# Spalling Mechanism

## Key for Structural Fire Resistance of Tunnels

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# Spalling Mechanism: Key for Structural Fire Resistance of Tunnels

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## Abstract

The need to consider tunnel safety, especially with respect to fire, has been highlighted in the past by various severe tunnel fires that have occurred throughout Europe. This article provides a general overview of the current rules and regulations governing the fire resistance design of tunnel structures. Subsequently, the engineering perspective is presented, focusing on the assessment of fire severity and the resulting thermal loading on the tunnel structure, which may result in spalling of concrete. Thereafter, a scientific perspective is provided, reflecting recent advances made in numerical calculations with respect to the spalling mechanism. From the numerical results and comparison with observations from full-scale tests, it is concluded that thermal restraint is dominant for spalling. Spalling is triggered by the buckling of concrete layers loaded with strains imposed by temperature, which is a new perspective for future scientific research and innovative engineering solutions.

**Keywords:** tunnels; concrete; fire safety engineering; structural fire resistance; full-scale testing; spalling mechanism; finite element model

## Introduction

The importance of tunnel safety is highlighted by various major tunnel fires that have occurred in Europe in the past few decades (*Fig. 1*). The safety requirements for tunnels in the trans-European road network (TERN) are stated on a legal level in the European Union (EU) directive 2004/54/EC. Also of importance is EU 2008/68/EC, which addresses the inland transport of dangerous goods ("ADR"). These EU directives have formed the basis for specific tunnel rules and regulations in the member states, for example the Dutch tunnel safety law. The common structural fire resistance requirements are stated to ensure that during a predefined time a fire does not cause the collapse of the tunnel structure. This is to make sure that users are able to escape from the tunnel, as well as to allow emergency services to search the tunnel and, if possible, suppress the fire. Often based on the important role of tunnels and their substantial financial investments, more stringent requirements demand that damage to the tunnel during the fire needs to be repairable or to be avoided. The aim is to ensure that through additional financial investments at the design stage, the tunnel can be reopened after repair and retrofitting works. This limits the disruption to traffic as well as economic losses.

Damage to an unprotected tunnel structure caused by a severe fire is largely induced by thermal deformations being restrained and (explosive) spalling may occur. Spalling is a phenomenon that is characterised by the separation of a layer of concrete from the heated surface. As such, spalling can either manifest as sequential individual occurrences of an explosive nature or reflect a more continuous, repetitive process of scaling off. The consequences for the cross-sectional capacity are determined by the possible exposure of the reinforcement bars to the fire, and the damage sustained may even progress deeper into the cross-section. This potentially severe damage mechanism also affects the level at which the structure is heated up by the fire. The resultant thermal stresses develop based on restraint of the heated outer layer of the cross-section. This could have a significant impact on the structural capacity, rigidity and stability, especially in the case of a severe fire and during prolonged exposure.

Based on the possible severity of a tunnel fire and the potential consequences for a tunnel structure, the determination of and possible improvements in structural fire resistance have been of interest both in the field of scientific research[1,2] and for engineering practice. In this article, an overview is provided on the structural fire resistance of tunnels and in particular for spalling of concrete, aiming to join both perspectives on these topics. This includes the current prescriptive


*Fig. 1: (a) Damage to the concrete lining of the Channel Tunnel after the fire on 18 November 1996* (picture by Eurotunnel)*; (b) partial collapse of the ceiling of the Gotthard Tunnel after the fire on 24 October 2001* (picture by Ti Press)

design approaches as well as fire safety engineering assessments currently used in the design of tunnel projects, including various examples of best practice. To enhance the understanding of fire-exposed concrete tunnel structures, the fundamental processes, numerical results and key findings of Dutch scientific research into the spalling mechanism are presented.

## Structural Fire Resistance in Practice

Engineering practice uses specific guidelines that have been established for tunnels in the main infrastructure networks[3] and which complement the generalised European design norms. These guidelines are expected to be a conservative basis for design, considering (a) the development of the fire and (b) the potential impact on the tunnel structure. In the case of specific project conditions (e.g. innovative fire safety solutions or circumstances not covered by the design rules), a fire safety engineering approach could be used. This generally involves a more detailed analysis of both the fire load and the structural resistance.

