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Improving tunnel resilience against fires: A new methodology based on temperature monitoring

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Monitoring temperatures during tunnel fires is of major importance for both the firefighters extinguishing the fire, and the engineers in charge of the subsequent repair work. However, current methods of assessing fire damage have limitations when applied to tunnels and only provide estimates of the maximum fire temperatures at specific locations of the tunnel. This is not a desirable situation, as the temperature–time curves associated with the fire event should be available for use in assessing the residual strength of the tunnel structure. This is the key parameter in defining repair work and the length of time the tunnel will need to be closed and thus the socio-economic cost of the tunnel fire. In addition, real-time recording of the temperature–time curves would provide valuable information to the firefighters engaged in extinguishing the fire.

This paper presents a new general methodology for the optimal placement of sensors in a tunnel to obtain the temperature evolution at any point along its lining during a fire. The methodology was applied to the Virgolo Tunnel in Italy, in which 100 potential high-temperature sensor configurations were tested and a set of optimal sensor configurations was proposed. The results of the analysis show that: (a) the proper location of the sensors is crucial; (b) it is possible to define a set of sensor configurations that minimize the cost of the monitoring system and maximize the accuracy of the estimated temperatures; (c) it is important to place at least three high-temperature sensors in each monitored cross section (at the crown and symmetrically on the haunches/side walls). The proposed methodology improves tunnel resilience against fires, as it enables safer infrastructure and a faster and more economic recovery of the tunnel after a fire event.

1. Introduction

The fires that broke out in the Mont Blanc tunnel in 1999, in the St. Gotthard tunnel in 2001, the Burnley tunnel in 2007 and the Wuxi Lihu tunnel in 2010 had catastrophic consequences in terms of loss of life and economic costs and aroused public interest in tunnel fire safety. They also gave rise to significant research in the field of tunnel fires (see e.g. Safe Tunnel, 2005; FIT, 2005; NCHRP, 2011; Beard and Carvel, 2012; Lai et al., 2014; Barbato et al., 2014; Ingason et al., 2015) with the aim of reducing fire risk in tunnels.

In the technical field of risk engineering, the term 'risk' is defined as the product of the probability of an event and the expected outcome—typically expressed as damage—of the event (Hardy, 2005). In the case of tunnel fires, adverse outcomes may include loss of life and injuries to victims, direct costs in the form of repairs and indirect costs in the form of loss of toll revenues and the economic impact on the region due to tunnel closure. To reduce fire risks, several prevention and protection measures have been developed to reduce the probability of tunnel fires, to ensure early fire detection and to keep loss of life and damage to a minimum (see Beard and Carvel, 2012). As regards the economic costs, the following aspects need to be considered:

- It is always cheaper to repair a tunnel after a fire than build a new one, since construction times and costs are higher if a new tunnel is built than if the tunnel is repaired (Corsi, 2008).
- Indirect costs due to tunnel closure after a fire are usually much higher than the direct costs associated with repairs (Corsi, 2008). For example, the 1996 fire in the Eurotunnel linking France and the United Kingdom was responsible for €87 million in repair work and €211 million in lost revenue (Peter, 2000).

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Therefore, in order to reduce the cost of tunnel fires it is essential to reduce closure times. This can be achieved through better and faster assessment of damage to the structure, as this assessment specifies the areas in need of repair and the methods to be used. However, assessing fire damage in a tunnel is a challenging task, especially when concrete linings are used, as the assessment involves non-destructive or destructive techniques and estimating the temperature–time curves associated with the fire event to calculate the residual strength of the structure (Corsi, 2008). Yet, the application of non-destructive techniques in tunnels is limited due to the non-verticality of the tunnel walls and the roughness of the tunnel surfaces (Felicetti, 2013). In addition, these methods do not give any information about the intensity and duration of the fire and the temperature–time curves associated with it. These are key parameters in assessing the damage to the tunnel structure and obtaining them can be difficult, as has been reported by several authors (Niels et al., 2008; Calavera et al., 2005; Wang et al., 2014).

Within this context, this paper proposes a new methodology to increase the resilience of tunnels against fires, i.e., to increase the capacity of tunnels to withstand fires with minimum losses and to recuperate a specific tunnel service level as fast as possible (see Bocchini et al., 2014 for a broad discussion on the resilience of civil infrastructure). The proposed methodology combines high-temperature sensors in certain sections of the tunnel with numerical models of different fire events to estimate the temperature–time curves imposed by a fire at any point on the tunnel surface. The methodology can be applied to both new and existing tunnels and provides optimal monitoring solutions, i.e., solutions that provide the maximum information at a minimum cost.

