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Review article

Progress over the last decade on how fire affects the structural behavior of tunnel linings

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A B S T R A C T

Tunnel fires are relatively rare, but the consequences of damage can be large. This paper addresses the influence of tunnel fires on the ensuing damage to the concrete lining. To address this question, the existing literature is reviewed. This review focuses on different methodologies to get a well-rounded insight into the problem: relevant aspects of tunnel fire dynamics, theoretical considerations on the relation between the fire source and the resulting damage to the concrete, experimental evidences from testing concrete elements subjected to fire as well as data from tunnel fires that have taken place in the past, and insights from numerical analysis. The result is a comprehensive overview of what is currently known about the relation between a tunnel fire and the ensuing damage in the concrete, as well as guidance for the assessment of concrete tunnel linings under fire hazard and recommendations for future research to address the remaining open questions on this topic. To conclude, this paper gives a valuable overview based on different methodologies from the literature to give researchers, engineers, and asset owners a better insight in how fires can affect the concrete tunnel structure.

1. Introduction

Tunnel fires are relatively rare events [1], but such fires can be devastating. Most research in the past has focused on preventing the loss of human lives during the event of a tunnel fire through adequate ventilation and escape routes [2,3], and by developing strategies for fire fighters when a fire occurs [4]. Less attention has been paid to the structural aspects of the problem in the light of assessment of the existing infrastructure: what is the relation between a tunnel fire and the ensuing damage in the concrete tunnel lining, and under which conditions can the collapse of a tunnel segment or even the entire tunnel structure occur? The structural modelling aspect is important, as damage as a result of a tunnel fire will require repair activities. Such repairs can be costly and time-consuming [5], and may require the closure of the tunnel for the duration of the activities. The result of such closure is major driver delays resulting in economic losses and the environmental burden of additional fossil fuel usage. Therefore, understanding how fires in tunnels result in damage to the concrete lining is a first step in being able to make better decisions regarding the management and maintenance of existing tunnels.

The structural requirements for fires are usually considered in the design stage by linking a certain performance requirement to limiting the temperature in the concrete (below 380 °C in the Netherlands, defined in the design guideline ROK [6]) and the steel reinforcement (below 250 °C in the ROK). For buildings, there are hand calculation methods to find the required concrete cover. Similar methods to directly assess the effect of a fire on concrete structural elements do not exist for tunnels. As such, for the case of assessment of concrete infrastructure, numerical models are typically necessary.

Past research, and in particular the UPTUN project, focused on cost-effective, sustainable and innovative upgrading methods for fire safety in existing tunnels [7]. In this work, technologies in the areas of detection and monitoring, mitigating measures, influencing human response, and protection against structural damage were developed and evaluated, and the main output of the project was a risk based evaluating and upgrading model.

When it comes to the risk of collapse of a tunnel segment or the entire tunnel structure, two aspects play an important role. The first aspect is

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the type of surrounding soil. For tunnels in bedrock, the surrounding bedrock will most likely remain in place so collapse is less likely than for the case of tunnels in soft soils. Similarly, for tunnels with a large overburden, the surrounding soil can be activated, and collapse can be prevented [8]. Secondly, the consequence of a tunnel collapse depends on the obstacle that is being crossed: a collapse of a tunnel under water will have more devastating effects than the collapse of a land tunnel. Moreover, when a tunnel segment loses its capacity as a result of a fire, load redistribution may occur, which prevents progressive collapse.

To answer the question on the relation between tunnel fires and the ensuing damage in the lining, this paper reviews the existing literature [9]. This review focuses on different methodologies to get a well-rounded insight into the problem: general information on fires in tunnels to highlight the aspects relevant to the current research question, theoretical considerations on the relation between the fire source and the resulting damage to the concrete, experimental evidence from testing concrete elements subjected to fire as well as data from tunnel fires that have taken place in the past, and insights from numerical analysis. Ultimately, the insights from this review are combined into an assessment strategy for the structural capacity of concrete tunnel linings subjected to fire loading, indicating which areas need further research to optimally leverage numerical tools. The review focuses on concrete tunnel linings consisting of concrete, concrete with polypropylene fibers, and concrete covered with fire protection plates. The novel contribution of this work is the identification of an assessment strategy using flowcharts for determining the fire safety of existing concrete tunnel linings, combined with research needs, sketching the path forward for this subfield and serving as a useful tool for asset owners looking for guidance regarding the assessment of the existing tunnel structures.

2. Evidence from tunnel fire cases

Internationally, a number of major tunnel fires have occurred. To answer the question on how these fires affect the concrete tunnel lining, an overview of the tunnel fire properties and the reported damage is compiled in Table 1 for some of the largest and most famous cases reported in the literature. Table 1 contains the name of the tunnel, country where the tunnel is located, the year of the tunnel fire, the HRR and T_{max} of the fire as reported in the literature. Moreover, since we are interested

Table 1
Overview of cases of tunnel fires and resulting damage.

Name of tunnel	Country	Year	HRR (MW)	T_{max} (°C)	Longitudinal distance of damage (m)
Velser Tunnel [14]	Netherlands	1978	40–50	800	-
Nihonzaka tunnel [15]	Japan	1979	-	-	1100
Caldecott tunnel [16]	USA	1982	-	1050	580
Chunnel [11]	France-UK	1996	370	1300	50
Mont Blanc tunnel [17, 18]	France-Italy	1999	190–300	300	900
Tauern tunnel [19]	Austria	1999	300–400	-	350
Daegu Municipal Subway [20]	South Korea	2003	200	800	172
Chunnel [21]	France-UK	2008	-	1000	650
Königshainer Berge tunnel [12]	Germany	2013	30–70, expected 45	800	50
Heinenoord tunnel [22]	Netherlands	2014	58	-	-
Rannersdorf tunnel [23]	Austria	2019	-	-	600

in the extent of the damage, we have included the longitudinal distance (i.e. driving direction distance) over which the fire resulted in damage to the concrete lining. For few of these cases, information about the spalling depth and rate is available. Other overviews of tunnel fires, focusing on aspects of evacuation and human safety, are reported elsewhere [3, 10].

The Nihonzaka tunnel fire involved 173 vehicles, and the sprinkler system allowed for safe evacuation. The fire lasted for several days. The 1982 Caldecott tunnel fire involved a tanker vehicle, several cars, and a bus, and had a duration of 165 min. The Tauern tunnel fire involved 16 heavy goods vehicles and 24 cars and lasted for 17 h. Two major fires have occurred in the Chunnel. The 1996 fire resulted in an average spalling depth of 230 mm and a maximum spalling dept of 380 mm, and spalling occurred over a length of 50 m [11], whereas in the 2008 fire, 650 m of damage was reported.

The Mont Blanc tunnel fire is the most catastrophic tunnel fire to date, involving 23 heavy goods vehicles and 10 smaller vehicles, lasting for 53 h. The Heat Release Rate (HRR) of the first heavy goods vehicle was about 75–110 MW and the maximum HRR has been estimated as somewhere between 190 MW and 300 MW. Of the Daegu Municipal Subway tunnel fire, a full damage profile with spalling locations is available in [5], showing spalling depths between 10 mm and 99 mm. Similarly, photographic evidence of the damaged zones of the Königshainer Berge tunnel is available [12]. This fire, involving a heavy goods vehicle, lasted 52 min and resulted in spalling up to 50 mm. Finally, the Rannersdorf tunnel fire was caused by a truck (tractor unit including trailer) that burnt out completely due to a technical defect. The tunnel had to be closed for a month for the most urgent repairs, and the complete renovation was finished 5 months after the fire, with a total cost of 3 million euro [13].