### *Design Fire Curves*

The legal requirements are implemented on a project level using the governing design regulations for fire as stated in Eurocode 1. The fire curve and duration of exposure are chosen as an assumed worst case fire scenario. Typical worst case scenarios considered are the complete burning off of a cargo or tanker truck or, alternatively, of a railway cart transporting (dangerous) goods. The fire curves are based on various international research programmes such as EUREKA and UPTUN. Fire tests were performed, involving cars, trucks and railway carriages as well as solid and pool fires using wooden pallets or (heptane) fuels respectively. During such fire tests, the development of the ambient air (gas) temperature in close proximity to the fire source was measured. These fire curves typically neglect the fire growth phase and assume a rapidly developing fire, reflected by the rapid development of high temperatures.

Typical fire curves are shown in *Fig. 2* as for example can be found in recommendations by the World Road Association (PIARC).

- Eurocode 1 states the hydrocarbon (HC) fire curve, which was originally designed for use in heavy industrial or offshore fires involving mineral oil-based products. This fire, or an increased version, is stated with a typical duration of 60 or 120 min for road and railway tunnels in, for instance, Norway [Public Roads Administration (Statens Vegvesen)], France [Centre for Tunnel Studies (CETU)], Switzerland [Swiss Society of Engineers and Architects (SIA)], Austria [Austrian Association for Concrete and Construction Technology (ÖVBB)] and the United Kingdom [Standards for Highways, Design Manual for Roads and Bridges (DMRB)].
- In Germany, for road and rail tunnels, the fire curves ZTV-ING [Federal Highway Research Institute (BASt)] and EBA [Federal Railway Authority (EBA)], respectively, are used, also reflecting a cooling-down phase.
- Based on Dutch scaled testing in 1980, the Rijkswaterstaat (RWS) fire curve has been defined, as also implemented by the US National Fire Protection Association (NFPA) as well as being used in other countries (for example Switzerland and the United Kingdom). This fire curve is required [Directorate-General for Public Works and Water Management (RWS)] for a duration of 120 min for Dutch tunnels situated under water or of great economic significance, otherwise 60 min is used.
- The minimal fire curve to be used, as stated by Eurocode 1, is the standard or ISO 834 fire curve [International Organization for Standardization (ISO)]. This fire curve is commonly applied to buildings or light industrial applications and reflects a compartmented fire of cellulose or wood materials. In various guidelines, specific cases are mentioned in which this more moderate standard fire curve may be used in the design of (parts of) a tunnel.

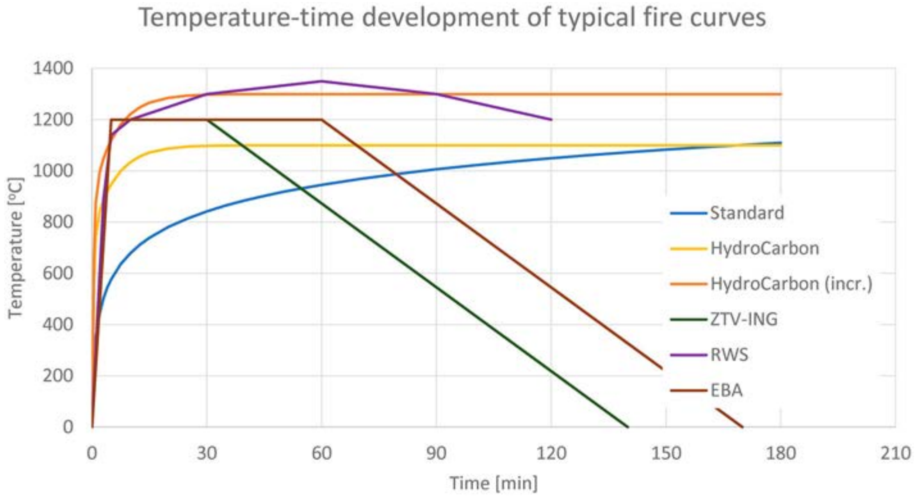

*Fig. 2: Typical fire curves used in structural fire resistance design of tunnel structures (based on respective guidelines)*

### *Fire Load Based on the Project Scenarios*

Alternatively, Eurocode 1 allows the structure to be assessed based on project-specific fire scenarios, reflecting probability and severity. The main reason for fires in road tunnels are accidents, depending on traffic density, composition and velocity, as well as tunnel layout and infrastructural integration. Other possibilities are fires originating from vehicular malfunctions or hidden heat sources in cargo. The fire severity is described by the maximum potential heat release rate (HRR). Fires involving cargo trucks or heavy goods vehicles have an HRR of 30–50 MW or even 100–200 MW (or more).[4] The most severe fire scenarios involve dangerous goods such as fuel. Leakage and formation of a fuel pool can potentially result in a very rapidly developing fire with an HRR of 200 MW or more.[4] Compared to road tunnels, rail tunnels have lower accident rates owing to regulated movement and less human interference. The highest fire loads are caused by cargo and/or fuel transports.

