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FIERCE: A COST BENEFIT ANALYSIS FOR TUNNEL FIRE SAFETY

[1]Schepers Melchior, [1]Deckers Xavier, [2]Jovanović Balša, [2]Chaudhary Ranjit Kumar,
[2]Van Coile Ruben

[1]Jensen Hughes, Ghent, Belgium
[2]Department of Structural Engineering and Building Materials, Ghent University, Ghent, Belgium

ABSTRACT

The Belgian fire engineering consultancy FESG – A Jensen Hughes Company - has been developing a risk assessment framework for tunnels called FIERCE (Fire Integrated Environment for Risk Comprehension and Evaluation) in cooperation with Ghent University. The goal of the framework is to develop a probabilistic approach towards fire safety measures in tunnels taking into account specific fire safety measures (sprinklers, water mist systems, ventilation) but also structural and financial considerations. The framework couples, CFD, 1D and evacuation simulations in order to asses the impact of a tunnel fire in terms of potential casualties. In order to evaluate the structural damage and subsequent downtime a finite element model of a representative tunnel was built in 'SAFIR'. This model was subjected to several fire curves, with a heating phase conforming to the RWS curve and an exponential decay phase. The evaluation of the damage and associated cost was done by mapping the depth of the 300 °C isotherm and residual deformations at the end of the decay phase to a damage state leading to an assessment matrix correlating the fire curve and the damage state. The damage state was subsequently linked to a repair cost as well as a cost associated with the unavailability of the tunnel.

Keywords: QRA, Tunnel Fire Safety, SAFIR, downtime, cost-benefit

1. INTRODUCTION

Notable accidents such as the Mont Blanc tunnel fire, the Tauern tunnel fire and the Channel tunnel fire have raised awareness for the need of effective fire safety measures in tunnels. This awareness was also reflected in the European Directive 2004/54/EC [1,2,3] which aimed at bringing the safety level of the tunnels throughout the Trans European Road Netwerk to a higher level. In this directive a strong emphasis is placed on the importance of a thorough risk analysis as forming the basis for the measures that need to be put into place to achieve an acceptable safety level. This triggered the development of several risk assessment methods for road tunnels [4, 5]. As a result different countries developed different risk assessment methods independently, based on local accident databases and fire events [6]. Currently there is no proprietary risk analysis tool for tunnels in Belgium. The FIERCE project therefore set out to investigate and develop a holistic framework that would allow an all-encompassing probabilistic, risk-based approach towards the design and assessment of fire safety systems in tunnels. By taking a probabilistic approach an integrated solution can be provided, considering structural, life safety and economic aspects optimized to the lifecycle of the tunnel.

2. QRA FRAMEWORKS IN EUROPE

The current risk assessment methods in use throughout Europe all have different levels of complexity and accuracy. The methods are either quantitative or qualitative, system based or scenario based and may or may not consider dangerous goods [7]. Depending on the risk assessment method that is applied to a certain tunnel, the outcome in terms of measures that need to be taken, might be vastly different. There is however always a trade-off that needs to be made between the cost and benefits of certain proposed measures. The current risk assessment methods do not allow to take such trade-offs into account, neither do they allow an easy integration of the probabilistic nature of the parameters and boundary conditions involved with the occurrence of a fire. When not taking into account the probabilistic nature of these variables the different methods can lead to widely different results for the same tunnel. This should be avoided and a more uniform approach should be used in order to provide consistent results [8]. A lot of the risk assessment tools in use today, such as the OECD/PIARC QRA model and the RWS method are spreadsheet-based tools working with a pre-set number of scenarios. Since the number of scenarios is limited these tools do not always deliver an optimal solution. Furthermore only the scenarios imposed by the issuing member states are considered in the respective QRA methods, while the type of road infrastructure might deviate substantially between different member states [7]. These methods focus mainly on possible control measures, while for example the reliability of the measures (e.g. reliability of sprinklers vs smoke and heat control systems) is not taken into account. Some notable shortcomings of the most used current methods are the inability to take into account one or more of the following aspects: sprinklers, new energy carriers, transversal ventilation, structural stability, the propagation of smoke or the impact of smoke on the evacuation of people from the tunnel. By providing a framework which can be extended with additional modules the proposed framework aimed to overcome the inherent deficiencies of the existing methods.

