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Determination of the combined heat transfer coefficient to simulate the fire-induced damage of a concrete tunnel lining under a severe fire condition

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ABSTRACT

To avoid underestimating the severity of damage to tunnel concrete lining under the high-temperature conditions of a fire using thermal analysis, it is important to consider the cross-sectional loss of a concrete lining during heating. This study simulates the structural loss by numerical analysis using an element elimination model and a combined heat transfer coefficient. A series of fire tests was performed with fire curves that differed in the initial temperature gradient and maximum temperature. Values of the optimized combined heat transfer coefficient were obtained from the coincidence of the results of the numerical analysis with experimental data. The results reveal that an increase in both the initial temperature gradient and maximum temperature causes greater damage to the concrete structures and also gives rise to an increase in the combined heat transfer coefficient. Values of the combined heat transfer coefficient can be inferred from values of initial temperature gradient and maximum temperature in the case of structural concrete loss. Two sets of regression equations were derived from the results depending on whether or not a structural loss occurs. The proposed method of thermal analysis outperforms the conventional method in terms of accurately simulating observed results.

1. Introduction

Generally, it is well known that fire damage to tunnels is more serious than damage in the open air due to the effects of ventilation and the difficulties of fighting underground fires. Especially, the heat release rate of fires in tunnels can be four times as high as that of similar fires in the open air (Carvel, 2002).

High temperatures can cause spalling and a reduction in the quality of concrete, thereby lowering the safety of concrete structures. Spalling observed on concrete exposed to fire can be divided into four categories: explosive spalling, surface spalling, aggregate spalling, and corner/sloughing spalling (Boström and Larsen, 2006; Khoury, 2000). Spalling of concrete is a complicated phenomenon due to the effects of high vapor pressure and internal thermal stress. Spalling causes severe damage to concrete structures such as tunnel concrete lining because of the loss of material through a reduction in section size, and because of the exposure of the reinforcing bar to high temperatures.

The deterioration of concrete under high temperatures is promoted by physicochemical changes in the cement paste and aggregate, and by the difference in thermal properties between these materials. Deterioration is also influenced by external environmental variables such as heat level, temperature gradient, loading condition, and moisture content of a concrete material (Khoury, 2000).

Although many studies of spalling and of the deterioration in the mechanical properties of concrete upon heating have been conducted, most have focused on the characteristics of spalling, the variation in thermal and mechanical properties of concrete, and the analysis of structural performance for concrete structures during heating without considering their structural loss (Caner et al., 2005; Dorgarten et al., 2004; Hertz, 2003; Khoury, 2000; Kodur and Phan, 2007; Phan, 1996; Pichler et al., 2006).

The resistance of concrete structures to fire depends on the extent of spalling and on the deterioration of the mechanical properties of concrete (Kodur and Phan, 2007). Common methods for assessing the fire resistance of reinforced concrete members include standard fire resistance tests or empirical calculation methods (ACI, 1997; ASCE, 1999). However, such methods do not effectively reflect the representative features of a real fire such as

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the variations in temperature and loading conditions (Kodur and Dwaikat, 2008). Moreover, although spalling can be accompanied by high-temperature conditions, most heat transfer models do not properly simulate spalling (Khoury et al., 2002). Boström and Larsen (2006) emphasized that the consideration of spalling in a numerical model needs to produce results that reflect reality; more precisely, a conventional numerical model without considering fire-induced structural loss may underestimate the extent of the damage to a concrete structure when spalling occurs. Therefore, the incorporation of spalling in either heat transfer models or coupled thermo-mechanical models is essential if modeled results are to better simulate observed data.

Recently, the element elimination model (EEM) based on finite element modeling has been proposed (Choi et al., 2013; Savov et al., 2005). The EEM differs from other methods by considering spalling in terms of the deactivation of spalled layers following a specified spalling scenario. The model considers the loss of material upon heating by converting finite elements corresponding to spalled area as null. Especially, Choi et al. (2013) proposed the temperature criterion for the elimination of as 600 °C, based on a series of fire experiments and EEM numerical analyses.

The proposed EEM uses a combined heat transfer coefficient as an input parameter to simulating heat transfer from a heat source to the surface of a concrete structure. Therefore, this coefficient is an important indicator of the structural damage induced by fire. Compared with other methods, the EEM is closer to practice in modeling the loss of material and the deterioration of material mechanical properties (Choi et al., 2013).