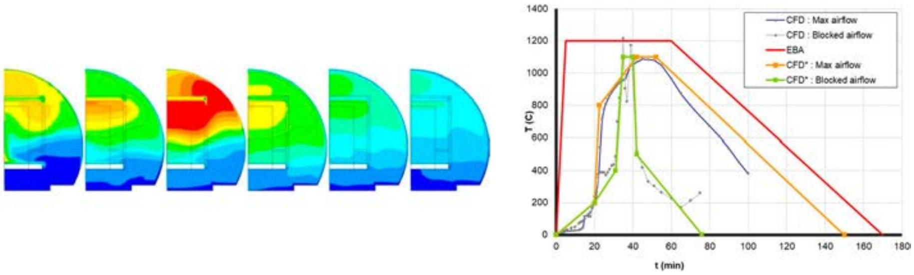

*Fig. 3: Design fire curve for the Amsterdam North/South metro line, established by computational fluid dynamics modelling of a metro fire scenario inside a bored tunnel. This indicated the thermal exposure in both the transverse and longitudinal directions of the tunnel (based on project documents)*

The actual heat loading of the structure by the fire event depends on many factors, which are also related to project specific conditions. Aspects to consider are the confined space and dimensions of the tunnel, as well as the fuel, oxygen and ventilation regime. For instance, in narrow tunnel cross-sections, the fire source tends to cause an almost uniform heating which diminishes in the longitudinal direction. In wide tunnels, the heat distribution is localised to the vicinity surrounding the fire source. Moreover, the HRR strongly depends on the availability of oxygen.[5] Ventilation adds oxygen and increases the HRR, but also extracts the heat. Lack of oxygen reduces the HRR. Smoke and soot reduce the amount of oxygen able to reach the fire location, reducing the HRR. Forced ventilation to remove smoke and soot, which is beneficial in allowing people to escape, increases the HRR.

Scenario-based fire development has been for example successfully incorporated into the design of the bored tunnels for the Amsterdam North/South metro line. Through computational fluid dynamics calculations, a project-specific fire curve has been established. The fire curves obtained are shown in Fig. 3 and reflect the full development of a metro fire inside a bored tunnel based on various predefined circumstances and conditions [the German rail (EBA) fire curve is provided for reference]. This allowed aspects such as the initial onset phase, the confined environment, the availability/lack of oxygen and the actual fire load provided by the railway cart to be taken into account.

Heat from the fire is subsequently transferred to the structure both by convection through the ambient air and by radiation from the flames, combined for modelling in the adiabatic surface temperature,[6] as for instance highlighted by the numerical work of Ref. [7]. The boundary conditions of the structural surface and the use of insulation influence the heat transfer. Heat progresses subsequently within the structure, which may cause structural damage and influences the resistance. As such, heat transfer depends on the material properties, with damage depending on structure and loading.

It is worth noting that for tunnel projects all possible relevant main accident scenarios must be taken into account, based on their probability and severity. This may include the special case in which gas explosions are to be considered, as is for example done in the project Oosterweel Link in Antwerp, Belgium. In this project the aim is to improve mobility in Antwerp by redesigning and extending the ring road surrounding Antwerp. Considered are accidents with pressurised tanker trucks, which could cause gas explosions. To limit the risks involved, the application of a fixed firefighting system (FFFS) and longitudinal ventilation have been studied using a scaled model test tunnel. These experiments enabled the analysis of the dispersion and dilution of propane gas under the combined influence of these measures. Typical experimental results at various longitudinal locations in the test tunnel are illustrated in Fig. 4, representing the gas concentration profiles in reference to the explosive limits, as well as indicating the mixing length and resulting mixed state.

