STRUCTURAL FIRE PROTECTION OF RAILWAY TUNNELS

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KEYWORDS: Fire, Structure, Railway, Tunnel, Passive, Protection

ABSTRACT

The recent fire in the Channel Tunnel has served to heighten interest on the issue of structural fire protection of rail tunnels. Opinions on the requirement and merit of passive fire protection in rail tunnels vary significantly, and there is as yet little harmonisation of the relevant international standards. The current paper provides a review of the criteria that are normally employed in assessing the risk and consequences of fires in rail tunnels, and the selection of suitable time-temperature curves that describe the evolution of 'worst-case' fires. The advantages and drawbacks of alternative fire protection methods, including sprayed-on fire protection materials, cementitious linings and the addition of polypropylene fibres, are briefly outlined. In addition, the issue of fixed fire fighting systems, and whether these can be viewed as a possible alternative or addition to passive fire protection measures, is discussed.

INTRODUCTION

The issue of tunnel safety has become urgent due to a number of large fires that have occurred worldwide, the latest being the Channel Tunnel fire in 2008. The Channel Tunnel has now experienced three significant fires in its 20-year lifetime (in 1996, 2006 and 2008), none with fatalities, although all of them have led to some structural damage. Other rail tunnel fires include the Summit Tunnel in the UK in 1984, the Great Belt Tunnel TBM fire in Denmark in 1994, the Daegu, South Korea metro fire in 2003 (182 fatalities) and the Funicular Railway Tunnel fire in Kaprun, Austria in 2000 (155 fatalities). On mainland Europe in the previous decade, there have been road tunnel fires with multiple fatalities at Mont Blanc (1999), Tauern (1999) and Gotthard (2001). As a response to these fires, a number of national and international initiatives were launched to investigate tunnel fire safety issues, and to propose new codes of practice (Tarada, 2007).

PURPOSE OF STRUCTURAL FIRE PROTECTION IN RAIL TUNNELS

Rail tunnel fires are rare events, and the provision of fire protection to rail tunnels usually represents a very significant investment. It is therefore important to consider the reasons why such fire protection should be considered in the first place.

It may be argued that the fire protection of a rail tunnel structure is not a life safety issue, since the temperatures required to effect structural damage would preclude human tenability in any case. However, fire protection may still be required for asset protection, the minimisation of 'down-time' following a major incident, and the protection of fire service personnel from falling debris. The minimisation of 'down-time' is particularly relevant for the protection of income streams for rail operators, and to minimise other social economic costs of traffic disruption and diversions while repairs to fire damage are undertaken. A societal cost-benefit analysis over a suitably long timescale (e.g. the expected length of the asset life, or a fraction of it) may provide a useful basis for decision-making. Such a cost-benefit analysis requires inputs from a quantitative risk analysis, which indicates the frequency and consequences of a range of fire sizes.

RELEVANT STANDARDS

United Nations Economic Commission for Europe's Group of Experts on Safety in Tunnels made the following recommendations in 2003:

“The need for structural fire protection and its type should be given careful consideration especially for those locations involved in any safe haven or rescue. The risk study should consider the likely fire size and its thermal impact on the type of structure involved (heat transfer, smoke leakage, structural damage, spalling, etc.) and the consequences of structural failure. Appropriate temperature development curves should be chosen for the testing of the materials involved. The standard temperature curve such as the ISO 834 Fire resistance tests – Elements of Building Construction – should be commonly used. Where high fire temperatures are possible, e.g. petrol fires, other test curves should be considered”.

The ‘draft technical specification for interoperability’ in the European Union Decision 2008/163/EC states that:

“This specification applies to all tunnels, irrespective of their length.

The integrity of the structure shall be maintained, in the event of fire, for a period of time sufficiently long to permit self-rescue and evacuation of passengers and staff and the intervention of rescue services without the risk of structural collapse.

The fire performance of the finished tunnel surface, whether in situ rock or concrete lining, has to be assessed. It shall withstand the temperature of the fire for a particular duration of time. The specified "temperature-time curve" (EUREKA-curve) is given in the following figure. It is to be used for the design of concrete structures only”.

