25mm boards: 3.22N (typical value) (bolt M8, washer 30mm)

All physical and mechanical property values are averages based on standard production and tested according to internal procedures. The typical values are given for guidance. The figures can change dependent on the test methods used. If a particular value is of prime importance or a specification, please consult Promat Technical Department.

APPENDIX 2: WORLDWIDE TUNNEL PROJECT REFERENCE

TABLE 18: WORLDWIDE TUNNEL PROJECT REFERENCE

Year	Country	City/Location	Project	Type of tunnel
2008-2009	Germany	Limburg	Schiedetunnel	Road tunnel
2007-2008	Germany	Frankfurt am Main	Theatertunnel	Road tunnel
2007	Australia	Brisbane	INB1 Tunnel	Busway
2007	China	Suzhou	Suzhou Dushu Lake Tunnel	Road tunnel
2007	France	Monaco	Monaco Tunnel	Road tunnel
2007	Germany	Düsseldorf	Werstener Tunnel	Road tunnel
2007	Germany	Hamburg	S-Bahn-Tunnel, Flughafen	Suburban railway
2007	Germany	Berlin	Bundesplatztunnel	Road tunnel
2007	Germany	Ettlingen bei Karlsruhe	Wattkopf-Tunnel	Road tunnel
2007	UK	Glasgow	Clyde Tunnel	Road tunnel
2007	United Arab Emirates	Abu Dhabi	Abu Dhabi Airport Tunnel	Road tunnel
2007	United Arab Emirates	Dubai	Palm Jumeirah Tunnel	Road tunnel
2006-2007	Australia	Sydney	Epping-Chatswood Rail Link	Rail tunnel
2006	France	Paris	Porte des Lilas	Road tunnel
2006	Germany	Hamburg	U-Bahn-Tunnel (U 4) Gänsemarkt	Underground railway
2006	Singapore	From East Coast Parkway to Tampines Expressway	Kallang Paya Lebar Expressway	Road tunnel
2006	Spain	Madrid	PIO XII	Road tunnel
2005-2006	Australia	Sydney	Lane Cove Tunnel	Road tunnel
2005	Austria	Vienna	Absberg Tunnel	Road tunnel
2005	China	Nanjing	Nanjing Jiuhua Mountain Tunnel	Road tunnel
2005	France	73 Novalaise	Tunnel de l'Epine	Road tunnel
2005	France/Italy	Frejus	Frejus Tunnel	Road tunnel
2005	Italy	Tindari	Galleria Tindari	Rail tunnel
2005	Italy	Lecco	Lecco Tunnel	Road tunnel
2005	Germany	Stuttgart	Messetunnel	Road tunnel
2005	Netherlands	Abcoude	Aquaduct Abcoude	Rail tunnel
2005	Netherlands	Roermond	Roer Tunnel	Road tunnel
2004-2005	Australia	Sydney	Cross City Link Tunnel	Road tunnel
2004	China	Shanghai	Shangphai Outer Ring Tunnel	Road tunnel
2004	France	09 Foix	Tunnel de Foix	Road tunnel
2004	France	34 Lodève	Tunnel de la Vierge	Road tunnel
2004	France	66 Porta Hospitalet	Tunnel de Puymorens	Road tunnel
2004	France	73 Moutier	Tunnel de Siaix	Road tunnel
2004	Germany	Hornberg (Schwarzwald)	Hornberg-Tunnel (B 33)	Road tunnel
2003-2007	France	73 Chambéry	Tunnel des Monts	Road tunnel
2003-2005	France/Italy	Frejus	Frejus Tunnel	Road tunnel
2003-2004	France	A40 Nantua	Tunnel de Chamoise	Road tunnel
2003	Australia	Sydney	Central Business District	Road tunnel
2003	Australia	Brisbane	INB3 Tunnel	Service tunnel
2003	China	Huangzhou	XiHu Lake Tunnel	Road tunnel
2003	France	Toulouse	Tunnel Metro de Toulouse	Road tunnel
2003	Netherlands	Terneuzen	Westerschelde Tunnel	Road tunnel
2003	Sweden	Gothenburg	Gotha Tunnel	Road tunnel
2002	Germany	Freiburg	Schützenallee-Tunnel (B 31)	Road tunnel