Besides the inability of most of the existing methods to address structural and monetary considerations, in Europe, differently than in other countries such as Japan or Australia, active suppression systems are not employed in tunnels [9] and thus not taken into account in the existing risk assessment tools. Water suppression systems can however strongly limit the growth and the size of the fire and as a result also the negative effects related to a large fire. On the other hand the suppression system will also affect the smoke stratification which in turn will affect evacuation conditions. Research has however showed that the use of water suppression in tunnels generally has a positive impact and consequently it should be possible to include such safety measures in the risk analysis [10, 11].

3. THE FIERCE FRAMEWORK

Fire safety in tunnels is a complex process with multiple interacting elements such as the fire, the traffic flow, the tunnel's structure and the fire safety measures influencing one another in multiple ways [12, 13, 14, 15]. The development of a new approach for assessing fire safety in tunnels, including the probabilistic nature of the processes involved, thus requires the integration of different fields of expertise combined in a single holistic approach. The FIERCE tunnel safety framework, encompasses different sub-models within a Performance Based Design (PBD) framework. As an alternative to the prescriptive approach a performance based design allows the fire safety engineer to propose alternative solutions which allow to satisfy the performance criteria in an optimized way. A deterministic approach takes into account only a prescribed set of expected worst case scenarios. These are then used to design the different safety systems: ventilation, suppression and or passive protection and detection. However, in choosing the fire scenario a lot of assumptions are made. Ambient conditions, traffic, failure rates of components,… all these variables rely on the constraints of the project on the one hand and on the experience of the designer on the other hand. They thus often rely on engineering judgement. As a result a too conservative choice of the input parameters leads to an overly expensive design while a non-conservative choice leads to a high risk in case of fire. Therefore, in order to propose design solutions which are optimized both in terms of life safety, structural safety and business continuity the risk assessment has to take into account all possible scenarios that can occur throughout the lifecycle of the tunnel. In order to do so a probabilistic approach is proposed.

In a probabilistic design it is possible to include a continuous set of fire scenarios which are then sampled and used to represent the probability of a certain scenario occurring throughout the lifecycle of the tunnel. The consequences of the design fire scenarios are then evaluated with a performance based approach and the final result of the assessment is represented in an FN curve. Such an FN curve is used to evaluate the risk for life safety by correlating the number of fatalities with the frequency of a certain accident. This concept of risk evaluation is further extended by the framework to also include the financial consequences of the fire and the effect of the fire on the structural stability of the tunnel. The framework aims to provide an integrated design approach where the different submodels, as shown in figure 1, influence one another and their mutual dependence is taken into account.