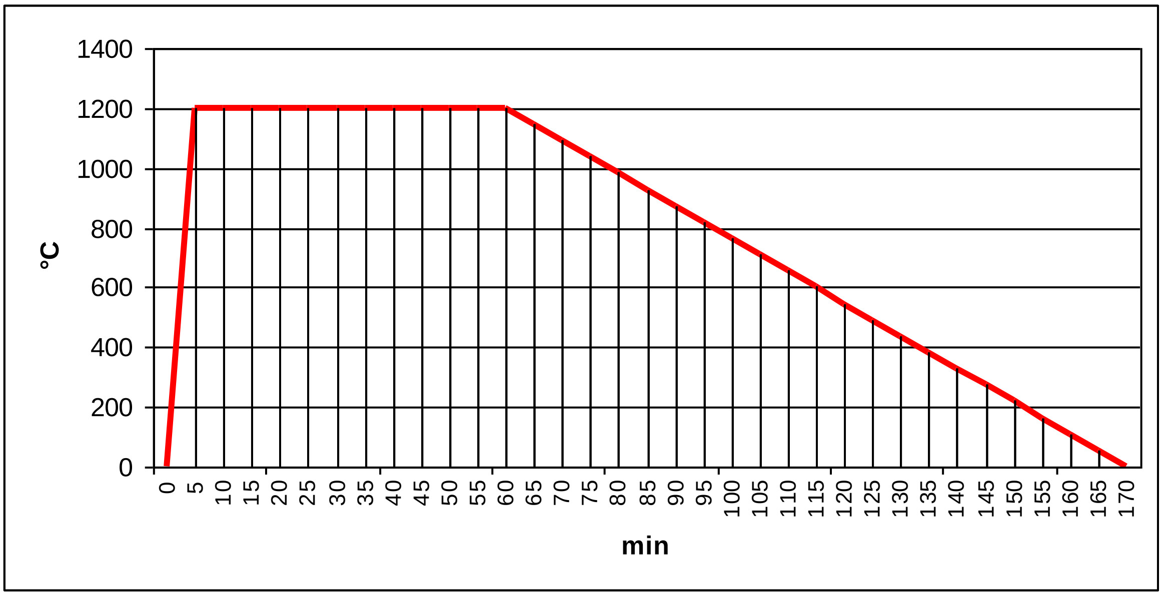

Figure 1: EUREKA fire time-temperature curve

FIRE TIME-TEMPERATURE CURVES

The EUREKA-curve proposed by the draft technical specification for interoperability is not unique – there are a number of fire time-temperature curves proposed for a variety of applications, ranging from the ISO 834 (1975) 'cellulosic' curve to the RWS curve (Figure 2). The selection of an appropriate time-temperature curve and the relevant fire duration is an important consideration, which should be driven by a risk assessment, in cases where no design standards apply.

