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Identification of the thermal properties of concrete for the temperature calculation of concrete slabs and columns subjected to a standard fire—Methodology and proposal for simplified formulations

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ABSTRACT

The fire resistance of concrete members is controlled by the temperature distribution of the considered cross section. The thermal analysis can be performed with the advanced temperature dependent physical properties provided by EN 1992-1-2. But the recalculation of laboratory tests on columns from TU Braunschweig shows, that there are deviations between the calculated and measured temperatures. Therefore it can be assumed, that the mathematical formulation of these thermal properties could be improved. A sensitivity analysis is performed to identify the governing parameters of the temperature calculation and a nonlinear optimization method is used to enhance the formulation of the thermal properties. The proposed simplified properties are partly validated by the recalculation of measured temperatures of concrete columns. These first results show, that the scatter of the differences from the calculated to the measured temperatures can be reduced by the proposed simple model for the thermal analysis of concrete.

1. Introduction

The fire resistance of reinforced concrete cross sections is mainly determined by the temperature dependent material properties. Therefore the accuracy of the calculated temperatures is crucial for the mechanical analysis of the considered member. Achenbach and Morgenthal perform a global sensitivity analysis of fire exposed reinforced concrete walls and columns [1,2]. The results indicate, that the uncertainty of the thermal analysis contributes the biggest part to the scatter of the results for concrete compression members subjected to a standard fire.

The recalculation of measured temperatures of concrete columns using the material properties of EN 1992-1-2 [3] reveals, that the temperatures at the surface are overestimated by calculation, while the calculated temperatures at the center are lower compared to the measured results [1]. The mean ratio of the calculated to the measured temperatures $\eta_t = \theta_{cal}/\theta_{exp}$ [-] is $\mu = 0.9$ with a standard deviation of $\sigma = 0.3$ for the examined laboratory tests.

The results of the recalculation of measured temperatures indicate, that the parameters of the thermal analysis could be improved to increase the accuracy of the results. The optimization of the formulation of the thermal properties of concrete for concrete slabs and columns heated by a standard fire is described in this paper. In Section 2, the physical model of the thermal analysis and the involved parameters are described. The identification of the most influential parameters – which are used for optimization – is performed in Section 3. The applied methods for the nonlinear optimization and the results are discussed in Section 4. The proposed simplified thermal properties are partly validated by the recalculation of laboratory tests on columns in Section 5.

2. State of knowledge

The temperature distribution in a concrete wall, heated on both surfaces as displayed in Fig. 1, is controlled by the differential equation [4]

$$\frac{\partial T(x,t)}{\partial t} = \frac{\lambda}{\rho \cdot c_p} \cdot \frac{\partial^2 T(x,t)}{\partial x^2}, \tag{1}$$

with λ= thermal conductivity [W/m K], ρ= density [kg/m^3] and c_p= specific heat [J/kg K]. The boundary conditions at the surface are described by the heat flux q [W/m^2]. With the surface temperature of the wall T_w [K] and the temperature of the heated gas T_g [K] these conditions are

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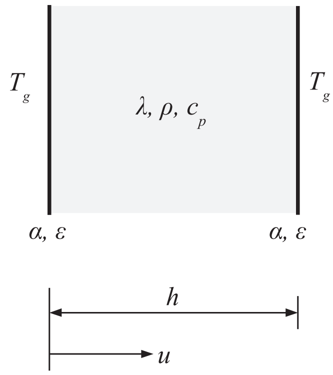

Fig. 1. Concrete wall, heated on both surfaces.

$$q = -\lambda\cdot\frac{\partial T_w}{\partial x} \quad (2)$$

for conduction and

$$q = \alpha\cdot(T_g - T_w) + \varepsilon\cdot\sigma\cdot(T_g^4 - T_w^4) \quad (3)$$

for convection and radiation, with α= coefficient of heat transfer [W/m^2 K], ε= emissivity [-] and σ= Stephan-Boltzmann constant [W/m^2 K^4]. The physical properties λ, ρ and c_p are temperature dependent and the above mentioned equations can only be solved in that case with numerical methods with the initial condition $T_g = T_w = T(x, t = 0) = (20 + 273.15)$ K.

The heat transfer from the heated gas to the concrete surface is mainly determined by radiation [5]. The corresponding parameter ε contains the emissivity of the flame and the surface [5,6] and is temperature dependent. The proposed constant value $\varepsilon = 0.7$ [-] for concrete members according to EN 1992-1-2 [3] is a simplification and derived from the recalculation of laboratory tests [6]. The coefficient of heat transfer α is dependent from the velocity of the heated gas at the surface [5] and describes the heat flux due to convection. The recommended constant values [7] – $\alpha = 25$ [W/m^2 K] for fire exposed and 4 [W/m^2 K] for unexposed surfaces – are also a simple approach.