### *Structural Resistance Requirements Related to Fire Loading*

Fire resistance requirements have been established based on the damage caused by actual fires in concrete tunnels. According to basic design principles, a structure must have sufficient load-bearing capacity to resist expected loading. As such, the tunnel structure is able to withstand the thermal load of fire and (partial) collapse of the structure does not occur. In general, thermal insulation is applied in projects to avoid the concrete structure being heated beyond the resistance level, since regular (unprotected) concrete will be unlikely to able to resist the extensive heat. Measures such as heat-resistant boards or sprayed mortar have been developed based on full-scale testing programmes, e.g. of importance for the Netherlands was the Brawat series. Aimed specifically at the spalling process, various research programmes have been conducted into identifying the main parameters.[8] This has resulted in the tendency for spalling being limited by the addition of

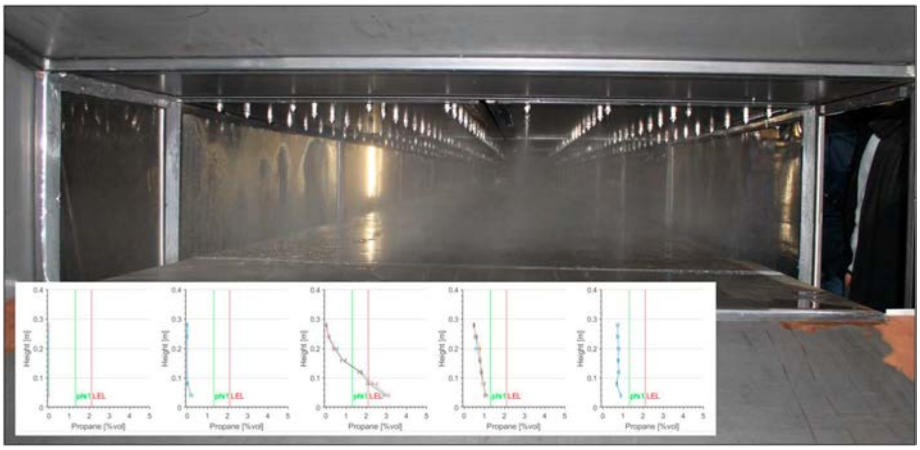

*Fig. 4: For the Oosterweel Link project in Antwerp, a scaled model of a traffic tunnel was developed to measure the joint effect of a fixed firefighting system and longitudinal ventilation on a heavy gas such as propane. This provided valuable insights into gas dispersion in the tunnel in reference to the LEL, lower explosive limit (based on project documents)*

polypropylene (PP) fibres to the concrete mixture. These PP-fibres are often used together with additional concrete cover to protect the main reinforcement from the fire.

Eurocode 2 provides the basis for structural resistance design during fire for all concrete structures. The most straightforward method is to make use of the tabular data. The standard fire-resistant duration classes provide cross-sectional dimensions and reinforcement cover thicknesses. It is stated that under these provisions, no additional checks are required with respect to spalling. Some guidelines use this approach for (parts of) a tunnel which have a more limited potential impact of collapse. Care should, however, be taken in using this approach for tunnel structures since spalling of concrete exposed to the standard fire curve can occur.[9]

The specific tunnel guidelines also provide a simplified method by limiting the thermal loading:

- In the German ZTV-ING (BASt) for road tunnels, it is stated that the temperature of the structural reinforcement may not exceed 300° C. It is added that this can be achieved by using sufficient concrete cover on the reinforcement and addition of PP fibres.
- In the Dutch ROK (RWS), and also in principle implemented by the NFPA, the temperature of the main reinforcement is not allowed to exceed 250°C. The concrete surface temperature at the roof and the upper metre of the walls for immersed tunnels is to be limited to 380°C to avoid cracking and subsequent leakage. For land-based tunnels, this criterion only applies for the concrete surrounding the main reinforcement bars. Load-bearing capacity of the walls is to be based on the cross-sectional thickness, reduced in accordance with a maximum temperature of 380°C. It is also stated that spalling is to be avoided through, for instance, the addition of PP fibres. In the ROK until 2017, limiting the cement content was also given as a spalling-preventing measure, based on a test of the Brawat series. However, more recent fire tests on unprotected concrete slabs exhibited spalling and in the current version of the ROK this measure is therefore no longer given. This has resulted in a reassessment of the fire resistance of various Dutch tunnels, mostly involving in-situ fire testing using a mobile furnace.[32]

The second possibility provided in Eurocode 2 is to calculate the cross-sectional thermal load and the resulting stress state, taking the temperature-dependent material properties of concrete into account. It is worth noting that Eurocode stipulates that spalling has to be avoided or that its influence on the structural capacity has to be taken into account. This requirement allows some level of damage to be included in the structural design of a concrete structure and thereby adheres to the principle that collapse should be avoided.

Various specific guidelines also provide calculation requirements:

- In the French CETU, the potential impact of collapse of an element on the overall stability of the structure forms the basis for both the definition of the fire curve and the fire resistance calculations. As such, the calculations can range from the use of the tabular data provided in Eurocode 2 to calculations of the cross-sectional thermal load and resulting stresses to assess more critical structural elements.
- The Austrian ÖBV provides various calculation methods and also gives the possibility of using a simplification in which, through equivalent temperature increases, the thermal load can be imposed on the tunnel structure.