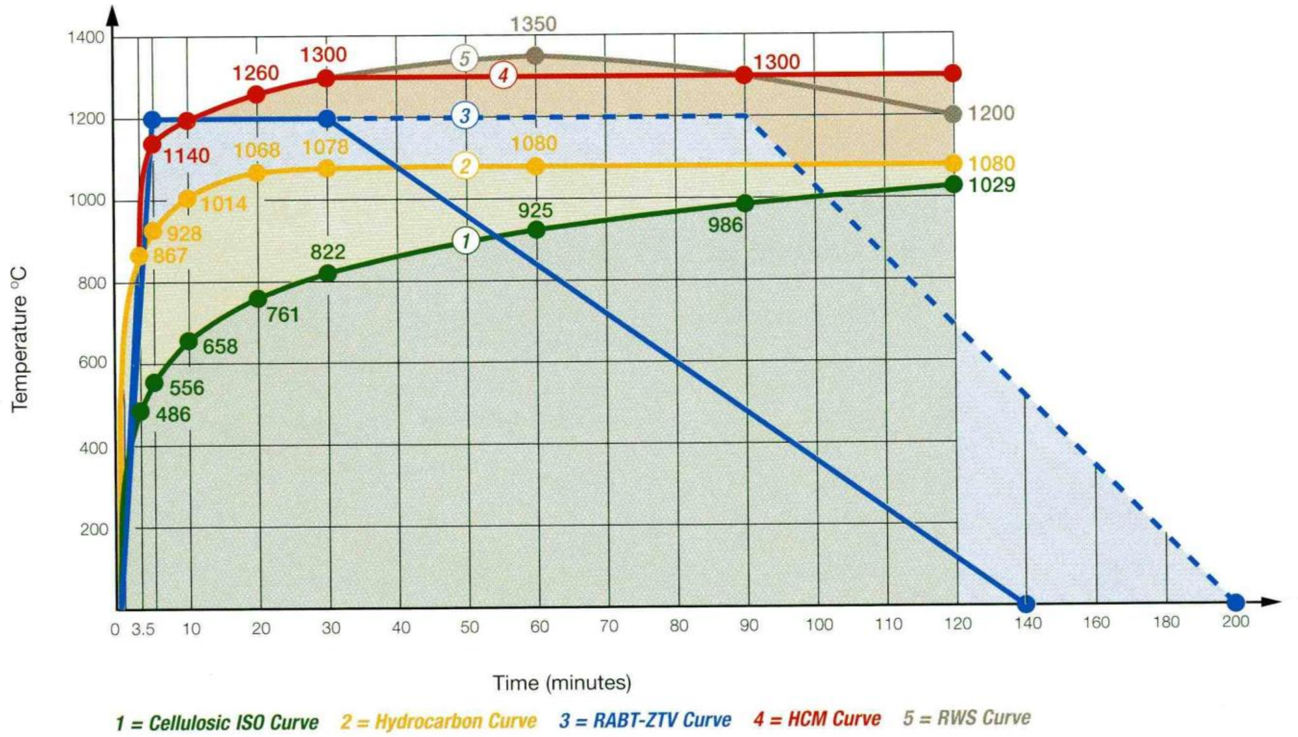

Figure 2: Fire time-temperature curves

Ingason (2006) reported on the UPTUN series of experimental fire tests on a disused tunnel, and made recommendations regarding the most appropriate fire temperature curve to select for a range of fire risks (Table 1). He proposes that the ISO 834 curve should be used up to an expected fire heat release rate of 50MW, above which the hydrocarbon curve (up to 100MW) and thereafter the RWS curve (up to the stoichiometric limit) should be applied. However, these recommendations should be considered as preliminary only, since they are not yet backed up by sufficient evidence. The International Tunnelling Association's Committee on Operational Safety of Underground Facilities will consider these issues within its remit (Haack, 2006).

Once a suitable fire time-temperature curve has been selected, the likely effects of such a fire on the tunnel's structure should be ascertained. European standard EN 1992-1-2:2004 provides methods of calculating the reduction of concrete strength due to high-temperature damage within the concrete and its steel reinforcement. EN 1992-1-2:2004 also provides also provides guidance on the reduction in the cross-section due to fire damage, based on cellulosic fires as per ISO 834. The calculation of the structural response to non-ISO 834 fires within concrete members is currently not prescribed by European standards.