The present study aims to understand the damage to concrete structures caused by fire, by examining the variation in the combined heat transfer coefficient depending on the characteristics of tunnel fire scenarios; that is, fire severity. Previous studies have shown that the main factors affecting the occurrence of spalling are the initial temperature gradient, the maximum temperature, the permeability of the affected material, the external load, and the moisture content of a concrete material (Buchanan, 2002; Hertz, 2003; Khoury, 2000; Kodur, 2000; Kodur and Phan, 2007; Peng, 2000; Phan, 1996). The present study considers only the characteristics of a tunnel fire scenario, such as the initial temperature gradient and maximum temperature, as the main drivers of spalling occurrence, and controls for material and environment factors such as permeability, loading conditions, and moisture content. Fire tests under different initial temperature gradients and maximum temperatures were also performed for similar concrete moisture contents. Values of the optimized combined heat transfer coefficient for tunnel fire scenarios were derived by comparing the EEM numerical results with observed data obtained from fire test experiments.

2. Numerical model

2.1. Main features of the adopted numerical model

The three types of heat transfer include conduction, convection, and radiation. They can occur individually or as combined heat transfer processes within or between material bodies (Buchanan, 2002). When fire occurs in a tunnel, the first mechanisms of heat transfer from the heat source to a tunnel concrete lining are convection and radiation. Afterwards, the temperature near the tunnel concrete lining increases and conduction takes place from the surface of the concrete lining towards the interior of the concrete. In the case where solid material is exposed to the flow of a fluid such as heated air, convection and radiation between the surface of the material and the air occur simultaneously. Therefore, heat transfer by conduction needs to also consider both convective and radiant heat transfer (Çengel, 2004). The combined heat transfer coefficient in this study includes the effects of both convective and radiation heat transfer.

This study uses the EEM proposed by Choi et al. (2013). The model was developed by those authors to simulate the structural loss of concrete structures upon heating, by eliminating elements in which the maximum temperature exceeded a specified critical temperature. In this study, the finite element analysis procedure with the EEM was implemented in “VisualFEA/Geo”, which is a commercial software program for finite element analysis (Intuition Software, 2001). The criterion to eliminate fully damaged or spalled finite elements can be either a thermo-mechanical failure criterion or a methodology of applying a critical temperature criterion. The thermo-mechanical failure criterion has the advantage of presenting a theoretical explanation for the damage to structural members upon heating. However, it is difficult to describe the numerical formulation and to acquire the related input parameters for the thermo-mechanical failure criterion. In contrast, the methodology of defining a critical temperature is much easier to present the numerical formulation than the thermo-mechanical failure criterion but it may be difficult to define the reasonable critical temperature to set up the procedure of element elimination.

The heat transfer equation in the model proposed by Choi et al. (2013) is presented as Eq. (1), which expresses one-dimensional heat transfer including convection (Logan, 1992):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial T}{\partial x}\right)+Q=\rho c\frac{\partial T}{\partial t}+\frac{hP}{A}(T-T_{\infty}) \tag{1}$$

where K_{xx} is the thermal conductivity in the x-direction, $\frac{\partial T}{\partial x}$ is the temperature gradient, c is the specific heat, ρ is the density, P is the perimeter enclosing the area A of a section, h is the convective heat transfer coefficient, T is the temperature of the contact surface between solid and fluid, and T_{∞} is the fluid temperature.

This model was originally developed for thermo-mechanical coupling analyses. However, the present study considers only the thermal behavior of a concrete structure depending on an initial temperature gradient and the maximum temperature during a tunnel fire. The procedure used in this study for the numerical analysis of thermal behavior using an EEM is presented in Fig. 1.

2.2. Modeling conditions

Choi et al. (2013) used critical temperature, element size, and the combined heat transfer coefficient as variables in their EEM. They performed parametric studies through comparing the results of a series of fire tests with those of numerical analyses using an EEM. Those authors reported that numerical analysis using element elimination is optimized when the element size is 2.5 cm and the critical temperature is 600 °C.

The present study determines values of the combined heat transfer coefficient using temperature–time histories from the numerical analysis that most closely matched fire-test experimental data under the above-specified conditions of element size and critical temperature. The fire tests from which the experimental data were obtained were conducted under several different tunnel fire characteristics. The parameters used in the study are summarized in Table 1.

3. Fire tests

3.1. Fire curves

A series of fire tests was performed to investigate the depth and range of fire damage resulting from different values of initial tem-