### *Designing for Structural Fire Resistance*

In today's engineering practice, the heating of the structure can be determined if it is assumed that the concrete is not spalling. This basic assumption enables physical nonlinear analyses with regard to the structural resistance under fire loading. In essence, heating of concrete results in a temperature gradient in the cross-section due to the relatively low thermal conductivity. These enhanced temperatures result in loss of strength and stiffness of the concrete and the reinforcement. Furthermore, thermal stresses arise in the cross-section owing to restrained thermal expansion of the heated surface layer and the forced deformation of the cooler interior. This load case will add to the forces present during service life and cause the possible formation and growth of cracks.

Various passive measures can be taken to ensure that the load-bearing capacity of a structure during a design fire is maintained. Thermal insulation measures, such as heat-resistant boards or sprayed mortar, could be applied to avoid heating of the tunnel structure. In case damage due to the thermal loading is allowed for, PP-fibres can be added to limit the spalling sensitivity. Besides these passive measures, an active measure such as an FFFS could be considered. The choice of fire resistance measures should preferably be based on adopting the ALARA (As Low As Reasonably Achievable) risk approach.

Tunnels under service life conditions are always loaded, depending mainly on the geometric shape, the depth and other surface-based loads. In an immersed tunnel, the rectangular shape combined with high water pressures at depth causes large bending moments to be present in the roof. The main reinforcement positioned at the fire-exposed side therefore needs to be protected, typically in the form of heat-resistant boards. This also applies to the connection of the roof to the walls due to the transfer of (shear) forces. Some form of damage could be allowed for in the walls in the case of loading in compression, assuming that sufficient cross-sectional thickness is present. This is, however, generally not the case for narrow tunnels, in which bending moments tend to be present in the walls and the reinforcement needs to be protected.

For bored tunnels, the surrounding soil conditions govern the structural load-bearing system. The lining constructed for tunnels in rock generally has a limited structural function and damage could, to some extent, be allowed. In soft soil conditions, a segmental lining is used, with the integrity and stability of the ring relying on force transfer between the individual lining segments. Spalling damage is therefore to be avoided, with typical measures being adopted such as adding PP fibres to the concrete mixture.

However, there are no or limited possibilities to determine beforehand the spalling sensitivity of a concrete mixture. As a result, full-scale testing

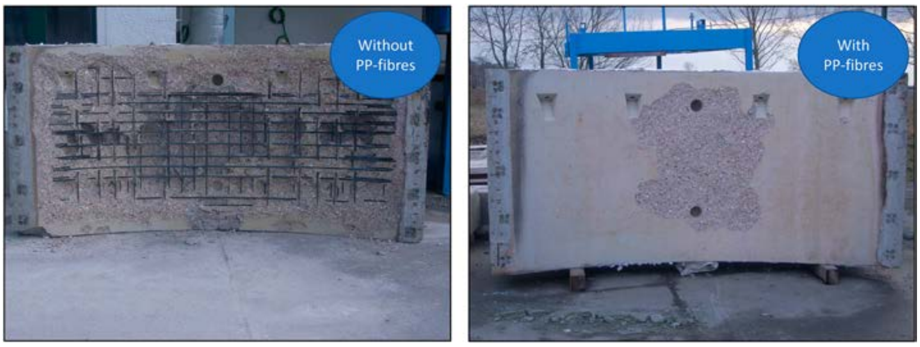

*Fig. 5: Fire resistance design for the Amsterdam North/South metro line involved full-scale fire testing of tunnel lining segments, showing the effectiveness of adding polypropylene (PP) fibres to the concrete mixture in largely mitigating the spalling sensitivity (based on project documents)*

has become part of large-scale tunnel projects. For example, the bored tunnels for the Amsterdam North/South metro line represented the first use of PP fibres in concrete tunnel lining segments in the Netherlands. To assess and prove the effectiveness of these PP fibres in preventing spalling, project-specific structural loading and the fire curve were used in the full-scale fire testing of lining segments (*Fig. 5*). In addition, the structural resistance of the tunnel structure during and after fire exposure was numerically proven using finite element method (FEM) calculations.