In the Netherlands, two major fires have occurred in tunnels since the Second World War: the fire in the Velser Tunnel in 1978 and the fire in the Heinenoord tunnel in 2014. In the Velser Tunnel, one heavy goods vehicle and four cars caused the fire, which lasted for 30 min, and reached a maximum temperature of 800 °C, with an HRR estimated to have been 40 – 50 MW. The concrete cover was 70 – 80 mm, of which 15 mm had spalled. Assuming 5 min to the onset of spalling, the spalling rate was 0.6 mm/min. The Heinenoord tunnel fire was caused by a heavy goods vehicle and a car, and lasted for 31 min with 18 min of peak HRR estimated as 58 MW, giving a total heat release of 85.4 GJ. This tunnel was protected with fire protection panels and the walls were covered with tiles, which locally fell off during the fire. The spalling depth was 25 mm, and, assuming 5 min to the onset of spalling, the spalling rate was 0.96 mm/min.

Tunnel fire experiments on real tunnels are available [24,25]. These experiments were carried out to study temperature development and ventilation aspects. It is important to carry out tunnel fire tests at full scale, as the fire dynamics cannot be scaled. At the same time, full-scale tunnel fire experiments are not very common, as the cost for carrying out these experiments has been reported to be very high (10 million USD for the Firetun test series and over 40 million USD for the Memorial tunnel tests [10]).

Experimentally, the development of fires in tunnels has been tested by carrying out car fire tests as well as crib fire tests [10], where the heat release rate development and airflow speed, as well as the temperature development were studied. To measure the temperature evolution in new tunnels, [26] suggested providing new tunnels with sensors for monitoring.

Two scaled experiments can be mentioned: experiments [27] to develop the flame shape and tunnel ceiling temperature distribution for arched and straight scaled tunnel fires, and targeted tests [28] to validate fire dynamics numerical models. A database of the fire dynamics is compiled in [29]. The Zwenberg tunnel fire experiments in Austria gave insight into the fire dynamics of pool fires, and the Runehamar experiments explored both pool fires and heavy goods vehicle mock-ups [30]. The Runehamer test gas temperature approximated the Rijkwaterstaat temperature curve. For these two iconic tests, no information about structural damage to the lining was monitored.

The Sydney Harbor tunnel tests involved the burning of two cars. The heat release rate peaked at 3 MW in the first test and 5 MW in the second test, giving a gas temperature of 900 ºC in the vehicle and on the tunnel lining of 800 ºC after 1.5 min in the first test and between 800 ºC and 1000 ºC in the second test. No spalling occurred [2,31].

In the Piaoli tunnel in China [32], the effect of passive fire protection was studied. A 30 MW fire for 2 h was designed by burning 270 liters of petrol and 20 liters of diesel, resulting in a smoke temperature of 675 ºC and a temperature on the lining of 600 ºC. The part without fire protection had spalling over an area of 0.8 m^2 and a spalling depth of up to 10 mm, whereas the part with fire protection resulted in complete failure of the fire-resistant coating but no damage to the underling concrete. A cut-and-cover tunnel in Greece was tested using a mobile furnace to apply the RWS temperature curve [33]. The spalling depth was 75 mm after 20 min, resulting in a spalling rate of 3.75 mm/min.

There are no standardized post-fire tunnel inspection and assessment strategies [34], but non-destructive evaluation methodologies can be recommended [18,35–37]. Based on the fire during construction of the St. Elijah tunnel, a methodology was developed by linking area of damage, visual appearance of the concrete to an assigned damage category and required actions [38]. Other authors focused more on the overall structural damage as a result of the fire [39,40]. An additional point to consider is that existing tunnels can have damage to the lining as a result of various types of degradation [41], and these should be considered together with the fire hazard [42].

3. Modelling of fire in tunnels

3.1. From fire source to structural response

Fig. 1 shows the relation between a fire source and, ultimately, the assessment of a concrete tunnel lining. When a tunnel fire occurs, convection and radiation result in a temperature loading on the tunnel lining. These topics are addressed in §3.2–3.5. Once a temperature load is applied to the tunnel lining, an internal temperature load results, as explained in §4.1. The result between this internal temperature distribution in the concrete and the structural response is affected by concrete spalling (§4.2), the reduction of material properties under elevated temperatures (§4.3), and the effect of thermal-induced deformations of the structure (§4.4), all of which are influenced by the tunnel fire protection system in place (§4.5). To come to an assessment strategy, evidence from experiments (§45, real tunnel fires (§2), and numerical studies (§6) are analysed. The literature emphasizes the importance of analysing the cooling phase as well, and the need for further development of numerical tools, which are discussed in §7 together with the proposed assessment strategy.

3.2. Introduction to fire dynamics

Fires require oxygen, a source of fuel, and a source of ignition. The temperature development of the fire over time is a function of parameters such as the combustible material and the boundary conditions of the fire [43–45]. In tunnels in particular, fires result from collisions or vehicle defects [3]. For that reason, in the past, several countries did not allow trucks with flammable and dangerous goods to use tunnels [3]. The tunnel geometry traps the heat generated by the fire, resulting in the most intense types of fires. The longitudinal ventilation in a tunnel can both result in providing oxygen which increases the fire as well as cold air that lowers the temperature, and the effect is a function of the fire source [10], and the tunnel geometry and fire source [46]. These aspects also directly influence the fire intensity, expressed as heat release rate (HRR) of the fire [1]. Most research has focused on roadway tunnels, but some information about railway tunnels is also available [47].

3.3. Modelling the relation between fire and temperature

For practical purposes (and to avoid complete fire dynamics calculations on a regular basis), fire curves that give a relation between temperature and time are used, such as the ISO 834 curve [48] based on burning of cellulosic material in buildings, the hydrocarbon curve and modified hydrocarbon curve (as used in France) which are based on burning of fuel, petrol, or oil [49], or the Rijkswaterstaat (RWS) curve, which is based on the worst case scenario (tanker fire with a fire load of 300 MW, duration of 120 min and maximum excess gas temperature of 1350 ºC [25]). In addition, the RABT fire curve includes an explicit cooling phase. This temperature-time curve is different for a car and a train in duration of the fire, and is characterized by a rapid increase in temperature (to 1200 °C in 5 min). Fig. 2 shows a comparison of different temperature-time curves that are used. The reader should note that these fire curves are deterministic and conservative in nature. They do not necessarily represent the thermal demands in time and space on the tunnel lining in the case of a large vehicle fire [50]. From Fig. 2, it