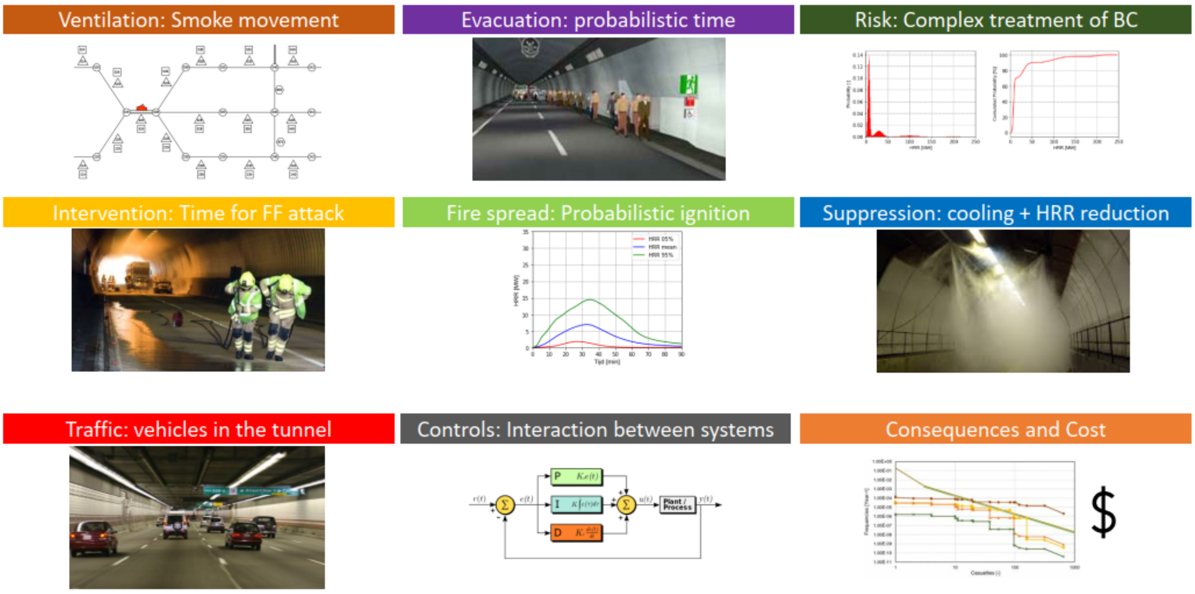


Figure 1: submodules making up the integrated design approach

3.1. Submodule interaction

The first layer in the consequence modelling of the FIERCE framework deals with ventilation and evacuation modelling. The ventilation modelling is based on a 1D approach in order to be able to run a great number of simulations in a reasonable time frame, which is not possible with current CFD packages. The evacuation model in turn is capable of running a large amount of simulations and directly takes into account the effect of the fire and smoke spread on occupant movement, slowing down occupants when they have to evacuate through smoke conditions. The coupling of the smoke spread and evacuation models allows for the calculation of the FED or FID and as such an assessment of the amount of possible casualties.

In the second layer the events that directly affect the HRR of the fire are considered such as suppression systems that may be present and possible suppression efforts by the fire brigade. In order to evaluate the effects of the suppression system a simplified model was developed that allows for a quick determination of the cooling effect of a watermist system. The firefighter intervention model is based on an event based approach where fire brigade operations are broken up into several activities including: gathering information, dispatch of resources, equipment set up, control and extinguishment of the fire, and search and rescue [16]. Amongst several parameters the success of the firefighter intervention largely depends on the intervention time, more specifically the so called ‘time to water on fire’, the moment at which the suppression activities are started [17,18]. The intervention time can be split into several stages as shown in the figure 2.

Figure 2: event flow for the fire brigade intervention

The model provides an estimation of the time required for the firefighters to reach and possibly suppress the fire, thus influencing the HRR of the fire [19].

In the final layer, the novelty of the proposed approach lies in the structural model that was developed and which allows for both a structural and financial assessment of the consequences of the fire. This model is expanded upon in the following section.

4. STRUCTURAL MODEL

To allow for a comprehensive risk evaluation, also the structural performance during and after fire is assessed. First of all, structural integrity during fire allows for evacuation and search and rescue operations. Secondly, service interruption following a fire can constitute very large indirect consequences, i.e., through increased travel times for users. In situations where structural repairs or reconstruction are required post-fire, this service interruption can extend over many months.

4.1. Fire exposure

Tunnel structures are commonly designed or assessed considering a heating phase exposure only. The structure's minimum capacity is however obtained during the decay phase, and permanent deformations and load redistribution imply that heating phase stability is no proxy for post-fire usability. Considering Li and Ingason [20], the temperatures achieved in severe tunnel fires (i.e., structurally significant fires) are capped by the characteristics of the tunnel, and not by the potential heat release rate (HRR) of the burning heavy goods vehicles. Therefore, as soon as the HRR is sufficiently high (order of 90 MW), the heating phase can be modelled considering the RWS fire curve. Here, the decay phase is modelled considering the equation below, with the decay phase coefficient b ranging between 0,0015min^{-1} and 0,0611 min^{-1}, based on experiments listed in [21]. The average value of 0,025 min^{-1} is adopted. Resulting exposures are visualized in figure 3

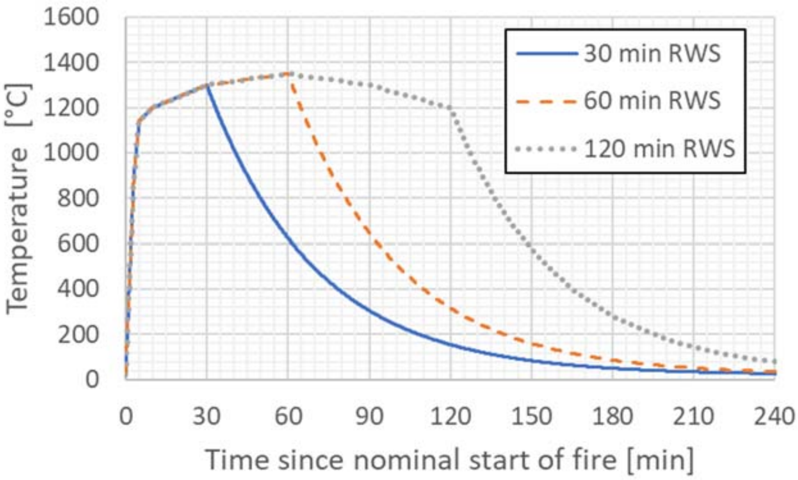


Figure 3: Exposure considered for structurally significant fires.