## Scientific Research Into the Spalling Mechanism

It has been shown that engineers lack the scientific possibilities to analyse spalling of concrete. This led to the initiation of a Dutch research programme, which was concluded in 2017. The main aim was to investigate both the development of pore pressures and of thermal stresses to assess the dominance of each in the spalling mechanism. The programme involved (a) experimental research into the dehydration processes in heated concrete,[11] (b) research on the movement of moisture in heated concrete,[12] and (c) derivation of an FEM-based model to investigate the formation of the mechanisms causing spalling.[13]

### *Temperature and Pore Pressure Development*

Two main theories are considered to explain the spalling of concrete:

- The first theory[14] is based on the concept that evaporation of water at increasing temperatures causes pore pressures to develop. Pressure could rise as a result of the limited flow of steam and moisture, causing a layer almost saturated with water to be formed, referred to as moisture clog. In this respect, the distinction is often made between normal-strength concrete (NSC) and high-strength concrete (HSC). This is mainly based on the observed increased spalling tendency of HSC, attributed to the higher density of the microstructure promoting the formation of pore pressures.
- The second theory[15] is based on the premise of restrained thermal deformation. This would lead to a continued build-up of the resultant compression force governing the stability of the heated surface layer. In this respect, the distinction is often made between siliceous aggregates such as river gravel and calcareous aggregates such as limestone. The higher thermal expansion with temperature of a siliceous based aggregate would give rise to higher thermal stresses and therefore could contribute to the spalling sensitivity.

Both theories are considered and used as a basis to derive and develop separate FEM-based models. These models are coupled and implemented for part of a structural element, using a multi-scale heterogeneous approach to characterise concrete. This element is exposed to a fire at the left edge, which is assumed constant across the height. Structural behaviour is reflected by loading and partial restraint at the top and bottom edges, assuming the in-depth direction to be infinitely long.

### *Numerical Modelling of Transport Processes in Heated Concrete*

Temperature and pore pressure development reflect the progress of heat and the drying processes, or desorption, in the concrete. For the purpose of the concrete schematisation used in the FEM model,[10] the mortar and the interfacial transition zones are assumed to be a porous material, partially saturated with liquid water and water vapour.[16,17] The transport processes are reflected by Fourier's law of thermal conductivity and Darcy's law of permeability.[18] The aggregate particles are assumed to be impermeable, forming obstacles to the flow of both water phases while only conducting thermal energy.

The above-described material is characterised by assuming thermodynamic equilibrium in conservation of thermal energy and mass of the water phases.[19,20] This is governed by a system of partial differential equations, consisting of the time-dependent development and the transport processes. The temperature and capillary pressure (pressure difference between both water phases) are chosen as the unknown variables.[13] This system is numerically solved using an FEM discretisation by linear triangular plate elements with an Euler backward integration scheme. Boundary conditions are implemented to reflect the imposed thermal energy and the drainage of the water phases across the outer model edges.

The characterisation of the thermal conductivity, and especially the permeability, reflects a directional dependence or anisotropy. The latter is used for coupling with the fracture mechanics model to characterise the permeability increase caused by flow along a crack. Gradual and limited implementation of the crack pattern is used to enhance numerical stability.

### *Numerical Modelling of Fracture Processes in Heated Concrete*

In a concrete cross-section, the thermal stresses may cause cracks, which tend to relieve tensile stresses. This local weakening of the concrete will allow for deformations, coinciding with a redistribution of forces. The internal loading by the pore pressure should also be considered, which is commonly not done in thermomechanical analysis. Furthermore, FEM models tend to base the thermal stress analyses on the partial differential equation describing the variation of stresses across a continuum.[21] The fracture mechanics FEM model adopted, however, uses a different approach in which, through strain transformation, each triangular space is schematised by (a truss with) three extensional bars.[13]

Numerical approximation of the system is subsequently obtained by stating the linear axial displacement along each bar. The statement of boundary conditions takes the form of rigid bodies, allowing structural conditions to be imposed while assuming plane strain. Time dependence is implemented by assuming separate steps based on the static equilibrium of forces. The resultant axial stresses are used to determine the brittle fracture of the individual bars under tension while using a stepwise simulation of the crack development.

From the definition of extensional stiffness, and especially the fracture of bars, a direction-dependent or anisotropic material schematisation is obtained. The removal of bars could, however, lead to localised deformations, which are numerically stabilised by the introduction of additional sets of triangular orientated Bernoulli–Euler beams, obtaining a traditional lattice model.[22,23]

## Numerical Analyses

### *Influence of Temperature*

To analyse the influence of both main processes, it is decided first to focus on the temperature gradient based only on Fourier's law. The numerical results of a one-sided heated vertical concrete element indicate that the imposed temperature (thermal) strain will almost immediately lead to crack development, especially in the case of heating according to the HC fire curve. This process starts in the interfacial transition zones surrounding the aggregates, which, especially in NSC, tend to be less well developed and consequently are modelled to be weaker.

