Passive protection against fire

G A Khoury, chairman of the FIB International Committee 4.3.1 "Fire design for concrete structures" and scientific manager of the UPTUN European project "Upgrading Tunnels" describes the options for passive tunnel lining protection

Right: Damage after the Great Belt fire

Bottom: Fig 1 - Standard nominal temperature-time curves for tunnels

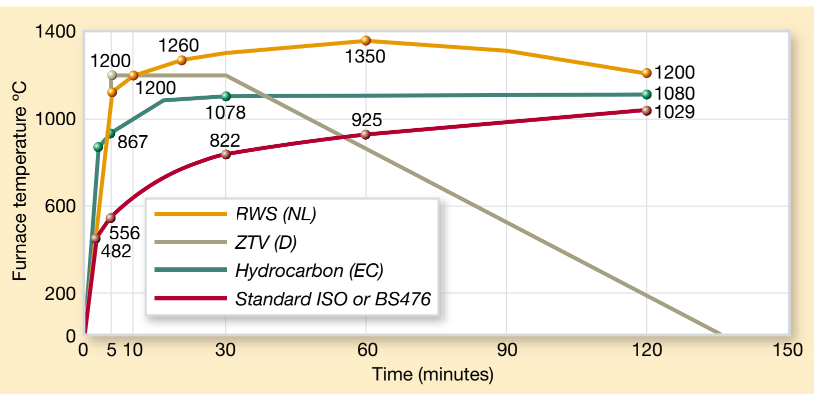
Passive fire protection of tunnel linings has become an important issue following a spate of fires in the past decade in which the structural integrity of the concrete lining was impaired. Fire safety in tunnels applies to both the safety of people and the safety of the structures. The fire safety design of tunnels has traditionally provided a higher priority to the issues relating to the safety of people, since the latter is considered merely as an economic issue. Nevertheless, structural integrity in fire does impact upon people in a number of ways (e.g. Heavy objects and/or hot spalled concrete falling on people, flooding when the tunnel lining is breached). In addition there are the financial and socio-economic impacts (e.g. costs of repair/loss of service, impact upon the local and wider economy).

Upgrading of fire protection in tunnels

While fires have always occurred in tunnels, it was in particular the damage caused to the concrete linings in the fires that took place in the 1994 Great Belt tunnel fire in Denmark and in the 1996 Channel Tunnel fire that has provided the impetus in both Denmark and the UK to take structural fire protection more seriously. Interestingly, while the statistics indicate a low frequency of tunnel fires in Europe the Great Belt fire took place during construction and the Channel tunnel fire soon after construction.

Table 1: Structural damage in recent tunnel fires

Tunnel (Year)	Concrete strength	Max temp	Fire duration	Length affected	Affect on segment
Great Belt (1994)	76MPa 28 day	800°C – 1,000°C	7hrs	16 segment rings (1.65m long) damaged in crown	Peak of spalling 270mm
Channel (1996)	110MPa mature	1,100°C	9hrs	500m with 50m severely affected by spalling	Up to 100% (400m) of thickness spalled showing grout
Mont Blanc (1999)	Not reported	1,000°C	50hrs	900m – tunnel crown most affected	Serious damage to tunnel structure