4.2. Concrete spalling

Spalling is modelled considering nominal spalling rates, as recommended in [22] and applied by Hua et al. [23]. Specifically, a set time for the onset of spalling is considered, followed by a constant spalling rate of, for example, 3 mm per minute. Spalling is stopped as soon as either (i) the reinforcement layer is reached, or (ii) when the fire enters the decay phase. Hua et al. [23] report spalling rates for tunnels of up to 5mm/min. In the current study nominal spalling rates of 1/2/3/3.75/5 mm/min are considered, as well as a no-spalling case. For each spalling rate a corresponding probability is specified considering the experimental dataset listed by Hua et al.

4.3. Structural model and performance during fire

A twin tunnel section with a smaller internal connecting tube is considered. This section is evaluated in order to allow for a fast and approximate assessment of similar designs. Cross-sectional dimensions for the tunnel are indicated in figure 4. The springs representing the soil restraint to outwards movement are represented by the blue lines. The tunnel section is symmetrical. Fire exposure is modelled for the left tube only, heating the walls and ceiling (not the floor). The calculations are done using the dedicated structural fire engineering software SAFIR [24]. Further details on the structural model are provided in [25]. Structural failure during fire was observed for high load combinations. When considering the expected load values (as is required for a risk-based design optimization), all considered tunnel structures maintained stability for the full fire duration.

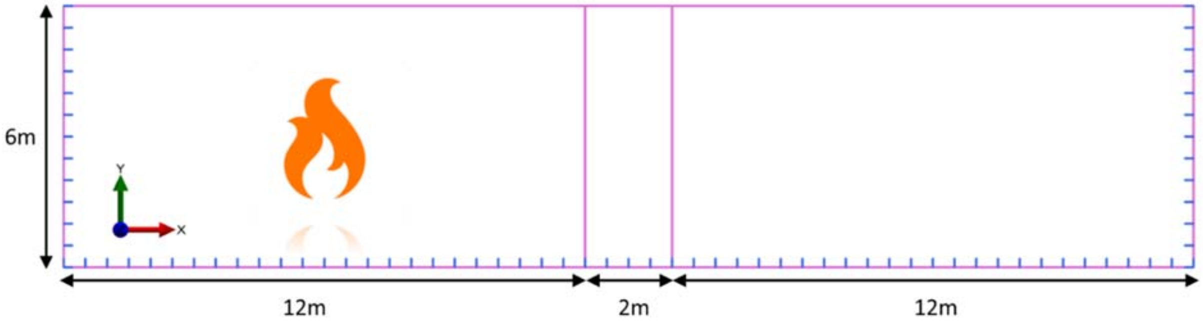
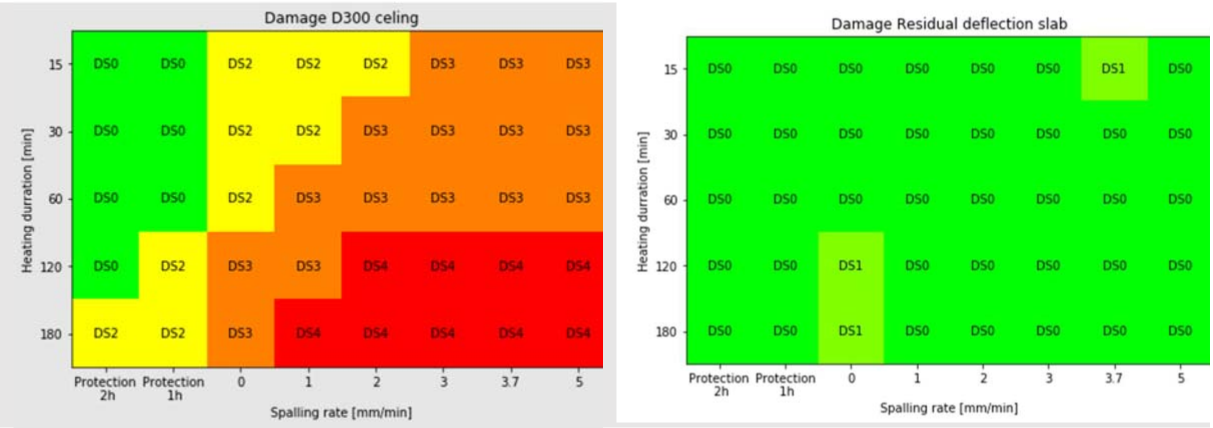