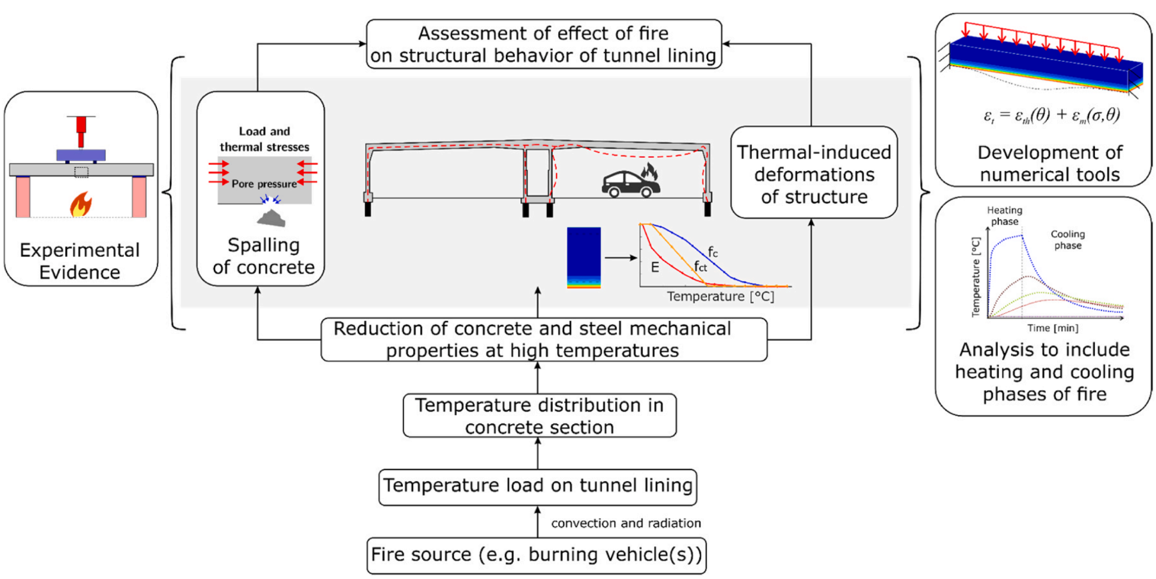

Fig. 1. Relation between fire source and structural behaviour, as required for assessment.

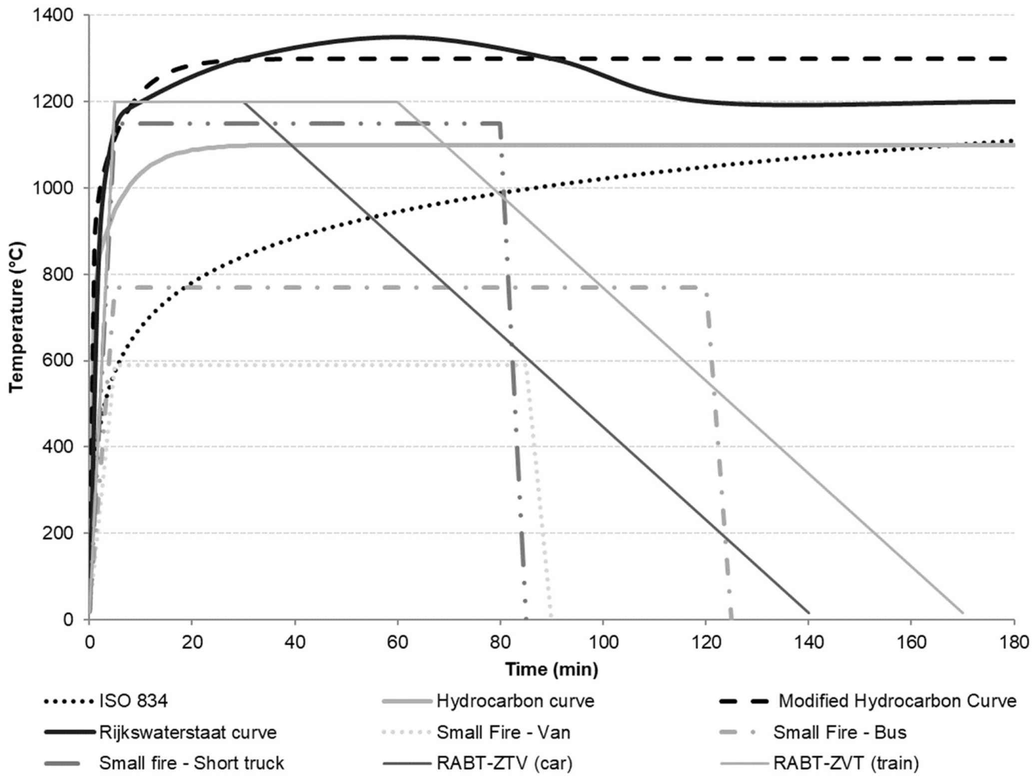

Fig. 2. Comparison of Temperature-Time curves.

can be seen that of the code-prescribed temperature-time curves, only the RABT curves take into account the cooling phase of the fire.

Computationally, the link between fire source and temperature on the lining can be determined with computational fluid dynamics analyses (CFD). Studies considering various scenarios of traffic composition and flow show that for tunnels with a through-shaped profile, a leaking tanker leads to only part of the liquid being consumed in the fire. The result is a lower demand than prescribed by the RWS curve [51,52]. For example, for the Brenner Base tunnel, CFD analyses studied the time history of a train coach fire as part of the design process [53]. A main unknown in CFD models is the selection of the turbulent model, for which no measurements are available [1]. The German National Annex to Eurocode 1 [54] prescribes case studies that can be used for validation, as well as recommendations for the input parameters and acceptable tolerances between the model and the reported case studies. Past work connected fire dynamics to estimates of damage in the concrete tunnel lining [55]. In addition, for the Netherlands, a few smaller fire scenarios have been defined in [56], based on CFD calculations. To compare these more realistic or more common fire scenarios to the worst-case scenarios, the situation of a van fire, bus fire, and short truck fire are added to Fig. 2. In addition, [57] studied the uncertainties in the parameters for railway tunnel fires, based on 540 fire scenarios modelled using CFD, and high-intensity fires (HRR $>$ 40 MW, mean maximum temperature of 1007 °C) were separate from low-intensity fires (HRR $<$ 30 MW, mean maximum temperature of 245 °C), and the T_{max} quantiles for these low and high intensity fires were also provided. These better-quantified temperature-time curves could be used in the future to make design recommendations within risk-based frameworks to achieve the performance levels that are desirable in terms of downtime and asset damage after an adverse event.

A more extensive approach includes looking at the probabilities of fires with different intensities, for which authors have made various suggestions [39,58–62]. In addition, national values of the probabilities of fires in tunnels are collected. The frequencies of fires per million motor vehicle km in France are higher due to burning of brakes on steep descents: in cars, the frequency is 0.01 – 0.02 for cars, 0.08 for heavy goods vehicles 0.01 for heavy goods vehicles leading to tunnel damage, and 0.001 – 0.003 for heavy goods vehicles leading to tunnel damage. On the other hand, in the Netherlands the frequence of fires per million motor vehicle km is only 1.5 – 2 $\times$ 10^{-4}. Recent data for Italy [59] and Austria [63] are available, as well as an international overview [3].

Finally, a novel approach includes the using artificial intelligence to achieve a realistic time prediction of the temperature distribution in space and time inside a tunnel, with an accuracy of around 97 %. As such, this work identified the potential for AI to develop real-time fire forecasts to inform firefighting decisions [64].

3.4. *Factors influencing resulting temperature*

To find the temperature on the surface of the tunnel lining for a given source of fire, fire dynamics considers the heat transfer from the fire to the tunnel lining via convection (movement of thermal energy through the material via motion of the material) and radiation (transfer of heat via electromagnetic waves) (see Fig. 1). In tunnel fires, radiation becomes important as the fire plume is trapped by the tunnel ceiling. The result is an agglomeration of hot gases above the fire source, causing radiation towards the fire.

The heat flux from radiation and convection can be written using analytical expressions. But, when these equations are applied to vehicle fires in tunnels, simplifications and assumptions are used. In reality, fire dynamics are influenced by various factors, relating to the origin of the fire, the tunnel properties (dimensions, slope, cross-sectional shape, materials), and the ventilation properties (e.g. ventilation speed). For truck fires, the flames and hot air move over the vehicles, which brings them closer to the lining than when no trucks are involved in the fire.

