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Thermal performance of composite slabs with profiled steel decking exposed to fire effects

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ABSTRACT

This paper presents a systematic investigation of the influence of various parameters on the thermal performance of composite floor slabs with profiled steel decking exposed to fire effects. The investigation uses a detailed finite-element modeling approach that represents the concrete slab with solid elements and the steel decking with shell elements. After validating the modeling approach against experimental data, a parametric study is conducted to investigate the influence of thermal boundary conditions, thermal properties of concrete, and slab geometry on the temperature distribution within composite slabs. The results show that the fire resistance of composite slabs, according to the thermal insulation criterion, is generally governed by the maximum temperature occurring at the unexposed surface of the slab, rather than the average temperature. The emissivity of steel has a significant influence on the temperature distribution in composite slabs. A new temperature-dependent emissivity is proposed for the steel decking to give a better prediction of temperatures in the slab. The moisture content of the concrete has a significant influence on the temperature distribution, with an increment of 1% in moisture content leading to an increase in the fire resistance of about 5 min. The height of the upper continuous portion of the slab is found to be the key geometrical factor influencing heat transfer through the slab, particularly for the thin portion of the slab. Heat transfer through the thick portion of the slab is also significantly affected by the height of the rib and the width at the top of the rib.

1. Introduction

The use of composite slabs in buildings has been common in North America for many years and has experienced a rapid increase in Europe since the 1980s. Typical construction of composite floors consists of a lightweight concrete slab cast over a profiled steel decking, as illustrated in Fig. 1. The concrete slab typically has welded wire mesh reinforcement to control cracking and may contain individual reinforcing bars, commonly placed within the ribs. Some advantages of composite slabs over conventional flat slabs include requiring less concrete as a result of a low center of reinforcement, and reducing construction time since the decking serves as permanent formwork. The presence of the ribs creates an orthotropic profile, which results in thermal and structural responses that are more complex than those for flat slabs, presenting challenges in numerical analysis and practical design for fire effects.

With regard to the thermal insulation provided by the slab, the temperature at the unexposed top surface is of particular importance, because fire resistance according to the insulation criterion is based on the time required for the unexposed surface temperature to rise by a specified amount [1]. With regard to the load-bearing capacity of the slab, which governs the fire resistance according to the stability criterion [1], the entire through-depth temperature profile of the slab is important, including the temperature of the steel decking and the reinforcement. Reductions in the structural resistance of the slab result from thermally induced degradation in the strength and stiffness of the concrete, the decking, and the reinforcement.

Challenges in numerical analysis of heat transfer in composite slabs include appropriate modeling of the thermal boundary conditions on the fire-exposed surfaces and proper modeling of heat transfer at the interface between the concrete slab and the steel decking. Previous studies have generally used a detailed finite-element modeling approach, with solid elements for the concrete slab and shell elements for the steel decking. Researchers from the Netherlands Organisation for Applied Scientific Research (TNO) developed 2D and 3D thermal models of fire-exposed composite slabs in which an artificial void was introduced to model the radiation heat exchange between the fire environment and the steel decking [2–4]. The artificial void was bounded by an additional artificial surface where the ISO 834 [5] standard fire curve was specified.

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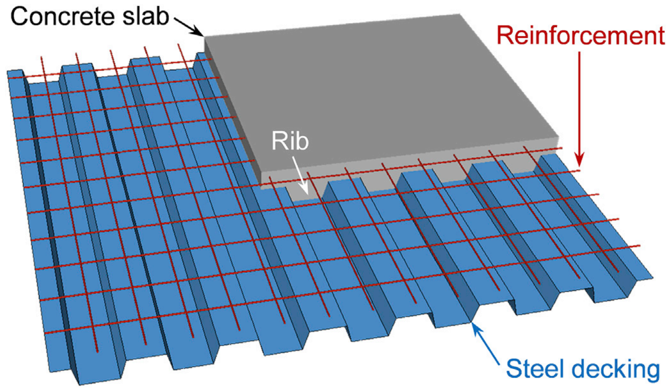

Fig. 1. Typical layout of a composite slab.

This method avoided the introduction of empirical view factors [6,7] introduced interface elements to model heat transfer between the steel deck and the concrete slab in finite-element thermal analyses of composite slabs. The model of this interface was simplified [8] in thermo-mechanical analysis of composite slabs by sharing nodes between the shell elements, representing the steel decking, and the solid elements, representing the adjacent concrete, assuming continuity of temperature at their interface.

Most of the previous studies of composite slabs in fire have focused on the structural response, with thermal analysis of the slab being used to provide input for the structural model. Few studies have systematically investigated the temperature distribution in composite slabs and its sensitivity to various parameters. Both [3] conducted parametric studies by varying the geometry of slabs using 2D thermal models, and the results were used to propose approximate closed-form expressions for the fire resistance based on the thermal insulation criterion, the temperature of reinforcement and decking, and the isotherms in composite slabs. These closed-form approximations are incorporated in Annex D of Eurocode 4 [9], hereafter referred to as EC4. However, as is discussed later in this paper, the range of slab geometries considered by Both [3] does not encompass the dimensions of many composite slabs used in current practice. Lamont et al. [10] conducted parametric studies to investigate the factors that most influence the temperature distribution in composite slabs. The results showed that the key factors were the conductivity of concrete, the moisture content of concrete, and the convective heat transfer coefficient at the fire-exposed surface. However, no steel decking was considered in the thermal model, and thus some key effects of the decking were not considered, including the temperature-dependent emissivity of the galvanized steel decking that results from melting of a zinc coating, as discussed later in this paper.