Year	Country	City/Location	Project	Type of tunnel
2002	Australia	Sydney	M5 Tunnel	Road tunnel
2002	Austria	Vienna	Rennweg train station	Train station
2002	Austria	Vienna	Sanki Marx train station	Train station
2002	China	Nanjing, Jiangsu	Xuan Wu Lake Tunnel	Road tunnel
2002	Denmark	Copenhagen	Copenhagen Metro Station	Metro tunnel
2002	France	Toulon	Toulon Tunnel	Road tunnel
2002	France	46 Valroufie	Tunnel de Constans	Road tunnel
2002	France	46 Pinsac	Tunnel de Terregay	Road tunnel
2002	Japan	Tokyo	Tokyo Port seaside tunnel	Road tunnel
2002	Netherlands	Amsterdam	A5 Schiphol Airport, airplane viaduct	Road tunnel
2002	Netherlands	Rotterdam	Caland Tunnel	Road tunnel
2002	Netherlands	Roelofarendsveen	High Speed Line Aquaduct	Rail tunnel
2002	Netherlands	Rotterdam	High Speed Line Oude Maas & Dordtse Kil	Rail tunnel
2002	Netherlands	Dordrecht	Kil Tunnel	Road tunnel
2002	Netherlands	Voorburg	Seitwende	Road tunnel
2001	Australia	Sydney	Eastern Distributor	Road tunnel
2001	China	Ningbo, Zhejiang	Ningbo river crossing tunnel	Road tunnel
2001	France	74 Chamonix	Tunnel du Mont Blanc	Road tunnel
2001	Germany	Hamburg	Elbtunnel, Western Tube	Road tunnel
2001	Germany	Hamburg	Elbtunnel, 4th Tube	Road tunnel
2001	Japan	Tokyo	Rinkaidoro	Road tunnel
2001	Netherlands	Rotterdam	1e Benelux Tunnel	Road under canal
2001	Netherlands	Rotterdam	2e Benelux Tunnel	Road tunnel
2001	Netherlands	Enkhuizen	Naviduct Enkhuizen	Road under lock
2001	Netherlands	Oud Alblas	Sophiatunnel	Underground route
2000-2001	Germany	Hamburg	Elbtunnel, Western Tube	Road tunnel
2000	Australia	Melbourne	Burnley Tunnel	Road tunnel
2000	France	73 Saint Michel de Maurienne	Tunnel d'Orelle	Road tunnel
2000	Germany	Hamburg	Elbtunnel, Central Tube	Road tunnel
2000	Germany	Hamburg	Elbtunnel, Eastern Tube	Road tunnel
2000	Netherlands	Leidschendam	Aquaduct onder de Vliet	Tramway route
1999	Germany	Hamburg	Krohnstiegtunnel	Road tunnel
1999	Germany	Freiburg	Schützenalleetunnel	Road tunnel
1999	Japan	Tokyo	Dainikouro	Road tunnel
1999	Netherlands	Rotterdam	2e Beneluxtunnel	Road under canal
1999	Netherlands	Rotterdam	Botlektunnel	Road under canal
1999	Netherlands	Amsterdam	Ij-tunnel	Road under canal
1999	Netherlands	Leidschendam	Seitwendetunnel	Road tunnel
1999	Netherlands	Zeeland	Westerscheldetunnel	Road under canal
1998	Australia	Perth	City Northern Bypass Tunnel	Road tunnel
1998	Switzerland	Grellingen	Eggflue-Tunnel	Road tunnel
1997	China	Hong Kong	Hong Kong International Airport Tunnel	Road tunnel
1997	Germany	Bad Godesberg	Urban tunnel, below the B9	Road tunnel