The continued development of the crack pattern is furthermore largely affected by the presence of structural restraint:

- In case the cross-section is allowed to expand, most of the thermal stresses are relaxed owing to the formation of cracks. Under these circumstances, the faster onset of the temperature development for the HC fire scenario causes the development of various large horizontal cracks, indicating that failure or collapse due to the thermal impact sustained would be possible. This behaviour has also been observed during full-scale fire testing of relatively thin concrete slabs,[24] but cannot be seen as spalling.
- In case partial restraint is added, the horizontal cracks no longer reach to the surface of the cross-section. In the heated surface layer, compressive stresses remain present, which cause a relatively dense pattern of small vertical cracks to develop. In *Fig. 6b*, it can be seen that various inclined cracks are formed, allowing part of the heated surface layer to be forced off the cross-section. The fact that the integrity of these layers is largely preserved and deformation is caused by restrained compression could point towards the instability of these thin surface layers by a thermal buckling mechanism.[13]

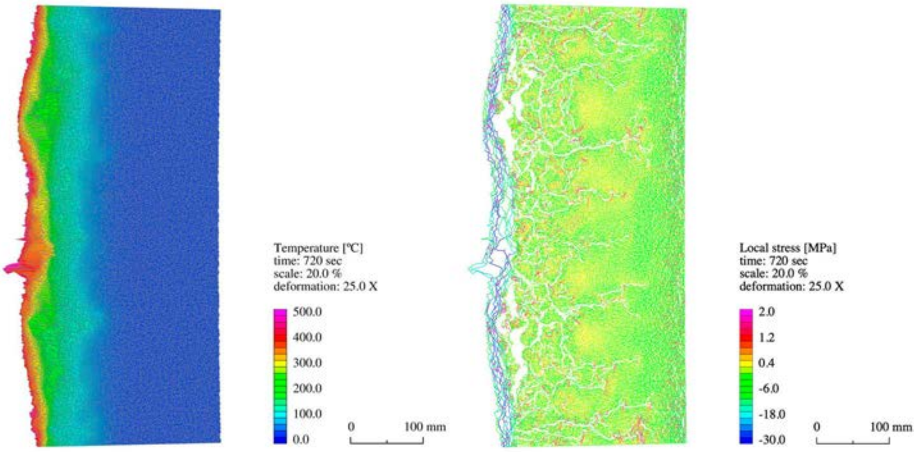

*Fig. 6: (a) Resulting development of the temperature gradient; (b) local stress-based crack pattern, after 720 s of fire exposure according to the hydrocarbon fire curve of a normal-strength concrete cross-section, reflecting instabilities at the heated surface*[13]

Finding evidence of this fracture mechanism causing spalling is challenging, but could perhaps be found in the distinctive pocket-shaped fracture surface[10] as, for instance, observed after fire exposure of lining segments.[25] The sudden nature of the spalling events, as commonly observed, could also indicate that a form of energy release is taking place,[26] as would be the case with stored elastic energy. It is worth mentioning that the reported negative influence of compression loading[8] could indicate that the cross-section is already cracked and therefore has become more susceptible to the spalling mechanism. In this respect, unfavourable test results of relatively thick concrete slabs[9] could reflect the increased restraint by the unheated parts of the cross-section. The fact that initial drying of slabs was found not always to be sufficient to avoid spalling[9] is more difficult to extrapolate, but could point towards microcracks acting as potential initial flaws. Promising results have been achieved by assuming spalling as a form of thermal buckling[27] and could form a starting point for future scientific research.

### *Influence of Pore Pressure*

The numerical results presented prompt the question as to the influence of pore pressure development in the formation of the spalling mechanism. To investigate this, the process of forced drying was included and various numerical simulations were repeated. From these calculations, various observations were made:

- The relatively dense crack pattern in the heated surface layer is sufficient to level off most of the formed water vapour. Only a small increase in pore pressure is present, which reflects a minor contribution to the stress state, especially considering the large impact of the temperature gradient. Only near aggregate particles, as well as between horizontal cracks, do some pockets of pore pressure development remain (*Fig. 7a*).
- The continued evaporation causes energy consumption, which is reflected by the development of a temperature plateau (*Fig. 6a*).[28] In *Fig. 7b*, the drying front is also observed to