<table>
<tr><th colspan="3">HRR MW</th><th>Road, examples vehicles</th><th>Rail, examples vehicles</th><th>Metro, examples vehicles</th><th>At the fire boundary</th></tr>
<tr><td rowspan="9">Risk to life</td><td rowspan="4"></td><td>5</td><td>1-2 cars</td><td></td><td></td><td>ISO 834</td></tr>
<tr><td>10</td><td>Small van, 2-3 cars, ++</td><td>Electric locomotive</td><td>Low combustible passengers carriage</td><td>ISO 834</td></tr>
<tr><td>20</td><td>Big van, public bus, multiple vehicles</td><td></td><td>Normal combustble passengers carriage</td><td>ISO 834</td></tr>
<tr><td>30</td><td>Bus, empty HGV</td><td>Passengers carriage</td><td>Two Carriages</td><td>ISO 834</td></tr>
<tr><td rowspan="5">Risk to construction</td><td>50</td><td>Combustibles load on truck</td><td>Open freight wagons with lorries</td><td>Multiple carriages (more than two)</td><td>ISO 834</td></tr>
<tr><td>70</td><td>HGV load with combustibles (approx. 4 tonne)</td><td></td><td></td><td>HC</td></tr>
<tr><td>100</td><td>HGV (average)</td><td></td><td></td><td>HC</td></tr>
<tr><td>150</td><td>Loaded with easy comb. HGV (approx. 10 tons)</td><td></td><td></td><td>RWS</td></tr>
<tr><td>200 or higher</td><td>Limited by oxygen, petrol tanker, multiple HGVs</td><td>Limited by oxygen</td><td></td><td>RWS</td></tr>
</table>

Table 1: UPTUN fire resistance recommendations (Ingason, 2006)

COMPARISON WITH ROAD TUNNEL GUIDELINES

In comparison with rail tunnels, guidelines for the structural fire protection of road tunnels are relatively well developed. The International Tunnelling Association (ITA) has issued joint guidelines with the World Road Association (Lacroix and Haack, 2004), that are summarised in Table 2. It should be noted that structural fire protection is definitely required for tunnels in unstable ground or immersed tunnels, or where high fire heat release rates are expected from truck or tanker fires. For other tunnels, 120 minutes of fire resistance to the ISO 834 curve is generally proposed, rising to 120 minutes to the RWS or the enhanced hydrocarbon curves for tunnels requiring additional asset protection, or no additional fire protection at all if it is not economically justifiable. NFPA 502 (2008) recommends the use of a two-hour RWS curve for the protection of road tunnel structures.

There are however some important differences between rail and road tunnels, which should be considered when considering the appropriate level of fire resistance for rail tunnels.

1. *Fire load*
   It can be argued that the potential fire load in rail tunnels can be controlled better than that in road tunnels, since the rolling stock materials can be specified to have good reaction-to-fire properties, or even to be non-combustible. For example, BS 6853:1999 specifies three vehicle categories in terms of operating environments (underground and surface), and proposes fire precautions for each category. No such control is available for road vehicles, whose fire load has actually been increasing in recent years due to the use of plastic materials. However, there may still be a substantial 'imported' fire risk on vehicle shuttles in rail tunnels, as evidenced by the Channel Tunnel fires, or due to freight traffic.

2. *Accident Risk*
   The risk of accidents in rail tunnels is very low, and can be reduced further by the design of derailment containment and automatic train control systems. Train driver training is usually well controlled and regulated by company or national standards, and this helps to drive down accident rates. Such training also extends to first responses in case of an incident, which may be critical to stopping fire spread and to saving passenger lives.

The risk of accidents in road tunnels is also low, but the risk of collisions is greater than that for rail tunnels, particularly in bidirectional road tunnels. Road vehicle drivers have variable driving expertise, and do not always follow the relevant speed limits or other driving regulations. It generally follows that the risk of accidents in rail tunnels is lower than that in road tunnels. However, the risk of deliberate fires (arson) remains, as evidenced by the Daegu, South Korea metro fire in 2003.

3. *Evacuation*
During normal operation, road tunnels generally have an even number of motorists along their length, whereas passengers in rail tunnels are 'concentrated' within trains. In case of an incident, providing safe evacuation conditions for rail passengers can be more challenging than in a road tunnel, since large groups of people may have to be moved along narrow walkways to the nearest station, cross-passage or portal. Tenable conditions may therefore have to be maintained for longer periods of time in rail tunnels in such circumstances, during which the tunnel structure should not be compromised.

Due to the low fire loads and accident risks, most rail tunnels do not have any additional fire protection beyond that naturally provided by the structure, e.g. by the depth of concrete cover that may be specified for durability reasons. In cases of 'imported' fire risks (e.g. vehicle shuttles or fuel tankers), or where the consequences of tunnel damage or even collapse may be economically damaging, a cost/benefit analysis should be undertaken to determine the most appropriate level of fire resistance.