4. Relation between temperature and effect on concrete lining

4.1. Overall effect and temperature profile

When a tunnel is subjected to a fire, the damage on the concrete lining results from the combination of three mechanisms as a result of the temperature increase in the lining: 1) spalling of the concrete, 2) reduction of concrete and steel mechanical properties at high temperatures, and 3) thermal-induced deformations of the structure (see Fig. 1).

When the surface temperature is known, the effect of the temperature on the concrete tunnel lining needs to be estimated via the temperature profile within the material. This profile is related to the heat transfer within the lining. In Austria, empirical curves for the temperature distribution in the material are used, but these are only valid for concrete with polypropylene fibres, and with a dry density between 2000 and 2600 kg/m^3 [65]. As an alternative, transient thermal analyses are also used.

4.2. Concrete spalling

Concrete spalling is a type of thermal instability that can happen when concrete is subjected to fire, resulting in loss of material and ultimately reducing the cross-sectional dimensions. It was first observed in 1854 [66]. When the concrete cover has spalled, reinforcement is exposed to an elevated temperature, which further leads to a loss of strength and stiffness of the reinforcing steel. The combination of these factors can result in a loss of strength of the element and risk of failure of the section, which, in turn, may lead to a progressive failure of the structure. After a fire, spalling will result in a reduced durability of the remaining concrete and reduced post-fire mechanical properties [67]. As a function of temperature, concrete undergoes various chemical and physical changes:

- Free water in the mix starts to evaporate at 100 °C,
- Water bound in cement gel starts to dehydrate at 180 °C,
- $Ca(OH)_2$ breaks down at about 500 °C,
- In quartzite and basalt aggregates, α-quartz transforms to β-quartz at about 580 °C,
- CSH breaks down at about 700 °C,
- In limestone aggregates calcium carbonate decarbonates at about 800 °C,
- The cement paste and aggregates start to melt at about 1200 °C,

These changes are linked to the colour of the fire-exposed concrete after the fire: no discolouration for $<$ 315 °C, pink colour for a probable maximum temperature of 315 – 593 °C, whitish-grey colour indicating a probable maximum temperature of $>$ 593 °C and buff (light tan) colour indicating a probable maximum temperature of $>$ 927 °C [68].

Different types of spalling have been described and observed: explosive spalling, corner spalling, violent surface spalling, post-cooling spalling, and sloughing off (progressive gradual spalling) [69]. Spalling is related to the increase in pore pressure in the concrete under elevated temperature. This pore pressure first leads to microcracking within the concrete and at the surface, which then develops further and result in pieces of concrete dislodging from the surface. When a concrete element is exposed to heat, two moving fronts develop: a moisture front and a heat front, so that the thermo-mechanical and the thermal-hygral processes occur simultaneously and interlinked. In addition, the thermal dilatation gradient results in additional thermo-mechanical effects, in particular tensile stresses perpendicular to the heated face. The thermo-hygral processes are related to transport of liquid- and vapor-phase water, and the air within the porous medium, and can be observed with a dedicated nuclear magnetic resonance setup [70]. The coupled models result in a system of differential equations that can be solved numerically [71].

No consensus and standard approach to determine concrete spalling exist yet [72]. The following families of theories have been developed: coupled fracture mechanics and pore pressure [69,73,74], a probabilistic model [75–77], a model using the conversion of the thermal energy stored in the material to kinetic energy of the fracture splinters [78], as well as a fully-coupled thermo-hygro-chemo-poro-mechanical model [79] and an earlier hygro-thermo-chemo-mechanical model of heated concrete [80–83] using a mathematical model [84,85]. At the same time, other authors have attempted to simplify these complex models for engineering practice [86].

A number of factors contribute to the occurrence or not of spalling. The first factor is the fire source [87]: gasoline may not lead to spalling, whereas motor vehicle lubricating grease, dry pine construction timber and roofing may result in spalling. The reason why roofing led to spalling are indicated as [87]: the tar is black (increases the slab's heat absorption), the fuel load is greater, the tar can seal the pores of the concrete (more so than a less vicious material such as gasoline), and the heat dissipation occurs closer to the concrete surface.

The properties that influence the fire spalling behaviour are: the heating rate in the experiment, the vapor pressure, the thermal gradient occurring in the sample, the mix, the age of the concrete (although there is no age where spalling will not occur anymore), the moisture content (the risk of spalling increases as the permeability decreases and as the saturation increases [79]), the specimen geometry (with sharp edges increasing the susceptibility to spalling as compared to round faces), the cement mixture, the maximum aggregate size (with smaller coarse aggregates worsening spalling [88]), the aggregate type [89], the concrete density (or permeability), the compressive strength, the tensile strength, the presence of reinforcement (and more so, the presence of prestressing), and, the load level and boundary conditions [90]. Due to the aggregates used, lightweight concrete is more susceptible to spalling [91]. Bored tunnels are more susceptible to spalling as compared to immersed tunnels, as the cross-section is subjected to compression and higher strength concrete is used.

If spalling occurs, the rate of spalling is also an important aspect, and these are a function of the applied temperature-time curve. Members under less intense fire conditions, typically spall after 10–15 min and have a slower spalling rate (1–3 mm/min), whereas those under an RWS curve or a (modified) hydrocarbon curve start to spall more quickly (within the first five minutes) and have a faster spalling rate ($>$ 2.5 mm/min) as compared to [92]. The database developed by [92] has also been used to develop a probability density function of the spalling rate. Moreover, the speed of spalling is higher than the speed of strength reduction [39].

In the Netherlands, the time to spalling is determined in some tunnels using a mobile furnace, which can apply the ISO 834 or RWS (see Fig. 2) fire curve, as well as any other "low temperature" fire curve. The furnace allows for on-site testing, considering the real circumstances of the lining, at a lower cost than laboratory experiments [93].

4.3. Influence of elevated temperatures on material parameters

Temperature influences a variety of concrete material parameters: concrete compressive strength, concrete modulus of elasticity, concrete tensile strength, concrete fracture energy, concrete ultimate strain, concrete peak strain, Poisson ratio, specific heat of dry concrete, and thermal conductivity of the concrete. Recommendations are available in design codes such as EN 1992–1–1 +C2:2011 [94] as well as in the literature for the concrete compressive strength [95], or for all aspects of modelling concrete behaviour at elevated temperature [65]. Most recommendations are geared towards the heating phase, and recent research has identified the importance of the cooling phase. For example, for the compressive strength, EN 1994–1–2:2005 recommends to consider an additional loss of strength of 10 % [96], whereas research has identified that this additional loss is higher [97,98]. [99] developed a model for the tensile strength reduction during cooling. For temperatures above 800 °C, there is discussion about the expressions for the concrete mechanical properties. In addition, the moisture content, which is usually not known nor considered, plays a major role in the relation between temperature and properties [100]. In addition, the post-fire properties of the concrete are influenced by the fire scenario that occurred. The effect on the concrete compressive strength has been made insightful by [101] through an analysis of reported experimental results, showing that for concrete with siliceous aggregates, the effect matches the recommendations of Eurocode 4 [96].

