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Sensitivity analysis of heat transfer formulations for insulated structural steel components

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Abstract

The aim of using fire protection in a building is to reduce the rate of temperature rise of its structural components in case of fire. For protected structural steel, the thermal properties of the insulation materials affect the rate of temperature rise and are crucial in determining the minimum requirements for fire safety for both the steel and the insulation materials. The determination of the required thickness of the insulation materials can be performed by means of test results, analytical solutions or numerical methods. The current Eurocode 3 provides simple analytical solutions for estimating the temperature rise of both protected and unprotected structural steel in a fire. This paper presents a sensitivity analysis to examine the appropriateness of using these analytical solutions for structural steel components protected with insulation materials of contrasting properties including thermal conductivity and density. Results of the analysis show that, for certain types of insulation materials, the temperatures predicted by the Eurocode may differ substantially from those by exact analytical solution. An alternative formulation is presented when these types of insulation materials are used for fire protection of structural steel.

Keywords: Fire engineering; fire protection; heat transfer; insulation; steel structures; thermal conductivity

1. Introduction

Current building codes in many countries stipulate fire-rating requirements for which the failure temperature profile of a structure needs to be assessed by, for

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Nomenclature

A_m/V	section factor = perimeter/cross-sectional area (m^{-1})
c_p	specific heat of insulation (kJ/kg °C)
c_s	specific heat of steel (kJ/kg °C)
d	insulation thickness (mm)
h_c	convective heat transfer coefficient
k_e	thermal conductivity of insulation (W/m °C)
$\dot{q}_{net,d}$	design heat flux (W/m^2)
$\dot{q}_c$	heat flux due to convection (W/m^2)
$\dot{q}_r$	heat flux due to radiation (W/m^2)
T	temperature (°C)
T_e	surface temperature of steel (°C)
T_g	gas temperature (°C)

Greek letters

α_g	total gas absorptivity
Δt	time increment (min)
ΔT_g	increase in gas temperature (°C)
ΔT_s	increase in steel temperature (°C)
ε_f	emissivity of fire
ε_g	total gas emissivity
ε_{res}	resultant emissivity
ε_s	emissivity of steel
γ_c	partial factor for convective heat flux
γ_r	partial factor for radiative heat flux
ρ_p	density of insulation (kg/m^3)
ρ_s	density of steel (kg/m^3)
σ	5.67×10^{-8} ($W/m^2\ K^4$)

example, elastic or plastic frame analysis [1]. For design purposes, the failure temperature profile has to be checked against the temperatures attained by the structural components with or without fire protection in a fire. In most cases, particularly in multi-storey steel-framed buildings, fire protection is needed for steel members of reasonable size. The choice of the insulation materials, such as gypsum boards and sprayed mineral fibre, is often up to the design engineer. The insulation material usually has low density and low thermal conductivity so that the resulting thickness of the insulation can be minimised. However, for aesthetic and practical reasons, the use of fire protection for steel members as insulation materials with high density and high thermal conductivity, such as brick and concrete, is not uncommon. A form of fire protection for steel column by concrete encasement has been a subject of investigation [2] and semi-empirical formula for the calculation of its fire resistance has been developed.