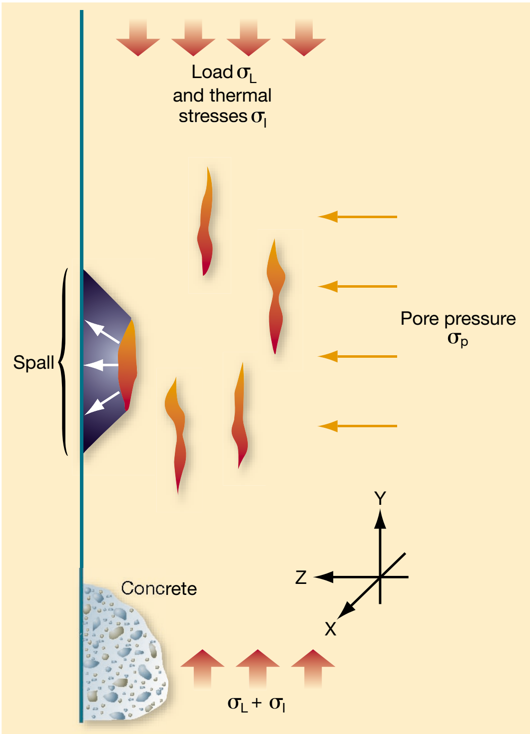
Fire scenarios

The structural response to a tunnel fire depends upon the nature of the fire which can vary considerably from fire to fire. The key feature is the temperature-time curve imposed by the fire at the structure's surface, and especially: (i) The heating rate (i.e. the rate of temperature increase) which influence the development of temperature, moisture and pore pressure gradients within the concrete, (ii) the maximum temperature level which influences the nature of the physico-chemical relations in the material and through this its properties; (iii) the duration of the fire which influences the temperature development into the structure with time; and (iv) the cooling regime (e.g. water cooling would have a different influence upon the material and the temperature distribution from "natural" cooling).

Given the confined nature of the tunnel, tunnel fires tend to generate temperatures higher than in building fires and last much longer due to the limited access for fire fighting crews and equipment. A number of nominal fire curves have been proposed for tunnels, the most severe of which is the Dutch RWS hydrocarbon curve where the temperature reaches 1,100°C after 5 minutes and 1,350°C after 60 minutes. In buildings, the combustion of cellulosic materials is modelled by the less severe ISO 834 curve where the temperature reaches 556°C in 5 minutes and 821°C after 30 minutes. The ISO fire is also being proposed for tunnels with small fires. All the other nominal tunnel fires fall in between these two extremes (figure 1).

Passive protection of tunnel linings

Despite its non-combustibility and low thermal diffusivity, concrete experiences explosive spalling from the build-up of pore pressures and internal tensile stresses during fire. This results in loss of section and exposure of the reinforcing steel to above critical temperatures. In addition, concrete loses strength upon heating, particularly at temperatures above about 300°C. These problems can be addressed by passive fire protection of the tunnel lining but depend upon the type of tunnel considered. In immersed tube, and cut & cover, tunnels the purpose of fire protection is mainly to protect the sagging reinforcement in the flat roof, whereas; in bored tunnels fire protection serves to prevent explosive spalling to which the higher concrete grade is more sensitive. In general terms, therefore, passive fire protection is required whenever any combination of the following problems becomes an issue; prevention of explosive spalling; protection of



Top: Fig 2 - Mechanism of spalling of concrete[2]

reinforcing and prestressing steel from exceeding critical temperatures; protection of the concrete from exceeding critical temperatures.

Explosive spalling

Explosive spalling is the violent breaking off of layers or pieces of concrete from the surface of a structural element when it is exposed to rapidly rising temperatures as experienced in fires. It normally occurs during the first 20-30 minutes into a fire.

Many material (e.g. permeability, saturation level, aggregate size and type, presence of cracking and reinforcement), geometric (e.g. section shape and size) and environmental (e.g. heating rate, heating profile, load level) factors have been identified from experiments as influencing spalling of concrete in fire. The main factors influencing spalling are the heating rate (especially above 2-3°C/minute), permeability of the material, pore saturation level (especially above 2-3% moisture content by weight of concrete), the presence of reinforcement and the level of external applied load.

Low permeability high performance concrete (HPC) is more likely to explosively spall, and to experience multiple spalling, than normal strength concrete despite its higher tensile strength. This is because greater pore pressures build up during heating owing to the material's low permeability. Also the peak in pore pressure occurs nearer to the surface for HPC which explains why thinner concrete sections spall repeatedly from HPC concrete in fire.

Mechanisms of explosive spalling

The mechanisms proposed to explain the explosive spalling of concrete fall under three categories: Firstly, Pore Pressure Spalling which is caused by the development of pore pressures within the concrete depending upon the moisture content, heating rate and the permeability of the material. Secondly, Thermal Stress Spalling as experienced in ceramics which contain no water but explode at very high heating rates. Thirdly, is Combined Pore Pressure and Thermal Stress Spalling, which is favoured by the author (figure 2).