Traffic Type	Main Structure				Secondary Structures[4]			
	Immersed or under/inside superstructure	Tunnel in unstable ground	Tunnel in stable ground	Cut & Cover	Air Ducts[5]	Emer-gency exits to open air	Emergency exits to other tube	Shelters[6]
Cars/ Vans	ISO 60 min	ISO 60 min	[2]	[2]	ISO 60 min	ISO 30 min	ISO 60 min	ISO 60 min
Trucks/ Tankers	RWS/ HC_{inc} 120 min[1]	RWS/ HC_{inc} 120 min[1]	RWS/HC inc 120 min[1]	RWS/HC inc 120 min[1]	ISO 120 min	ISO 30 min	RWS/ HC_{inc} 120 min	RWS/ HC_{inc} 120 min[7]

[1] 180 min maybe required for very heavy traffic of trucks carrying combustible goods
[2] Safety is not a criteria and does not require any fire resistance (other than avoiding progressive collapse). Taking into account other objectives may lead to the following requirements:
– ISO 60 min in most cases
– No protection at all if structural protection would be too expensive compared to cost and inconvenience of repair works after a fire (e.g. light cover for noise protection)
[3] Safety is not a criteria and does not require any fire resistance (other than avoiding progressive collapse). Taking into account other objectives may lead to the following requirements:
– RWS/HC_{inc} 120 min if strong protection is required because of property (e.g. tunnel under a building) or large influence on road network
– ISO 120 min in most cases, when this provides a reasonably cheap protection to limit damage to property
– No protection at all if structural protection would be too expensive compared to cost and inconvenience of repair works after a fire (e.g. light cover for noise protection)
[4] Other secondary structures should be defined on a project basis
[5] In case of transverse ventilation
[6] Shelters should be connected to the open air
[7] A longer time may be used if there is a very heavy traffic of trucks carrying combustible goods and the evacuation from the shelters is not possible within 120 min

Table 2: Joint ITA/WRA structural fire protection recommendations (ITA, 2004)

EFFECTS OF FIRE ON CONCRETE STRUCTURES

Fire can affect concrete structures in a number of ways, and it is important to appreciate these mechanisms when designing fire protection measures. Concrete with siliceous or calcareous aggregates heated up in excess of 200°C will begin to lose its compressive strength, although this will initially be restricted to a thin layer of concrete exposed to the fire. At temperatures between 250°C to 400°C, spalling may occur, with pieces of concrete breaking away from the surface. The steel reinforcement will be affected by temperatures in excess of 400°C, although it is likely that concrete would have spalled by then.

Spalling is a complex process, which may be explained by the generation of high pore pressures due to the conversion of water bound in the concrete into steam. In the absence of any relief, the steam may crack the concrete substrate, leading to spalling. High grade concrete mixes (grades C60 and above) are generally more susceptible to spalling than low grade concrete mixes, due to the lower water to cement ratios used in high grade concrete, which implies a reduction in permeability (Clayton and Lennon, 2000).

PASSIVE FIRE PROTECTION OPTIONS

A number of options for the passive fire protection of rail tunnels are available, as outlined below.

Polypropylene Fibres

An effective measure to control spalling is the use of micro mono-filament polypropylene fibres added to the concrete mix. The polypropylene fibres melt at 160 degrees and thereby increase the porosity of the concrete enabling the dissipation of pore pressures. Consequently no or very limited spalling occurs.

The effectiveness of polypropylene fibres has been confirmed by large-scale fire tests performed by TNO Fire Research for the CTRL Tunnels in the UK (Shuttleworth, 2001) and the Westerschelde Tunnel in the Netherlands (Both, 1999). The tests have been performed on pre-compressed tunnel lining segments under RWS and RABT-ZTV fire conditions respectively.

The test results show that the addition of polypropylene fibres can satisfactorily control explosive spalling for temperature developments described by the ISO 834 and hydrocarbon design fire curve. The test results show however that under RWS design fire conditions polypropylene fibres cannot adequately control explosive spalling. Consequently, this measure should either be replaced by or combined with panels or coating.