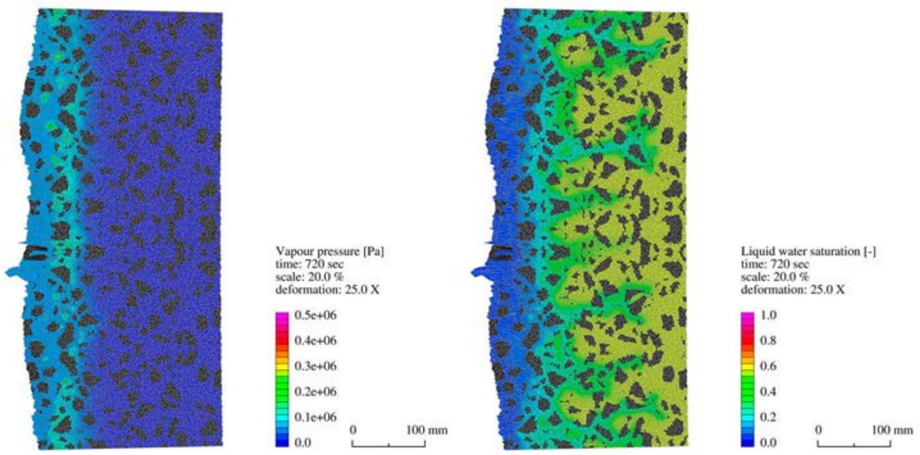

*Fig. 7: During hydrocarbon-based fire exposure of the normal-strength concrete cross-section, pore pressures are levelled off by the cracks in the heated surface layer (a), with the drying front extending further into the cross-section along horizontal cracks (b)*[13]

surpass the heated surface layer and progress deeper into the cross-section, with water being expelled along the horizontal cracks.[28]

Next, the possibility is investigated of whether, under specific circumstances, pore pressures could still develop and contribute to the spalling mechanism. For this purpose, the cross-section is modelled using a characterisation as an HSC which, owing to its dense microstructure, could promote the formation of pore pressures. Limestone is chosen as the aggregate type, aiming to reduce the development of thermal stresses and therefore the level of cracking. The numerical simulations involving restraint, however, indicate that although the development of the crack pattern is more moderate than for NSC, pore pressures have largely levelled off. Only through exposure to the standard fire curve could the level of cracking be considerably reduced and therefore pore pressures could still develop, to some extent. Consequently, the reduced thermal exposure limited the surface-based damage mechanism.

Based on these numerical results, pore pressures are indicated to be of less importance in the formation of the spalling mechanism than commonly perceived. Providing proof for this premise is difficult since temperature measurements are mainly taken during fire exposure of concrete elements. Thus, evidence can be found that the formation of a temperature plateau can indeed take place.[25] Measurements of gas pressures inside a concrete element at low heating rates,[29] with no spalling occurring, could perhaps serve as an indication for the more limited influence of pressures. Some gas pressure measurements of concrete slabs heated to a standard fire curve can be found in the literature, and these seem to suggest that substantial mitigation of pressure development could occur.[30] Proving the experimentally demonstrated effectiveness of PP fibres[24,31] in mitigating spalling could be key in providing a link between the calculated fracture mechanism and the drying processes. This, however, requires more scientific research, covering key areas such as the energy consumption causing the formation of a temperature plateau and possibly affecting the steep thermal stress gradient driving the fracture process.

## Conclusions

The fire resistance of tunnel structures, and the spalling sensitivity of concrete in particular, are of key importance for the safety levels in today's road and railway tunnels. The current practice in fire safety design is based on prescriptive rules and regulations defining the design fire curves and fire resistance requirements.

Optimisation can be achieved through a fire safety engineering approach in which both the probability of fire scenarios and fire loading, as well as the structural load transfer and the behaviour of concrete at high temperature, are assessed. In this context, spalling of concrete has to be considered. The economic costs of fire protection measures are substantial and the choices made should be based on a balance between economic investment and structural necessity.

Full-scale testing is today's preferred method to assess the effectiveness of fire protection measures. Choices made in the test set-up thereby require an understanding of the fire load and the structural impact, as well as the damage mechanisms, to both concrete and fire protection systems.

Scientific advances in numerical calculation methods regarding the spalling mechanism indicate that thermal restraint triggers the buckling (i.e. the spalling) of slender, heated surface layers. Pore pressures have a more limited influence, contrary to common perceptions. These findings provide new research opportunities and directions, as well as innovative engineering solutions for use in fire safety design of tunnel structures.

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