Temperature also influences the properties of the reinforcing steel, such as the steel constitutive relationship (which, for commonly used hot-rolled reinforcement bars can be separated into a stress-strain relationship at room temperature, during heating, and during cooling), and the bond between concrete and steel reinforcement. Moreover, the detailing choices play an important role. For hot-rolled reinforcement, the yield plateau vanishes from the stress-strain diagram during heating and for temperatures higher than 200 ºC. Cooling leads to both loading and unloading in the reinforcement: loading results from moment redistribution to the span, whereas unloading is related to the reduction in temperature. A model for the behaviour of the steel reinforcement during the cooling phase is given in [102].

Bond between steel reinforcement and concrete degrades under increasing temperatures as a result of a difference in expansion, resulting in a differential stress and a loss of splitting capacity. In terms of detailing choices, couplers were found to influence the ductility of threaded splices, while stiffness and strength remain similar to elements with non-spliced details at elevated temperatures [103]. Numerical studies also indicated that beams with tension lap splices have an improved fire resistance as compared to those without splices [104].

4.4. Deformations due to thermal gradients

Limited attention is paid in the literature on the topic of deformations due to the thermal gradients. This effect depends on the overall geometry and boundary conditions. Some fire tests in which no spalling occurred are discussed in Section 5, showing that tensile membrane action can develop in slabs subjected to fire loading.

4.5. Influence of tunnel fire protection systems

Tunnel fire protection systems reduce the temperature on the tunnel lining, and thus the aforementioned effects. These systems can be divided into two categories [24]: 1) passive fire protection of the tunnel lining (spray mortars [105], board panels [90], concrete mixes with fibers [106], or 2) active fire protection (sprinkler or ventilation systems). Whereas spray mortars and board panels reduce the temperature development on the lining, linings with fibers (such as polypropylene) are protected by a different mechanism: the fibers melt during the fire, which results in relieving the pore pressure that builds up in the porous network during heating [91,107,108]. This mechanism means that repairs are necessary after a fire [109]. As passive fire protection systems limit the temperature and speed of temperature increase in the concrete lining, spalling, and in particular explosive spalling, will be reduced [90]. For high-strength concrete, particular attention needs to be paid to shrinkage cracks to utilize fully the fire protection layer [110].

5. Evidence from experiments

5.1. Availability of experiments on structural behaviour of tunnel linings under fire

Several series of experiments of concrete members under fire and service loading are reported in the literature. Full-scale tunnel fire tests addressing the structural behaviour are not available, only full-scale tunnel fire tests to study the fire dynamics have been carried out.

5.2. Beam and column experiments

Experiments on linear elements consider beam specimens with one or three sides subjected to fire loading. While these experiments are typically developed to study building fires, they can serve as benchmarks for finite element models. In [111], the focus was on the influence of the concrete compressive strength, where the high-strength concrete specimens resulted in spalling. For beams with axial restraint, [112] made similar observations. To study the interaction between shear and fire loading, [113] compared the shear capacity of beams after fire exposure, and found that the shear strength loss increases with fire exposure time, and that the shape of the critical shear crack changed after fire exposure, indicating dowel failure. Finally, experiments on T-beams with web openings are available as well [114].

Column specimens are subjected to axial compression and can give insight in the influence of confinement on the behaviour of tunnel linings subjected to fire. The influence of high-strength concrete was studied in [115], showing 40 % spalling in the high-strength concrete columns within 33 min, and no spalling in the normal-strength columns. As such, [116] recommended the use of polypropylene or polyvinyl-alcohol fibres in high-strength concrete members to reduce or avoid spalling. Recent research on the cooling phase [117] showed that failure of columns can occur during the cooling phase after a 60-minute fire. [118] studied the effect of confinement in concrete columns, indicating a marked influence of the layout of ties and confinement on the fire performance of both normal and high-strength concrete columns, whereby confinement resulted in an increased fire resistance. Ultimately, [119] noted that the beam-to-column connections, rather than the columns, should be studied experimentally, as the connections play a crucial role in the overall integrity of the building. Moreover, different testing conditions result in different conclusions.

5.3. Slab experiments

Reinforced concrete slabs were tested in New Zealand [120] subjected to the ISO 834 fire and a service load. All slabs deformed in double curvature as a result of the thermal loading, but spalling did not occur. Yield lines formed during the advanced stages of fire exposure, and tensile membrane action was activated. In Manchester, small-scale slabs were tested [121,122], showing again that tensile membrane action develops in slabs when fire loading results in large deflections. These specimens also did not show spalling. If spalling does not occur, tensile membrane action can result in an increase in capacity of up to 2.7 times the capacity determined using yield lines [123]. Recent experiments on larger slabs clamped at one edge and simply supported at three edges resulted in large deflections, U-shaped cracking near the clamped support, and limited spalling [124].

For building slabs, there is also a risk of a premature punching failure at slab-column connections [125]; a condition that is generally not considered when studying fire scenarios. Arching mechanisms and tensile membrane action were also observed in circular slabs that were tested to failure after fire exposure [126].

For waffle slabs, the rib height did not affect the average temperature in the concrete flange (important for the fire safety design) [127]. Finally, several researchers have tested plain concrete slab specimens to study spalling, with a focus on the relation between the concrete mix design and spalling characteristics [128–132].

5.4. Slabs with axial compression

For slabs to better represent tunnel linings, axial compression needs to be applied. This axial restraint can be induced by using centric post-tensioning strands [133,134]. It should be remarked here that the axial restraint was not constant, as the post-tensioning was affected by the elevated temperatures. Spalling was recorded, and the authors concluded that even under a moderate fire scenario irrecoverable damage can result. In other experiments of prestressed slabs, the prestress loss as a function of the temperature in the strands was studied. This loss resulted in a reduction of the axial compression, which reduced the spalling. In addition, less spalling occurs around the edges than in the middle of the fire-exposed area [135].

Actual shield tunnel segments have also been tested. Using a newly developed test setup than can mimic the actual loading conditions in a tunnel segment, [136] tested both reinforced concrete and hybrid fiber reinforced concrete (HFRC) tunnel lining segments, finding that the spalling resistance of the HFRC segments under thermo-mechanical loading was excellent, whereas the reinforced concrete segments showed better overall structural performance. In addition, it was found that the initial loads have a significant effect on the behaviour of the lining segments, and that the role of the lining joints is crucial for the overall performance of shield tunnel linings constructed using a tunnel boring machine [137].

Finally, continuously supported prestressed slabs have also been tested [138]. The effect of specimen size was explored in slabs subjected to an external axial load, indicating that small and medium specimens are not sufficient to evaluate the behaviour of full-sized tunnel elements under fire [139–141].

Just as for the plain concrete slabs, a number of plain concrete slabs with axial loading have been studied to find the relation between the concrete mix and spalling properties (including different types of spalling as a function of the velocity of the pieces) [142–144]. Interestingly, in [143] spalling was observed even though the pore pressure was low, contradicting traditional spalling theories.

Tunnel linings are generally curved in shape for bored tunnels, so that another series of experiments have focused on testing curved slabs with axial restraint [145]. As observed in the slab experiments looking at the effect of size, testing full-scale tunnel lining segments in Australia led to the conclusion that testing structurally loaded tunnel linings at full scale is crucial, because flat panels without service loading result in less spalling than in the real tunnel linings [146].

5.5. *Scaled tunnel fire experiments*

Recently, three interesting experiments on scale models of tunnels with double tubes have been conducted in China: one experiment with fire protection [147], one experiment with fire in both tunnel tubes [148], and one experiment with fire in a single tunnel tube [149]. The maximum temperature of the fire exceeded 1300 °C as the tunnel was subjected to a hydrocarbon fire for more than 3 h, followed by cooling using ventilation In addition, the tunnel was loaded by service loading.