Following a fire event, a risk assessment should be carried out to determine appropriate measures to be taken where the fibres have melted. The assessment should include at the very least consideration of:

- Strength reduction of the heat affected concrete and required structural capacity
- Permeability of the remaining concrete and the impact this may have on corrosion or other deterioration mechanisms
- Risk of concrete spalling over time

The associated overall repair costs are relatively high. In addition, the tunnel cannot remain operational during the repair works.

Panels

Effective passive fire protection can be provided by proprietary boards formed from calcium silicate aluminate materials, which can be post-fixed to the structural lining or used as false shuttering during casting of the concrete (Figure 3). A steel frame may be required to provide a clearance behind the secondary lining (for water ingress and inspection, for example), but this can prove to be expensive in terms of cost and installation time.

Figure 3: Westerschelde Tunnel, Netherlands (showing fire protection boards on ceiling and the upper part of the walls).

The panels have good insulation properties and can withstand temperatures exceeding 1350°C. They can be designed such that the temperatures at the face of the structural lining do not exceed 350°C, which will prevent spalling and any changes in the mechanical properties of the concrete. The required panel thicknesses vary between 20 and 30mm depending on the temperature development over time.

Panels fixed against the structural concrete can generally withstand multiple fires. If required, the panels can be replaced relatively easily. The structural lining behind the panels is deemed to remain undamaged.

Cementitious Coatings

Passive fire protection can also be provided by applying a cementitious coating. The materials primarily consist of Portland cement with fine aggregates and can be applied in varying thicknesses ranging between 20mm and 40mm. The required thickness depends on the design fire load and the required temperature at the interface between the barrier and the concrete of the structural lining. The coating can be designed such that the temperatures at the face of the structural lining do not exceed 350°C, which will prevent spalling and significant changes in the mechanical properties of the concrete. A small diameter coated reinforcement mesh might be required to fix the coating to the structural lining.

Protective coating which is spray-applied on the structural lining undergoes chemical changes during the fire event. Therefore it can only withstand a single fire after which it has to be removed and replaced. The structural concrete is deemed to remain undamaged.

An example of a rail tunnel with a cementitious fire protection coating is the 8-km long Groene Hart tunnel in the Netherlands (Figure 4), which contains both cut-and-cover and bored lengths. The average depth of the coating is 42mm, designed to protect the structure against a 30MW fire heat release rate.

Figure 4: Application of cementitious fire protection lining to the Groene Hart Tunnel (Gijsbers et al, 2006)

ACTIVE FIRE SUPPRESSION

Significant changes have occurred recently with respect to the guidance provided by a number of international organisations with respect to road tunnel fire suppression, which may in time have implications on rail tunnels as well. Such fire suppression systems are now viewed more favourably than before, in terms of their asset protection and life safety benefits. The key issue is to control any fire spread, by early application of water at the affected tunnel locations.

The World Road Association (2008) has issued a report on fixed fire-fighting systems, which recommends a feasibility study, a risk analysis as outlined in European Directive 2004/54/EC (European Union, 2004) and a cost-benefit analysis prior to the selection of a fixed fire-fighting system for a road tunnel.

Appendix E of NFPA 502 (2008) deals with water-based fixed fire-fighting systems in road tunnels. It concludes that such systems should be considered where an engineering analysis demonstrates that the level of safety can be equal to or exceeded by the use of water-based fixed fire-fighting systems and is a part of an integrated approach to the management of safety.

The issue of whether the installation of a fixed fire suppression system can partially or wholly negate the requirement for passive fire protection to a tunnel structure is currently an issue for debate. Clearly, any reduction in levels of passive fire protection must be justified by a risk assessment. It is likely that in order to be considered as a mitigating measure in place of prescriptive fire safety designs, any fire suppression system would need to have an appropriate Safety Integrity Level (as per BS EN 61511-

3:2004 and BS EN 61508-6:2002). Even so, the possibility of failure or non-operation of a fire suppression system should be considered in the risk assessment, as well as the possible consequences.