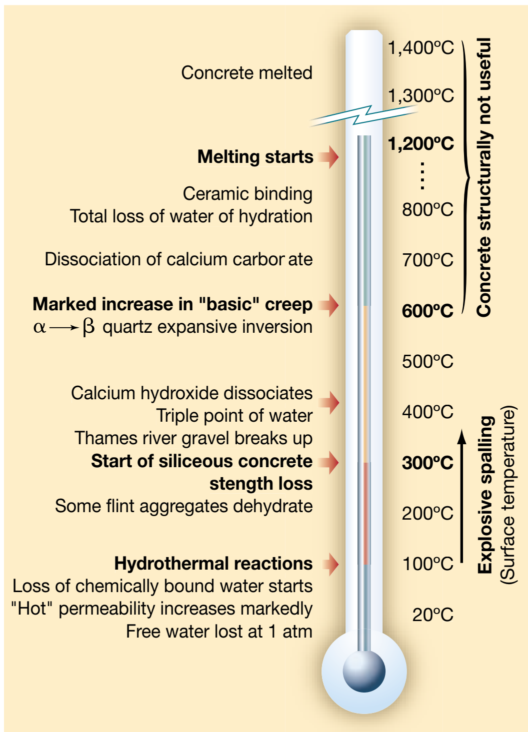
Preventing explosive spalling

While a whole raft of measures have in the past been proposed to combat explosive spalling, the most effective methods are:

- A thermal barrier to protect the surface of the concrete from the fire. These are particularly effective in that they act by substantially reducing the heat flow to the substrate material and thus limiting the rise in temperature. There are several types of thermal barriers ranging from boards, to vermiculite type coatings to recently developed sprayed concrete. The successful use of sprayed concrete shows that properly designed concrete is inherently fire resistant and that, ironically, concrete can be used to protect concrete against fire;
- Polypropylene fibres cast in the concrete mix for the purpose of increasing permeability during heating thus reducing pore pressures and the risk of spalling. PP fibres melt at about 160°C and provide channels in the concrete for moisture to escape. In addition, microscopic analysis has revealed fine cracks around the fibres that also contribute to pressure reduction. Tests to date have shown that the most effective type of fibre is an 18 micron diameter monofilament fibre. A further recent advance has been the development of low melt pp fibres (130°C) which promise to be even more effective. However, the effectiveness of pp fibres is yet to be optimised for high performance and self compacting concretes;

The decision as to which method to use (or both) depends upon a number of factors:

- Existing vs new tunnels: In existing tunnels only a thermal barrier may be used. In new tunnels there is the option of employing either, or both, methods;
- Cost and excessive temperatures: Polypropylene fibres are the cheaper option and can be mixed into the concrete during casting. Polypropylene fibres act to prevent the build-up of excessive pore pressures but do not reduce temperature development within the concrete. Therefore, where excessive temperatures are to be avoided (e.g. crown of the tunnel and/or in the reinforcement) then thermal barriers should be used in new tunnels as well.



Left: Fig 3 - Physico-chemical processes in concrete at high temperature[4-5]

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Table 2: Evaluation of preventative measure for the spalling of concrete

Method	Effectiveness	Comments
Polypropylene fibres	Very effective even in high strength concrete	May not prevent spalling in expansive ultra-high strength concrete. Does not reduce temperatures – only pore pressures
Air-entraining agent	Effective	But can reduce strength
Thermal barrier	Very effective	Also reduces concrete temperatures and increases fire resistance
Choice of aggregate	It is best to use low expansion and small size aggregate	If low moisture lightweight concrete is used, additional fire resistance is possible – but in high moisture conditions violent spalling is promoted

Fire and steel material

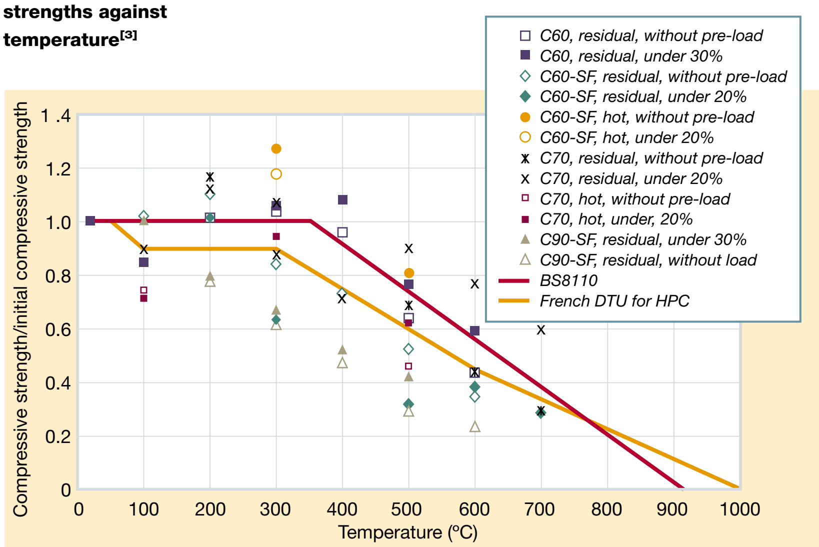
Fire resistance of reinforced concrete[6] is not only dependent upon concrete properties but also very largely upon the properties of the reinforcement at high temperatures, this is the case particularly in structures exposed to tensile loading as in immersed tube and cut and cover tunnels.