TABLE 18: WORLDWIDE TUNNEL PROJECT REFERENCE *Continued from page 65*

Year	Country	City/Location	Project	Type of tunnel
1997	Netherlands	Alphen/Rhine	Aquaduct Alphen	Road tunnel
1997	Netherlands	Delft	Aquaduct Delft	Tramway route
1997	Netherlands	Amsterdam	Schiphol (kaagbaan)	Road under runway
1997	Netherlands	Schiphol	Schipholtunnel	Road tunnel
1996	Netherlands	Akrum	Aquaduct Akrum	Road tunnel
1995	Singapore	Marina Centre	Suntec City Convention Centre	Underground parking facility
1994	Belgium	Brussels	Belliard Tunnel	Road tunnel
1994	Germany	Hamburg	Elbtunnel	Road tunnel
1994	UK	London	Leicester Square	Electricity substation
1994	Italy	Mont Blanc	Mont-Blanc-Tunnel	Road tunnel
1994	Malaysia	Shah Alam	Shah Alam Sports Complex	Road tunnel
1994	Netherlands	Barendrecht	Heineoordtunnel	Road under canal
1994	Netherlands	Velsen	Wijkertunnel	Road under canal
1993	China (formerly UK)	Hong Kong	Times Square Shopping Complex	Underground parking facility
1993	UK	Wadham	Power transmission tunnel	Service tunnel
1993	Malaysia	Kuala Lumpur	Denmark House	Underground parking facility
1993	Malaysia	Shah Alam	Shah Alam Sports Complex	Underground parking facility
1993	Malaysia	Kuala Lumpur	Sogo Department Store	Underground parking facility
1993	Netherlands	Schiphol	Schipholtunnel 2	Road under runway
1993	Netherlands	Ijmuiden	Wijkertunnel	Road under canal
1993	Singapore	Orchard	Ngee Ann City	Underground parking facility
1992-1998	China	Hong Kong	Hong Kong MTR	Underground stations
1992	China (formerly UK)	Hong Kong	Route 5	Road tunnel
1992	Germany	Munich	Munich Airport, tunnel	Suburban railway
1992	UK	London	Bow Road Station	Underground station
1992	UK	London	Eurostar Waterloo	International rail terminal
1992	Malaysia	Kuala Lumpur	Swiss Garden Hotel	Underground parking facility
1992	Netherlands	Grouw	Aquaduct Grouw	Road tunnel
1992	Netherlands	Schiphol	Schipholtunnel	Road under railway
1991	Belgium	Antwerp	Bevrijdingstunnel	Road tunnel
1991	Netherlands	Zeeland	Vlaketunnel	Road under canal
1990	Belgium	Antwerp	Beveren Tunnel	Road tunnel
1990	Belgium	Zelzate	Hoge Weg Tunnel	Road tunnel
1990	Belgium	Antwerp	Liefkenshoek Tunnel	Road tunnel
1990	Belgium	Antwerp	Tijsmans Tunnel	Road tunnel
1990	China (formerly UK)	Hong Kong	Pacific Place	Road under canal

Year	Country	City/Location	Project	Type of tunnel
1990	UK	London	St. Pauls Thames Link	Underground station
1990	Netherlands	Barendrecht	Heineoordtunnel	Road under canal
1990	Netherlands	Velsen	Velsertunnel	Road under canal
1989-1992	Singapore	Singapore	MRTC	Underground stations
1989	Australia	Sydney	Sydney Harbour Tunnel	Road tunnel
1989	Belgium	Brussels	Leopold II Tunnel	Road tunnel
1989	China (formerly UK)	Hong Kong	Second Cross Harbour Tunnel	Road tunnel
1989	China (formerly UK)	Hong Kong	Eastern Harbour Crossing	Road tunnel and suburban railway
1989	Germany	Bad Ems	Ems Tunnel	Road tunnel
1989	Netherlands	Schiphol	Schipholtunnel	Road tunnel
1989	Netherlands	Schiphol	Schipholtunnel	Road under runway
1989	Netherlands	Hendrik Ido Ambacht	Tunnel onder de Noord	Road tunnel
1989	Netherlands	Amsterdam	Zeeburgertunnel	Road tunnel
1989	USA	Boston	Harbour Tunnel CANA	Road tunnel
1988	Belgium	Antwerp	Kennedy Tunnel	Road tunnel
1988	UK	Medway	Power transmission tunnel	Service tunnel
1987	China (formerly UK)	Hong Kong	First Cross Harbour Tunnel	Road tunnel
1987	Netherlands	Schiphol	Schipholtunnel	Road under runway
1987	Switzerland	Genf	Suburban railway	Suburban railway
1986	Belgium	Antwerp	Jan de Voslei Tunnel	Road tunnel
1986	Netherlands	Schiphol	Schipholtunnel	Road under runway
1985	Belgium	Brussels	Rogier Tunnel	Road tunnel
1982	Belgium	Brugge	Tunnel 't Zand	Road tunnel
1981	Belgium	Antwerp	Craeybeckx	Road tunnel
1980	Germany	Berlin	Schlangenberger	Road tunnel
1980	Switzerland	St. Gotthard	Gotthard Tunnel	Road tunnel
1975	Germany	Hamburg	Elbtunnel	Road tunnel
1963	UK	Dartford	Dartford Tunnel	Road tunnel

The information contained within this table is believed to be accurate at the time of preparation of this document. Latest and complete information on this worlwide tunnel project reference can be obtained from www.promat-tunnel.com.

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