Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Engineering Structures 27 (2005) 2036–2043
ENGINEERING STRUCTURES
www.elsevier.com/locate/engstruct

Determination of the steel fire protection material thickness by an analytical process—a simple derivation

Valdir Pignatta e Silva*

Department of Structural Engineering and Foundations, Polytechnic School of the University of Sao Paulo (EPUSP), Sao Paulo, Brazil

Received 19 January 2005; received in revised form 19 March 2005; accepted 17 May 2005
Available online 19 August 2005

Abstract

Structural fire safety is assured if the design value of the effect of the actions (thermal and mechanical) is lower than the design value of each structural element fire resistance or, in other words, structural safety is assured when the steel temperature in a fire situation only reaches values less than the structure critical temperature. The critical temperature is the temperature that causes structural collapse in a fire situation. The temperature in the structural element can be determined either experimentally or analytically. In the case of a structure covered with thermally protective material, such methods serve, in practice, to determine the thickness of the protective material. In this work, a previously unpublished expression for the calculation of the temperature in thermally protected steel structural elements in fire is derived. Comparisons with international recommendations and with experimental and numerical analysis results are made. In view of its simple form and derivation, the use of such expression is recommended for the revision of the Brazilian Standard "Steel structures fire design".

Keywords: Steel structures; Fire protection; Steel fire safety design

1. Introduction

Thermal action is the action on the structure by means of convective and radiant heat flux, due to the difference between the temperatures of the hot gases from the fire environment and the structure components. The exposure of a structural material, such as steel, to high temperature reduces its strength and rigidity and may lead to structural collapse, when the critical temperature is reached. The true critical temperature could be determined by tests for each structural element, but this is not economically feasible. Usually, one fixes an arbitrary and conservative conventional value of the critical temperature. A more accurate value, based on recommendations set by technical standards or codes, still conservative in relation to the true critical temperature, can be estimated.

The safety conditions for a building structure in a fire situation are fulfilled when the temperature of the structural elements during a fire remains less than their critical temperature. The temperature of the structural element can be determined either experimentally or analytically.

In the case of structures lined with thermally protective materials, such methods are actually used to determine the thickness of the protective materials. In fact, there is neither a solely experimental nor a purely theoretical method. The so-called experimental methods are based on simplified assumptions (for instance, they use a fire hot gas time–temperature curve that is known to be hypothetical) and depend on the strict calibration of heating furnaces that is, sometimes, gauged from theoretical results. The so-called analytical methods, in turn, depend on experimental checking of the parameters (thermal conductivity, specific heat) that are considered. In this work, analytical methods will be used to determine the temperature of steel structure elements. One of them will be derived. In view of its simple

* Tel.: +55 11 3091 5562; fax: +55 11 3091 5181.
E-mail address: valpigss@usp.br.

0141-0296/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engstruct.2005.05.018

Nomenclature

A_a	steel element exposed surface area (m^2)
A_m	protective material exposed surface area (m^2)
F	section factor, the ratio between the exposed surface area and the volume of the steel (m^{-1})
$\dot{Q}_{\mathrm{abs},a}$	heat absorbed by the steel element (W)
$\dot{Q}_{\mathrm{abs},m}$	heat absorbed by the thermally protective material (W)
$\dot{Q}_c$	convective heat flux (W)
$\dot{Q}_k$	heat flux by conduction (W)
$\dot{Q}_r$	radiant heat flux (W)
V	volume of steel (m^3)
c_a	steel specific heat (J/kg °C)
c_m	thermally protective material specific heat (J/kg °C)
$\dot{h} = \dot{h}_c + \dot{h}_r$	heat flux (convective and radiant) to unity surface area (W/m^2)
$\dot{h}_c$	convective heat flux to unity surface area (W/m^2)
$\dot{h}_r$	radiant heat flux to unity surface area (W/m^2)
t	time
t_m	thermally protective material thickness
$\alpha = \alpha_c + \alpha_r$	coefficient of heat (convective and radiant) transfer (W/m^2 °C)
α_c	coefficient of heat transfer by convection (W/m^2 °C)
α_r	coefficient of heat transfer by radiation (W/m^2 °C)
ϕ	$\frac{\rho_m c_m}{\rho_a c_a} d_m F$
λ_m	protective material thermal conductivity (W/m °C)
θ	temperature (°C)
θ_a	steel temperature (°C)
θ_{cr}	critical temperature (°C)
θ_e	temperature on the external surface of the thermally protective material (°C)
θ_g	hot gas temperature (°C)
θ_m	temperature at the middle of the thermally protective material (°C)
θ_o	room temperature (°C)
$\Delta\theta_a$	variation of the steel temperature
ρ_a	steel density (kg/m^3)
ρ_m	thermally protective material density (kg/m^3)

form and derivation it is recommended for the revision of the Brazilian Standard NBR 14323 [1,2].

2. Unprotected structure

The temperature on non-thermally protected steel structures exposed to a fire can be evaluated with Eq. (1):

$$\Delta\theta_a = \frac{F}{c_a \rho_a}\dot{h}\Delta t. \tag{1}$$

One derivation of Eq. (1) is presented in Silva [3] using the following assumptions:

- The structural element is completely immersed in the flame environment. Structures belonging to the sealing elements of the compartment which is in flames as well as the building's external structures, although subjected to flames, will reach lower temperatures than the ones calculated from Eq. (1).
- Unidimensional analysis and, therefore, uniform temperature distribution in the section and along the structural element are considered. This assumption holds good for sections composed of thin walls and errs on the safe side for robust sections.
- Unidimensional heat flux.

3. Thermally protected structure

In the temperature evaluation for a structural element lined with thermal protection, one must consider the thermal equilibrium involving: heat emitted by hot gases, heat absorbed by the lining material and heat absorbed by the structural element. The heat is transferred through the protective material by conduction. Conduction is the process by which the heat flows from one high temperature area to another of lower temperature, in the same body. The differential Eq. (2), which governs the phenomenon of heat transfer by conduction in the steady state (temperature