Figure 4: Tunnel section and dimensions (axis position).

4.4. Post-fire damage and downtime assessment

Post-fire damage is considered to relate to (i) permanent damage to heated concrete, and (ii) permanent deformations in the tunnel cross-section. Damage limit states based on [26] are adopted. Specifically, concrete heated above 300°C is considered to require replacement, while deflection limits apply for the walls and ceiling (e.g., a ceiling deformation exceeding span/120 requires full reconstruction).

The resulting damage states are defined for different nominal spalling rates and cases where the concrete is protected with fire protection boards, considering different RWS heating phase durations. For the ceiling the thermal damage state generally dominates the mechanical (deformation) damage state, meaning that the repair strategy for the ceiling is defined by the thermal ingress. The obtained damage state due to the thermal and mechanical damage is listed in figure 5. As the damage state relates to a repair strategy, the damage states are then directly linked with a cost for repair and repair duration (i.e., downtime). The repair costs of the tunnel structure can then be estimated, based on the damage parameters D300 and the residual deformations, and its associated damage state classification. The repair cost for a repairable structure is the sum of cost of labor and materials required to carry out the repair, while in case of an irreparable structure, the cost is a sum of demolition and reconstruction cost. The same applies to the evaluation of downtime, which can also be represented as a cost. Depending on the level of damage, and the considered costs, it may be ‘cheaper’ to rebuild than to repair. Considering [27], downtime costs can be very high for critical infrastructure (order of 1M EUR per day) and these downtime costs can dominate the overall cost-benefit assessment. In other words, decisions on the effectiveness of fire protection measures (notably passive fire protection) are generally governed by downtime considerations.



Damage D300 celing

Heating durration [min]	Protection 2h	Protection 1h	0	1	2	3	3.7	5
15	DS0	DS0	DS2	DS2	DS2	DS3	DS3	DS3
30	DS0	DS0	DS2	DS2	DS3	DS3	DS3	DS3
60	DS0	DS0	DS2	DS3	DS3	DS3	DS3	DS3
120	DS0	DS2	DS3	DS3	DS4	DS4	DS4	DS4
180	DS2	DS2	DS3	DS4	DS4	DS4	DS4	DS4

Spalling rate [mm/min]

Damage Residual deflection slab

Heating durration [min]	Protection 2h	Protection 1h	0	1	2	3	3.7	5
15	DS0	DS0	DS0	DS0	DS0	DS0	DS1	DS0
30	DS0	DS0	DS0	DS0	DS0	DS0	DS0	DS0
60	DS0	DS0	DS0	DS0	DS0	DS0	DS0	DS0
120	DS0	DS0	DS1	DS0	DS0	DS0	DS0	DS0
180	DS0	DS0	DS1	DS0	DS0	DS0	DS0	DS0

Spalling rate [mm/min]

Figure 5: thermal damage state classification (left) and mechanical damage state for the ceiling (protected and unprotected) under RWS fire exposure in function of heating phase duration and nominal rate of concrete spalling.

5. SUMMARY AND CONCLUSION

The FIERCE framework provides a holistic approach to the risk assessment of tunnels under fire conditions. The different submodules making up the framework interact with another to ensure the dependencies between them are taken into account as accurately as possible. The ventilation, evacuation and additional submodules that may influence the HRR of the fire allow the assessment of the fire safety measures in terms of life safety. The structural module on the other hand allows insight into the structural fire performance, the possibility of structural failure, and the extent of the damages post-fire. This in turn allows for an assessment of the damage caused by the fire and the associated cost due to repairs and downtime of the tunnel. The results of an analysis via the framework allow for a trade-off to be made between the fire safety measures and their cost, thus allowing an optimal solution to be obtained in terms of costs versus benefits.

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