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ABSTRACT

Methodological approach for the analysis of safety in road tunnels with reference to the thermal effects on the structure

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Abstract

The major risks for users in the event of a tunnel fire derive from the high temperatures generated by the burning vehicle, the smoke that progressively fills the tunnel reducing the visibility for people evacuation, the production of carbon monoxide and toxic substances that, associated with the consumption of oxygen, can cause intoxication and, consequently, loss of consciousness and anoxia. However, in addition to the consequences on human health, the negative effects on the tunnel structure due to high temperatures should also be considered, as well as the direct costs of repairing the damaged structures and the indirect costs associated with the temporary closure of the tunnel and the use of alternative routes.

Directive 2004/54/EC, adopted in Italy in 2006, requires, in addition to a quantitative risk analysis aimed at identifying the risk level for users in the event of a tunnel fire, the assessment of the fire resistance of the tunnel structure in cases where its local collapse might cause catastrophic consequences, such as, for example, to important adjacent structures or immersed tunnels.

Most existing tunnels are made of unreinforced or reinforced concrete, while new tunnels are more especially of reinforced concrete. When concrete structures are subjected to high and rapidly rising temperatures, more or less violent detachments of material can occur. This phenomenon, known as *spalling*, can lead, in the case of reinforced concrete, to the breaking-off of the concrete cover, so that a more or less extensive area of concrete might remain with the steel rebars directly exposed to high temperatures. In these circumstances, since steel has a lower fire resistance than concrete, the steel reinforcements might no longer be able to fulfill their function of absorbing tensile stresses, thus contributing to a structural collapse, even if localized. This, in addition to reducing the safety level for tunnel users not yet evacuated and obstructing rescue teams, might cause the collapse of buildings located above the tunnel vault or water infiltrations.

In the light of the above considerations, in order to reach the optimal fire resistance design of tunnels, it is very important to be able to quantitatively predict spalling. In this respect, the main scope of the present thesis was to develop predictive models, namely an analytical method, capable of evaluating fire-induced damage as a function of both the tunnel geometry and the fire scenario. For this aim, three-dimensional Computational Fluid Dynamics (CFD) modeling was coupled with the statistical approach. In this work, among the different codes available, the Fire Dynamics Simulator (FDS) was used as a CFD simulation tool, while the LIMDEP statistical package was applied as a statistical simulation tool.

The first step in order to set up the analytical method aimed at predicting spalling was to develop, given the lacuna, a new 3D CFD model able to estimate fire-induced damage. Once this model was validated by comparing its results with those provided by a competitive model present in the

international literature, the relevant conclusions were drawn with reference to the case study investigated.

Based on the above-mentioned developed 3D CFD model, the second step to reach the fixed scope was to identify the variables that had the greatest influence on fire-induced damage. For this aim, certain assumptions were made, and several preliminary simulations were carried out. In this respect, the longitudinal ventilation within the tunnel, the heat release rate, the tunnel cross-section area, and the longitudinal slope of the tunnel were found to be the variables with the greatest impact on spalling; as a result, the latter were assumed to be the independent variables of the proposed predictive models. Specifically, these predictive models were univariate Negative Binomial (NB) models with fixed parameters. The dependent variables were the maximum spalling depth, the spalling start time, and the maximum length of the tunnel affected by spalling.

On this basis, certain predictive models were set up. The results showed that the developed analytical method was capable of providing a good to excellent prediction of maximum spalling depth, spalling start time, and maximum length of the tunnel affected by spalling.

Therefore, the author is confident that the proposed predictive models represent an important advancement of knowledge, given the lacuna, in the field of tunnel fire safety engineering. In fact, the results obtainable from these predictive models would be useful not only to the international scientific community but also to both road engineers and Tunnel Management Agencies (TMAs) in order to estimate how fire-induced damage varies with longitudinal ventilation, maximum heat release rate, tunnel cross-section area, and longitudinal slope.

Finally, in order to mitigate fire-induced damage, certain coatings such as cement-based mortars, panels, and an intumescent paint were used. In this respect, the results showed that all investigated coatings were able to prevent spalling, thus reducing the risk of structural collapse. Specifically, based on the criterion of the ratio between thermal performance and application thickness, the best insulation-material used in this study was the intumescent paint.