A characteristic feature of reinforced concrete structures exposed to fire is that the minimum in the load-bearing capacity occurs not when the surface temperature is at its peak but when the steel temperature reaches its peak value, which could be some time later. Failure occurs when the steel temperature exceeds its critical value. The steel may be protected against excessive temperatures by the concrete cover if this cover is not at risk from spalling (e.g. by the use of polypropylene fibres). In such a case, and for a given fire scenario, minimum reinforcement axis distance tables may be used. However, if the steel does not have sufficient concrete cover and/or it is at risk of spalling, then thermal barriers should be used.

Fire and concrete material

Heating induces a range of physical and chemical processes in the concrete from ambient up to melting at temperatures in excess of 1,000°C (figure 3). The nature of these processes depends upon the mix constituents and proportions used, as well as the moisture and environmental conditions during the fire. Depending upon these factors, the compressive strength of concrete at high temperatures can, for example, vary at 300°C from below 60% to as high 130% of the unheated strength (figure 4).

Below: Fig 4 - Spread of relative HPC compressive strengths against temperature[3]



Given the possible variations in practice of material and environmental factors, it would be erroneous to assume that a single "typical" curve exists for a given property of concrete against temperature. The important roles of loading-heating sequence, load level, and type of aggregate upon the properties of heated concrete are not fully appreciated. Spalling is essentially a structural phenomenon rather than a material one. Even if spalling does not occur, concrete can experience significant strength loss at temperature above about 300°C and is unable to carry sustained load at temperatures in excess of 550-600°C. Fortunately, because of the low thermal diffusivity of concrete, only the surface regions will be exposed to these high temperatures. It is normal practice to remove, after a fire, concrete that has previously been exposed to temperatures in excess of 300°C.

Criteria for thermal barriers

The main function of thermal barriers is to protect directly the substrate material from the fire. So the thermal function is the primary function.

- Critical interface temperature criteria: The practice to date has been to specify critical interface temperatures between the substrate and the thermal barrier. While this is correct in terms of steel substrates (or when only temperature criteria are important in protecting concrete and/or reinforcement), it is not adequate for concrete spalling. The only really effective critical temperature against spalling at the interface is that which is below 100°C - probably too severe a criteria;
- Critical heating rate criteria: In fire, explosive spalling occurs during the first 10-30 minutes when the inner regions of the concrete are only at temperatures of about 100-200°C. Since explosive spalling is a function of the heating rate more than of the maximum temperature it is more appropriate to specify critical heating rates than critical interface temperatures. This should become the approach of the future, but at present no critical heating rate criteria has been proposed except by the author.

It should be strongly emphasised that, in a fire, there is no zero risk of spalling. Essentially spalling is a stochastic phenomenon and the use of thermal barriers and fibres help to reduce the risk of spalling substantially. Nomograms showing spalling and no spalling zones should be used with great caution and only as an indication of trends.

Guidelines in some countries

In Germany, constructional design aims against fire are for temperatures below 300°C at the reinforcement during the fire; no damages threatening the load-bearing capacity of the tunnel structure; and no resting deformations diminishing the usability of the tunnel construction almost retaining the watertightness.

In the Netherlands, because of the many underwater tunnels in this country, fire design according to the RWS-curve is specified. To avoid flooding, the tunnel structure must fulfil the following criteria when a fire load due to the RWS-curve is applied; no loss of water tightness; no collapse of the tunnel. Test specifications for fire protection should meet the following criteria; temperatures below 380°C at the interface on a fire protective insulation to concrete; temperatures below 250°C at the bottom of the reinforcement; temperatures below 60°C at rubber gaskets. In bored tunnels where spalling is the main problem, the Dutch propose critical interface temperatures of 200-250°C[1].