Section 2 of the paper contains a general description of the method, Section 3 validates the method with a case study on the Virgolo Tunnel, and Section 4 details the main conclusions of the research carried out.

2. Methodology

The aim of this paper is to present a monitoring strategy that increases the resilience of tunnels against fires. Defining this monitoring strategy involves: (a) designing the sensor network, i.e. deciding on the sensor layout; (b) defining the data treatment, i.e. the information to be obtained from the raw sensor data; and (c) evaluating the total cost of the system. As there are an infinite number of sensor configurations, the monitoring problem also has infinite solutions, so that the final choice depends on the characteristics of the tunnel under study (geometry, importance, traffic, etc.) and any financial or political constraints. The general procedure for defining monitoring strategy can be divided into the following steps:

1. *Step 1. Data collection*. First of all, all the available data on the tunnel under study should be gathered and analyzed. This should include the tunnel geometry (type of cross section, dimensions, length, etc.), the materials and fire protection used, existing firefighting protocols, ventilation systems and the characteristics of the traffic going through the tunnel.
2. *Step 2. Definition of possible fire scenarios*. Defining fire scenarios involves determining: fire load, characterized by its location in the tunnel, its size and Heat Release Rate (HRR) as a function of time. The HRR is the rate at which heat is generated by fire. If there is no traffic restriction, the nine fire scenarios proposed by Ingason (2006) can be used as the starting point.
3. *Step 3. Numerical modeling of fire scenarios*. Models of the most critical fire scenarios are built using Computational Fluid Dynamics (CFD) techniques. CFDs models can be built with different software packages. In this study we used the Fire Dynamic Simulator software (FDS henceforth) (McGrattan et al., 2010), developed at the National Institute of Standards and Technology (NIST) in the USA. To build a CFD model with FDS we must define: (1) a control volume with its boundary conditions representing the volume for which the entire analysis is carried out; (2) the geometry included in the control volume which represents the geometry of the case study; (3) a mesh or discretization of the control volume; (4) material properties (conductivity, density, specific heat and emissivity); (5) fire sources; (6) a combustion model; and (7) the outputs of the model. FDS can provide several outputs, such as gas temperatures, gas velocity and smoke density. In the monitoring strategy presented in this paper, temperatures are the outputs of the CFD models as they are aimed at providing the evolution of gas temperatures with time for each fire scenario at specific points in the tunnel.
4. *Step 4. Proposal of temperature sensor configurations*. In the proposed monitoring strategy, temperature sensors such as high temperature thermocouples or the high temperature fiber optic sensors developed by Rinaudo et al. (2015a) are located near the internal surface of the tunnel at equidistant cross sections. To define a sensor configuration, the following parameters need to be established: the number N_x of monitored cross sections and their separation n_x, the number N_y of sensors placed at each monitored cross section, and the location of these N_y sensors within each monitored cross section. Fig. 1 shows an example of a sensor configuration in which six cross sections are monitored by five sensors arranged as displayed in Fig. 1c. It should be remembered that sensor layout is a key parameter, since for each number of sensors many different configurations are possible and each one will have a specific performance and cost.
5. *Step 5. Assessment of the performance of each proposed sensor configuration*. For this, it is assumed that CFD models predict accurate values of the temperature–time curves at all points in the tunnel and for each fire scenario considered. The basic assessment procedure has two steps:
   5.1 Calculation of temperatures in a grid of points ("interpolation grid" henceforth) close to the tunnel surface. Using different interpolation techniques, the temperatures in the grid shown in Fig. 1 are obtained for each fire scenario using the temperatures at the sensor locations as input data. To simplify this process, the tunnel surface is unrolled to transform the 3D coordinate system (x, y, z) to a 2-D coordinate system (x, y^*) as shown in Fig. 1b.
   5.2 Definition and evaluation of error indexes and selection of an interpolation technique. For each interpolation technique and fire scenario and every point on the grid, the temperatures obtained by interpolation are compared to those obtained by the CFD models. This comparison provides the values of the error indexes that measure the overall error associated with each interpolation technique. The interpolation technique with the smallest error is then selected as the best technique to estimate fire temperatures.
6. *Step 6. Comparison of error indexes versus cost*. Sensor configurations are compared as regards their precision (error indexes) and cost (measured indirectly through the total number of sensors in the configuration), after which a set of optimal monitoring configurations is proposed. Note that a set of solutions and not a single solution is obtained since a multi-objective evaluation (precision versus cost) is carried out.

The above mentioned steps are explained in detail in Section 3, when the method is applied to the Virgolo Tunnel as a case study.