The specimens were well-instrumented, providing both measurements of the temperatures at multiple positions in the sections, as well as deformations from LVDTs and inclinometers. The deflections were much smaller than the axial deformations. The concrete spalling was maximum 100 %, and the maximum depth of spalling reached 142.2 mm for the cases without tunnel fire protection. The concrete started to spall quickly. Spalling occurred for about 60 min. Based on these observations, the maximum spalling rate is estimated as 2.45 mm/min and the average spalling rate was estimated as 1.02 mm/min in the left tube and 1.06 mm/min in the right tube for the scenario with fire in both tubes.

The authors concluded that the structural capacity of the tunnel in the event of a fire was sufficient, but that serious plastic deformations occurred in the middle walls as a result of the increased eccentricity of the loads. Moreover, cracks on the outside of the tunnel formed, which can result in water leakage into the tunnel. Those cracks were observed even in the tunnel segment with fire protection.

6. Insights from numerical studies

As tunnel fire experiments are rare due to their cost, numerical modelling can be used to study the problem.

When wanting to use numerical models to relate the tunnel fire to the concrete tunnel structure, both the thermal and mechanical analyses need to be coupled as shown in Fig. 3. For the mechanical analysis, the effect of temperature on the mechanical properties of the concrete and the steel needs to be considered. The thermo-mechanical analysis can be fully coupled, for which the thermal and mechanical unknowns are solved simultaneously; or sequentially coupled, for which the heat transfer equations are solved first and then the temperature field is imposed on the mechanical model [150]. The latter approach is most commonly used, although it is known that the behaviour of concrete subjected to thermo-mechanical loads depends on the order in which the thermal and mechanical load are applied [151], and it influences the transient creep component of the strains [152].

For concrete under increased temperatures, the total strain in the Eurocode is composed of the thermal strain and the mechanical strain, which is a combination of: 1) the transient strain, 2) the creep strain, and 3) the stress-related strain. By considering the transient creep implicitly, it is assumed that this component is fully reversible, which is not realistic because this strain is related to inelastic deformations from diffusion and evaporation of concrete subjected to both mechanical loading and increasing temperature. As this component is related to changes in cement matrix's chemical composition, it is indeed not reversible. As such, the implicit model is less accurate when the cooling phase needs to be considered. As a result, explicit models have been proposed in the literature [153,154]. In these models, the transient creep strain depends both on the temperature and stress as well as on the stress-temperature path to which the material is subjected, and this component is not recoverable during cooling or unloading. Recent numerical work on the cooling phase showed that, when modelling the RABT curve (see Fig. 2), the joint opening can be reduced by more than 30 % on average, and up to 50 % for rectangular shield tunnels assembled with composite segments. The inclusion of the cooling stage also allows for recovery of mechanical behaviour in the numerical model [155].

The software packages that have been used, and for which researchers have included software-specific discussions are SAFIR [120,133,134,152,156], the constitutive model 2D-PARC-FIRE [115], FORTRAN routines [157], HITECOSP as developed by ENEA in Italy and applied in [107], ABAQUS [114,158,159], DIANA [160] and ATENA [161].

Studying the different outcomes as a function of the choice of element type (beam element, shell elements, and solid elements), [133] concluded that shell elements are the recommended option for capturing the displacement of slabs (both maximum and residual). Beam models lead to unconservative results but can give an idea of the overall trend, and solid elements may pose convergence problems during cooling. As such, the authors recommended shell elements for analysing the behaviour of reinforced concrete tunnel linings under fire.

Similarly, [162] observed that the computational outcomes are related to the choice of a 2D or 3D model. Initial guidance on possibilities for modelling choices can also be found in *fib* Bulletin 108 [97] that can be applied for the modelling of tunnels. Among these general recommendations, the use of beam elements and 2D plane stress/strain is favoured despite the impossibility of considering the extension of a localized fire in the longitudinal direction. A full model of a tunnel, or even a tunnel segment, made of 3D solid elements is not recommended for engineering practice due to the high computational cost.

For modelling material properties, the concrete cracking modelling assumptions influence the results. This observation can be explained by the fact that the lining design is often governed by crack control for durability and to keep maintenance costs low [163]. Other crucial parameters include the thermal expansion [164], the assumptions for confinement [162], and the assumed spalling location [165]. It should be noted here that it is difficult to predict spalling in numerical models. As such, different spalling scenarios need to be included before the simulation. For the reinforcement during the section thermal analysis, a circular cross-section should be selected for the reinforcement bars, and

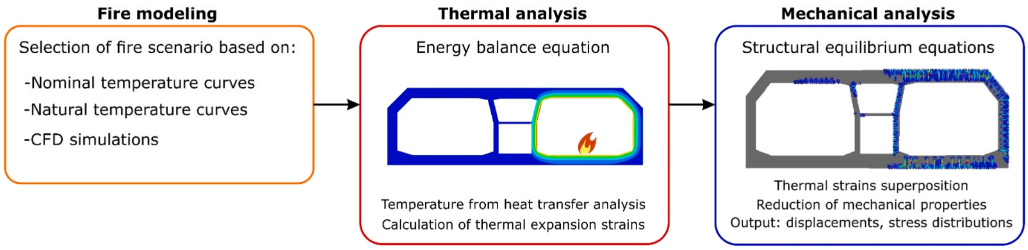

Fig. 3. Approach used in numerical analysis for fire assessment.

an adequate mesh size should be selected, to properly capture the effects related to the reduction of the rebar area [165].

In terms of general modelling choices, the following parameters have been identified as important: including the temperature-induced stresses and resulting thermal deformations, modelling the passive soil pressures [162], modelling the interaction between the soil and the degradation of the concrete tunnel lining [160], modelling the road level, including indirect actions, modelling the construction phases of the tunnel to estimate the initial stresses, the mesh [165], modelling the cooling phase [166,167], when the unheated face of the tunnel may crack as well.

As most global thermo-mechanical approaches cannot explicitly model concrete spalling, a workaround of using the damage holistically based on observations from tunnel fires [40] or by removing concrete cover over time (to mimic the spalling rate) has been proposed. Besides global coupled thermo-mechanical models, researchers have also used meso-scale numerical simulations to study particular topics, such as spalling of layers of concrete cross-sectional surfaces under fire by combining pore pressure and fracture mechanics [69]. Such models address one of the main drawbacks of the global thermo-mechanical models: the uncertainty on the occurrence and spatial variation of spalling. This uncertainty requires a probabilistic analysis using random fields [75].

A more advanced approach than the typical thermo-mechanical models is modeling the fire using CFD and then importing the temperature distribution into a numerical package. This methodology may be necessary when real fire development needs to be studied. To model composite linings, [168], combined CFD and finite element modelling for a large composite lining shield tunnel. The induced temperature from the fire increases the bending moments and axial forces in the lining, whereas the deformations during the fire are a function of the timing of the secondary lining application (influencing stresses at the tunnel arch position) and burial depth (influencing stresses at the tunnel top and arch position). However, [159] emphasized that standard temperature are an sufficient assumption for the temperature distribution.

Ultimately, when the linings of existing tunnels are assessed using numerical analyses, a safety format [169] needs to be used. Research found that the global resistance factor to be used in combination with nonlinear finite element analyses is a function of: the concrete cover and its assumed standard deviation, the ratio of the moment due to the variable load over the sum of the moment due to the permanent load and the moment due to the variable load, and the duration of the fire [170]. Another study evaluating slabs subjected to fire loading [171] showed that the resulting safety level depends on the variation of the material properties in relation to the temperature effect.