The physical properties λ, ρ and c_p – determined by different scientists – show a remarkable scatter, which is caused by different experimental methods [8,9]. The heat transfer in the concrete wall is described by the thermal diffusivity $a = \lambda/(\rho\cdot c_p)$, which means that all variables are put together and the scatter of the different physical properties can be "equalized". This can also be seen in the published values for a [8,9].

The temperature dependent functions for the physical properties λ, ρ and c_p given in EN 1992-1-2 [3], must be understood as a compromise among the involved specialists [10]. The lower limit for λ has been derived from the recalculation of concrete members [10], while composite members have been used for fitting the upper limit [11].

3. Sensitivity analysis

3.1. Applied methods

A Monte Carlo simulation [12] of a concrete wall, heated on both sides by a standard fire according to EN 1991-1-2 [7], is set up. The wall is displayed in Fig. 1 and the parameters are given in Table 1. In lack of more detailed statistic key data for the thermal properties, each stochastic variable is assumed to be normally distributed with the nominal value as mean value μ and a coefficient of variation $v = \sigma/\mu = 0.1$ (Table 2). The symmetric normal distribution has been chosen to avoid any preferences, which may be caused by the choice of an asymmetric distribution, e. g. a log-normal distribution. It is also assumed, that there is no correlation between the variables. The temperature dependent physical properties and the gas temperature θ_g are multiplied by X_i, which is also normally distributed with $\mu = 1.0$ and v=0.1. One X_i is generated for each variable. The uncertainty of the physical model, described in Section 2, is modeled by the variable X_t and contains all uncertainties, which are not covered by the scatter of the other variables. These uncertainties are for instance: the radiation conditions in the testing furnace, the error in temperature measurement of the thermocouples and the possible incompleteness of the mathematical model. It is assumed, that these uncertainties can be described by normally distributed ($\mu = 1.0$ and v=0.1), multiplicative variable X_t. The calculated temperatures are multiplied by X_t to consider these model uncertainties.

Table 1
Parameters of the sensitivity analysis.

parameter	unit	value
height: h	[cm]	10
fire duration: t_f	[min]	30
heat transfer coefficient: α	[W/m^2 K]	25
emissivity: ε	[-]	0.7
density: ρ(20 °C)	[kg/m^3]	2400
moisture content: u	[%]	1.5
thermal conductivity: λ	[W/m K]	lower limit

Table 2
Basic variables of simulated walls (DET=deterministic, N=normal distribution).

variable	distribution	description
h	DET	Table 1
θ_g	N	EN 1991–1–2, standard fire
ε	N	Table 1
α	N	Table 1
λ	N	Table 1
ρ	N	Table 1
c_p	N	EN 1992–1–2, u acc.Table 1
X_t	N	model uncertainty

A number of 5000 samples is generated and the temperature distributions for $t_f = 30$ min are calculated. The results for a distance to the surface u=0, 2.5 and 5.0 cm are evaluated in the sensitivity analysis. Spearman's rank correlation coefficients [13] and first order Sobol [14] indices are used for the assessment of the sensitivities of the results against the stochastic variables.

The Spearman rank correlation coefficient r_{Si} is a measure for the correlation between the values oft the considered variable X_i and the results Y [13]. Values $|r_{Si}| \approx 0$ indicate, that there is no correlation between the values of the considered variables. Results $|r_{Si}| = 1$ show, that there is a full linear or nonlinear monotonic correlation – all other values need interpretation. Values of $r_{Si} \geqq 0$ show, that increasing values for X_i lead to increasing values for Y (positive correlation).

The first order Sobol indices are a variance based measure for the sensitivity. They are based on the assumption, that a completely unknown function y can be described by a function $f(x)$ with terms of increasing dimensionality [15]:

$$f(x) = f_0 + \sum_i f_i(x_i) + \sum_{i<j} f_{ij}(x_i, x_j) + \cdots + f_{12\ldots n}. \quad (4)$$

The variance of each term is $V_i = V(f_i(x_i))$, $V_{ij} = V\left(f_{ij}(x_i, x_j)\right)$, … and it can be concluded that the total variance is described by

$$V = \sum_i V_i + \sum_{i<j} V_{ij} + \cdots + V_{12\ldots n}. \quad (5)$$

The ratio

$$S_i = \frac{V_i}{V} \quad (6)$$

is the so called first order Sobol index and is a measure for the contribution of the variance of one single variable to the total variance