The focus of this study is to validate a detailed finite-element modeling approach for heat transfer analysis of composite slabs against experimental measurements available in the literature, and to conduct a parametric study using the validated model to systematically investigate the influence of various parameters on the thermal performance of composite slabs. The parametric study presented herein considers a broader range of parameters than those used by Both [3], to encompass the geometry of composite slabs used in current practice. A key motivation for the detailed modeling presented in this study was the development of a reduced-order modeling approach presented by Jiang et al. [11], in which alternating strips of layered composite shell elements were used to represent the thick and thin portions of the composite slab. The reduced-order modeling approach allows engineers to efficiently analyze and evaluate large structural systems exposed to fires, thus facilitating the investigation of three-dimensional effects associated with localized and traveling fires. Calibration and verification of the reduced-order modeling approach required a validated detailed modeling approach that was capable of capturing the influence of various thermal and geometric parameters on heat transfer in composite slabs. The detailed modeling approach in this study used solid elements for the concrete slab and shell elements for the steel decking, with shared nodes at their interface [8]. After validating the detailed finite-element modeling approach against experimental data, detailed models were used to conduct a parametric study by varying the thermal boundary conditions, thermal properties of concrete, and geometric parameters of composite slabs to investigate the influence of these parameters on the thermal performance of composite slabs.

2. Heat transfer analysis

2.1. Heat equation and boundary conditions

Heat can be transferred by three methods: conduction, convection, and radiation. Conduction is the transfer and distribution of heat energy from atom to atom within a substance. Convection is the transfer of heat by the movement of medium (i.e., advection and/or diffusion of a gas or liquid). Radiation is the transfer of heat via electromagnetic waves. The heat conduction balance in a solid structural member under fire conditions is given by the heat equation (e.g. [12]),:

$$\lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2} + \lambda_z \frac{\partial^2 T}{\partial z^2} = \rho c \frac{\partial T}{\partial t} \tag{1}$$

where λ_x, λ_y, and λ_z are the thermal conductivities of the material in the x, y, z, directions, respectively; T is the temperature; t is time; ρ is the density of the material; and c is the specific heat of the material.

To solve Eq. (1), heat transfer boundary conditions (i.e., convection and radiation heat fluxes) should be provided on the surface between the structural member or fireproofing and gas environment. The boundary conditions can be written as:

$$-\lambda_n \frac{\partial T}{\partial n} = \dot{q}''_c + \dot{q}''_r = h_c\left(T_s - T_g\right) + \sigma \varepsilon_r \Phi\left(T_s^4 - T_g^4\right) \tag{2}$$

where n is a coordinate in the direction of the surface normal; $\dot{q}''_c$ is the heat flux per area from convection, W/m^2; $\dot{q}''_r$ is the heat flux per area from radiation, W/m^2; T_g is the temperature of the gas adjacent to the surface, K; T_s is the surface temperature, K; h_c is the convective heat transfer coefficient, W/(m^2·K); ε_r is the resultant emissivity, defined as $\varepsilon_r = \varepsilon_f \times \varepsilon_s$, where ε_f is the emissivity of fire, usually taken as equal to 1.0, and ε_s is the emissivity of the surface material; $\sigma = 5.67 \times 10^{-8}$ W/(m^2·K^4) is the Stefan-Boltzmann constant; and Φ is the view factor or configuration factor, which is explained in the next section.

2.2. View factor

The view factor Φ in Eq. (2) quantifies the geometric relationship between the surface emitting radiation and the surface receiving radiation. The view factor depends on the areas and orientations of the surfaces, as well as the gap between them. For composite slabs subjected to standard fires or post-flashover conditions, the view factor of the lower flange of steel decking is generally taken as unity, $\Phi_{low} = 1.0$. The view factors for the web and upper flange of steel decking are less than unity due to obstruction from the ribs. The latter can be calculated following the Hottel's crossed-string method [13], as illustrated in Fig. 2, which is also the approach adopted by EC4. Resulting expressions for the view factors of the upper flange and the web of the steel decking, denoted Φ_{up} and Φ_{web}, respectively, are presented in Eqs. (3a) and (3b), where the geometric parameters h_1, h_2, l_1, l_2, and l_3 are illustrated in Fig. 2.

$$\Phi_{up} = \frac{ad + cb - ab - cd}{2ab} = \frac{\sqrt{h_2^2 + \left(l_3 + \frac{l_1 - l_2}{2}\right)^2} - \sqrt{h_2^2 + \left(\frac{l_1 - l_2}{2}\right)^2}}{l_3} \tag{3a}$$