7. Discussion

The structural safety of tunnel linings subjected to fires has been receiving more attention in recent years. One of the reasons is the renewed attention in general to the fire safety of concrete structures, as unexpected collapses of concrete bridges under fire have been reported in recent years [68]. These collapses have been attributed to the lower fire performance of higher-strength concrete [172].

Ten years ago, [173] reviewed the state of the art of concrete tunnel linings for fire safety. The main focus for the structural behaviour of tunnel linings under fire at that time was related to explosive spalling, as this effect had been observed in a number of major tunnel fires (as mentioned in Table 1). In comparison, nowadays, the focus is on the interplay between the deformations resulting from elevated temperatures, the changes in material properties, and the sectional losses as a result of spalling. The focus nowadays has also shifted from the design of new tunnels to assessing the fire safety of existing tunnels. While the work in 2014 focused on the need for practical methods (such as design charts) for designing tunnel linings (with and without various forms of passive fire protection), such simplified approaches cannot be used for the assessment of existing linings. At the same time, the 2014 call for the development of more sophisticated numerical procedures still holds true.

For existing tunnel linings, the state of damage is also relevant. [174] modelled the effect of the damage in terms of deformations exceeding pre-established limits as a loading intensity effect (LIE) and found that the LIE influences the temperature distribution, deformation development and inner force distribution, aggravates heat flow invasion, resulting in uneven temperature distributions in segmental tunnel linings. Moreover, the pre-damage influences the deformations, and can result in excessive deformations at early heating stages, potentially leading to failure of a segment. Therefore, understanding the deformation deviations in existing tunnel linings for segmental tunnel linings is important for the assessment.

The current challenges to developing a uniform assessment method to determine the structural safety of existing tunnels under fire loading are the following: simplified hand calculations are insufficient for the problem, the number of full-scale experiments is limited, and few reports of existing tunnel fires contain detailed information on the observed damage to the tunnel lining. In general, the analysis in this review shows that tunnel fires result in damage to the lining due to spalling, changes in the material properties of the concrete and steel subjected to elevated temperatures, and thermal gradients.

When needing to assess the safety of existing tunnels under fire, first of all one should remember that no two similar fires are ever exactly the same [10]. At this moment, the overall assessment strategy that can be recommended is as given in Fig. 4, with details regarding modelling choices in Fig. 5, considerations for the influence of the fire on the concrete tunnel lining in Fig. 6, and relation to the assessment goals in Fig. 7. The blocks indicated in yellow in these flowcharts require further research.

The assessment strategy outlined in these flowcharts start from the global assessment strategy, see Fig. 4. A first global study of the problem should address the modelling choices (including the basic choice of modelling tools), chart the expected effect of a fire on the tunnel lining and identify potential issues, and, as for each assessment, clearly identify the objectives of the outcome of the assessment. Examples of the latter include: evaluating the expected damage after a major fire, checking overall structural safety and code compliance, or exploring fire proofing strategies. Once this input for the assessment is obtained, a strategy for data collection, modelling, analysis of the results, and resulting recommendations can be developed, to guide the calculation actions and planning of the assessment activities. In terms of modelling choices, §6

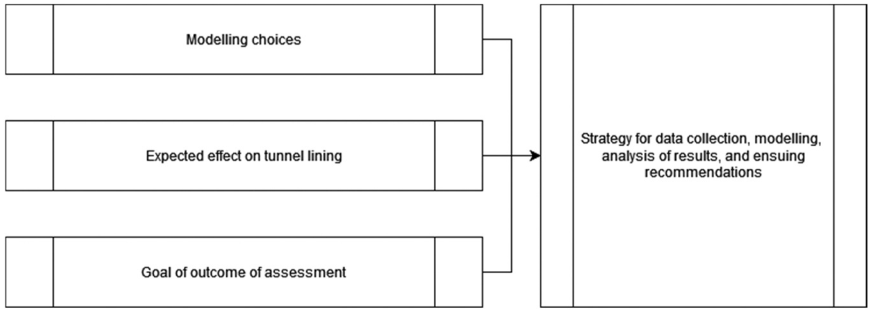

Fig. 4. Overall assessment strategy.

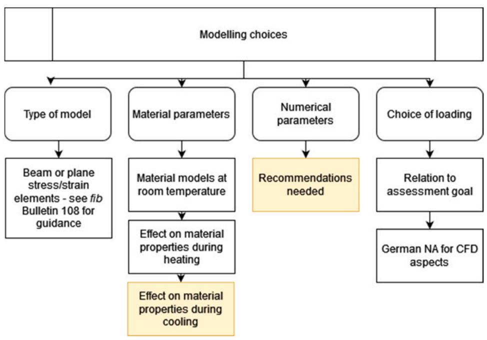

Fig. 5. Modelling choices and considerations.

highlights the need to evaluate the type of model to select, the material parameters to select, the numerical parameters to model, and the choice of loading to apply, as summarized in Fig. 5. As can be seen in Fig. 5, research is needed to address the material properties during the cooling stage of a fire, and to develop recommendations for the choice of numerical parameters to include.

In terms of the structural response of the tunnel lining under temperature changes, Fig. 6 shows the aspects to consider: spalling of the concrete (which requires typically experimental evidence), changes in material properties under elevated temperature (which can be modelled as recommended in the codes and literature), and thermal-induced deformations of the structure (which typically requires numerical models, ideally capturing the full 3D behaviour of the structure), as also indicated in Fig. 1 and studied in §4.2–4.5. At this stage, knowing the actual condition of the tunnel cross-section is necessary, and should be obtained by inspections. In the inspections, special attention should be paid to the condition of the tunnel in general, the fire safety equipment, and the condition of the concrete and potential deterioration and degradation which needs to be taken into account in the numerical models and assessment. Various topics of further research are identified here: the influence of the cooling phase in terms of residual deformations, modelling choices, and material properties, as well as link between patch testing using a mobile oven and realistic spalling behaviour of concrete considering the size effect of patch testing.

Finally, in terms of the objectives of the overall assessment, Fig. 7 gives guidance on important modelling choices. When compliance with the safety philosophy of the code is sought, the RWS fire curve is usually modelled, but the topic of safety formats is not defined for these assessment cases yet. When the assessment aims at developing insights of different fire scenarios, the focus should lie on modelling different fire curves to explore the effect of different scenarios. If the goal is to evaluate different fire proofing measures, the difference in temperature development in the concrete section (for the case of passive protection) or the difference in the fire dynamics (for the case of active protection) should be the modelling priority.

At the same time, having a better understanding of the behaviour of an existing tunnel structure under fire can help the post-fire damage evaluations and decision-making regarding required repairs and actions to restore a tunnel's functionality. A methodology for post-fire assessment is discussed in [175], which combines visual inspection, non-destructive testing, and material sampling with advanced modelling (using a CFD analysis, a heat transfer analysis, and a thermo-mechanical analysis) to come to an approach for damage classification, repair requirements, and evaluate the tunnel downtime and economic losses. To determine the repair actions necessary, the authors emphasize the need for input and discussions with stakeholders, as well as the need for guidelines and the need for the input from researchers.

Topics that require further research are the behaviour of the tunnel lining during the cooling phase and the potential for cracking on the outer face of the tunnel (where potential cracking can lead to water infiltration in the tunnel after the fire, and for which repair actions are complicated). In addition, at this moment the spalling potential of concrete tunnel linings is studied by testing small patches with a mobile oven. However, since there is a size effect in the response, experiments are necessary to study the size effect of patch testing and the validity of extrapolating the results.