CONCLUSIONS

The provision of passive fire protection to rail tunnels is not usually required, if the fire loads are low and the safety provisions within the rolling stock and rail infrastructure are specified and maintained to a high standard. However, the existence of ‘imported’ fire risks such as vehicle shuttles and fuel tankers may imply significantly higher fire loads, as the recent fire in the Channel Tunnel has demonstrated. In addition, there may be cases where the collapse of a tunnel may imply unacceptably high social costs. In such cases, a cost/benefit analysis, informed by a quantitative risk assessment, may demonstrate a strong case for additional fire protection measures, including passive fire protection and/or fire suppression systems.

REFERENCES

Both, K. (1999) ‘Evaluation of passive fire protection measures for concrete tunnel linings’, Proceedings of international conference on Tunnel Fires and Escape from Tunnels, Lyon, France, 5-7 May 1999

British Standards Institute (2004), BS EN 1992-1-2:2004, ‘Eurocode 2: Design of concrete structures — Part 1-2: General rules — Structural fire design’

British Standards Institute (1999) BS 6853:1999, ‘Code of practice for fire precautions in the design and construction of passenger carrying trains’

British Standards Institute (2004) BS EN 61511-3:2004, ‘Functional safety — Safety instrumented systems for the process industry sector — Part 3: Guidance for the determination of the required safety integrity levels’

British Standards Institute (2002) BS EN 61508-6:2002, ‘Functional safety of electrical/electronic/ programmable electronic safety-related systems — Part 6: Guidelines on the application of IEC 61508-2 and IEC 61508-3.

Concrete Society (2007), ‘Guidance on the Use of Macrosynthetic Fibre-Reinforced Concrete’, Technical Report 65

Clayton, N. and Lennon, T. (2000), ‘Effect of polypropylene fibres on performance in fire of high grade concrete’, Building Research Establishment, UK

European Union (2008), Decision 2008/163/EC, Interoperability of the Trans-European Conventional Rail System, Draft Technical Specification for Interoperability, Aspect: ‘Safety in railway tunnels’

European Union (2004), Directive 2004/54/EC of the European Parliament and of the Council on Minimum Safety Requirements for Tunnels in the Trans-European Road Network

Gijsbers, F.B.J, Klok, G.J and van de Linde, F.W.J. (2006), ‘Brandwerende bekleding Groene Harttunnel’, Onderzeok & technologie, Tunnelbou, Cement.

Haack, A. (2006), ‘ITA-COSUF Work Programme’, Safe & Reliable Tunnels - Innovative European Achievements, Second International Symposium, Lausanne

Ingason, H. (2006), 'Design Fires in Tunnels', Safe & Reliable Tunnels - Innovative European Achievements, Second International Symposium, Lausanne

International Organization for Standardization (1975), ISO 834 "Fire resistance tests. Elements of Building Construction", Geneva

International Tunnelling Association (2004), 'Guidelines for Structural Fire Resistance for Road Tunnels', Working Group No.6 Maintenance and Repair

Lacroix, D. and Haack, A. (2004), 'PIARC Design Criteria for Resistance to Fire for Road Tunnel Structures', Routes/Roads, World Road Association, No. 324 - October 2004

National Fire Protection Association (2008), NFPA 502 Standard for Road Tunnels, Bridges, and Other Limited Access Highways

Shuttleworth, P. (2001) 'Fire Protection of Concrete Tunnel Linings', Proceedings of the Third International Conference on Tunnel Fires, Oct. 9-11, 2001, Washington, DC, pp. 157-165

Tarada, F. (2007), 'Improving Road Tunnel Safety', Eurotransport, Issue 5

United Nations Economic Commission for Europe (2003), 'Recommendations of the Multidisciplinary Group of Experts on Safety in Tunnels (Rail)'

World Road Association (2008), 'Road Tunnels: An Assessment of Fixed Fire Fighting Systems', Technical Committee C3.3 on Road Tunnel Operations