Moreover, as numerical analyses are necessary to study the problem, more research is needed to develop a consistent analysis of modelling choices, to ultimately develop recommendations for the modelling choices (such as already exists for the nonlinear finite element analysis of concrete structures [176]). First steps in this direction, through the modelling of typical land tunnels structures in the Netherlands, have been developed in the mean time [177–179]. In addition, the safety format to use [180] needs to be developed, for which a combination of probabilistic studies and nonlinear finite element analyses are required. These aspects are highlighted in yellow in Figs. 3–5. The necessary recommendations can also serve in the future for the application to bridges and residential buildings.

8. Conclusions

Fires in tunnels are rare events that can have catastrophic consequences. In this paper, the relation between tunnel fires and the ensuing damage to the concrete lining is reviewed. Based on this review, we can draw the following conclusions:

- The first step is to link the fire to the resulting temperature on the tunnel lining. This relation can be modelled using computational fluid mechanics, but is in practice often replaced by using a prescribed temperature-time curve.
- The damage results from three aspects: 1) potential spalling of the concrete, 2) reduction of mechanical properties of concrete and steel at elevated temperatures, and 3) deformations resulting from thermal gradients. Spalling is not well-understood yet, but can be modelled based on assumptions regarding the onset of spalling and spalling rate. The deformations resulting from thermal gradients are difficult to estimate, and require ideally the use of three-dimensional models.

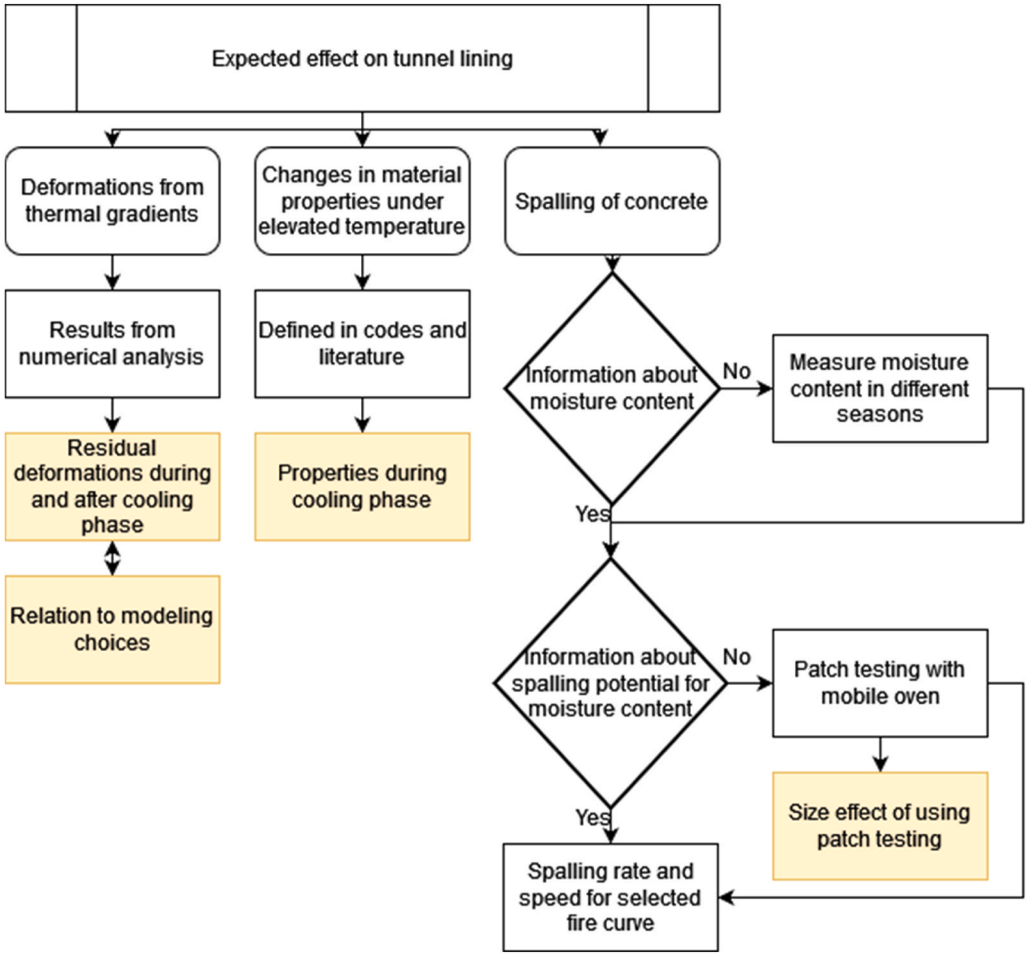

Fig. 6. Considerations for the effect of fire on tunnel lining.

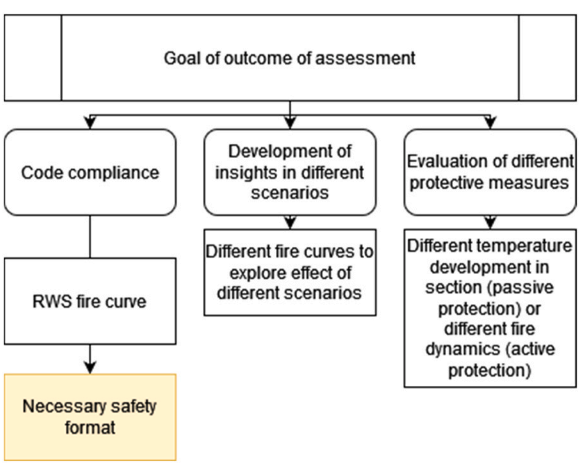

Fig. 7. Relation to the goal of the assessment outcome.

- Current experimental evidence at full scale is not available and the scale effect is a topic of discussion. Three scaled-down experiments on tunnel structures have been carried out, resulting in new insights regarding spalling depth and rate, as well as on the effect of the cooling phase and post-fire residual deformations. These experiments are a worse-case scenario compared to the tunnel fires that have occurred in the past and for which a relation between damage and maximum heat release rate is compiled in this work.
- Three-dimensional nonlinear finite element models of tunnels subjected to fires are not used commonly. Typically, a tunnel segment is modelled using a thermo-mechanical coupling. Choices for the material parameters, both during the heating and cooling phases, as well the numerical parameters, become crucial for the resulting damage after the fire, and overall structural performance of the tunnel cross-section in the model during the fire.
- For assessment, it is necessary to study the influence of material degradation on tunnel fire performance, and develop standard post-fire inspection protocols.

  This paper gives flowcharts for the assessment of existing tunnel assets subjected to fire, indicating relevant areas for future research:
- nationally or international accepted guidelines for the numerical parameters;
- description of the material properties during cooling;
- residual deformations and ensuing damage during and after cooling;
- influence of size effect when using patch testing to determine spalling properties of a particular tunnel lining;
- required safety format for assessment.

Considering the current state of knowledge, this paper ultimately gives guidance for the assessment of tunnel linings under fire loading, and indicates needs for future research.

CRediT authorship contribution statement

Eva Lantsoght: conceptualization, formal analysis, investigation, methodology, project administration, supervision, writing original draft. **Rafael Sanabria Diaz:** investigation, validation, visualization, writing review & editing. **Max Hendriks:** funding acquisition, supervision, writing review & editing.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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