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A simplified approach for predicting temperatures in fire exposed steel members

M.M.S Dwaikat [a], V.K.R. Kodur [b,*]

[a] Research Associate, Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI, United States
[b] Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI., United States

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ABSTRACT

For evaluating fire resistance of steel structural members, temperatures in the cross section of the member are required. In this paper, a simplified approach for evaluating cross sectional temperature in contour protected steel members exposed to fire is presented. The approach is derived utilizing simplifying assumptions to the general heat transfer equation for standard fire and is then extended for application under design fire scenarios. The proposed approach is applicable for both protected and unprotected steel sections. The validity of the approach is established by comparing predicted temperatures with those obtained from finite element analysis generated via ANSYS. In addition, predictions from the proposed method are also compared with the temperatures predicted by "best-fit" method. The comparisons to test data, finite element results and best-fit method indicate that the proposed simplified method gives good predictions of fire induced thermal gradient and temperature history in steel sections under any fire exposure. The simplicity of the proposed method makes it attractive for use in design situations.

1. Introduction

For evaluating fire resistance of a steel structural member an accurate assessment of cross sectional temperatures is required. Any discrepancy in cross sectional temperatures could lead to an incorrect sectional size of the structural member or an increase/decrease in the thickness of the required fire protection levels [1–3]. Therefore, proper evaluation of steel temperature as a function of fire exposure time is the most important step in structural fire engineering, which focuses at assessing the performance of structural members under fire conditions [1].

In fire resistance calculations, the development of temperature profile in a steel section as a function of time is referred to as thermal analysis and is generally carried out using complex numerical models that are based on either finite element or finite difference methods [1]. These approaches, though provide accurate results, may not be attractive or practical because detailed numerical modeling of thermal analysis is quite complex, requires trained skills and large number of input parameters, such as temperature-dependent thermal properties and boundary conditions. Also, results from such numerical analysis are generally sensitive to numerical parameters needed for the solver subroutines, such as time increment and element mesh size [1,2]

Other simpler methods for calculating steel temperature include "spreadsheet method" that is based on one-dimensional finite difference techniques, and "best-fit method" that is based on statistical regression [1]. While the accuracy of spread sheet method is dependent on the selected time increment, the accuracy of the best-fit method is bounded within the range 400–600 °C. The limitations can be ascribed to the fact that the spreadsheet method is a simplified one-dimensional finite difference incremental solution. Also, the best-fit method, for instance, was derived for calculating average steel temperature in proximity to the critical temperature of steel, which corresponds to 50% strength loss (yield strength) in steel. Thus, the temperature predicted by best-fit method may not be reliable at temperatures beyond roughly $\pm 25\%$ of critical temperature of steel which is 538 °C [1]. In addition, the best-fit method is applicable for standard fire exposures only and cannot be used for design fire exposures.

Therefore, there is a need for a simple yet sufficiently reliable approach for evaluating temperatures in a steel cross section. Such simple method can facilitate reliable assessment of cross-sectional steel temperature without the need for using complex algorithms that are sensitive to various input parameters.

2. Heat transfer equation

2.1. Governing equations

The governing partial differential equation for heat transfer within the cross section of a structural member (beam, column, etc) can be

* Corresponding author. Tel.: +1 517 353 9813.
E-mail address: kodur@egr.msu.edu (V.K.R. Kodur).

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Nomenclature

a, n	regression coefficients for fitting growth phase of fire scenarios
A_s	cross sectional area of the section (or the steel plate)
c_s, c_p	specific heat of steel and insulation, respectively.
F_1, F_2	expressions resulting from simplifying heat equation
F_p	heated perimeter of the cross section (or the steel plate)
h_{con}	convective heat flux
h_{rad}	radiative heat flux
k	thermal conductivity
m	constant used for averaging temperature of insulation layer around steel section
q_b	total heat flux on the boundary
r	decay rate of design fires according to Eurocode parametric fires.
s	coefficient used for computing steel temperature in the proposed approach
t	time
T, T_s	temperature of steel
t_1, t_2	times corresponding to maximum fire temperature and end of decay phase of design fires, respectively.
T_f	temperature of fire
$T_{f,max}$	maximum temperature of design fire scenario
t_p	insulation thickness
$T_{s,1}$	steel temperature at the time of maximum fire temperature (proposed approach)
$T_{s,max}$	the maximum average temperature attained in steel under design fire.
$t_{s,max}$	time at which steel temperature is maximum under design fire exposure.
α, β, γ	regression coefficients for describing steel temperature in the cooling phase of fire
Δs, ΔT_s	the error in computing s and T_s, respectively
δ_s	$=\Delta s/s$; the relative error in s $\nabla=(\partial/\partial x)+(\partial/\partial y)$
Γ	parameter determining the severity of fire temperature in growth phase of parametric fires as specified in Eurocode 1.
ε	effective surface emissivity
ρ_s, ρ_p	density of steel and insulation, respectively.
Σ	stefan–Boltzmann constant

written as [2]:

$$\rho c \frac{dT}{dt} = \nabla \times (k \nabla T) \tag{1}$$

where k=conductivity matrix, ρc=heat capacity, T=temperature, t=time, and ∇= is the spatial gradient operator.

At the fire-member (e.g., beam) interface, heat is transferred through radiation and convection. The heat flux on the boundary due to convection and radiation can be given by the following equation:

$$q_b = (h_{con} + h_{rad})(T + T_f) \tag{2}$$

where h_{rad} and h_{con} are the radiative and convective heat transfer coefficients, and are defined as:

$$h_{rad} = \sigma \varepsilon \left(T^2 + T_f^2\right)(T + T_f) \tag{3}$$

T_f=temperature of the atmosphere surrounding the boundary (in this case it is the fire temperature), σ=Stefan–Boltzmann constant=5.67×10^{-8} W/(m^2 °K^4), and ε=emissivity factor and it is related to the "visibility" of the surface to the fire.

The heat flux and temperature gradient are related through Fourier's Law of conduction:

$$q = -k \nabla T \tag{4}$$

Using Fourier's Law, the governing heat transfer equation on the boundary of the beam can be expressed as:

$$k\left(\frac{\partial T}{\partial y} n_y + \frac{\partial T}{\partial z} n_z\right) = -q_b \tag{5}$$

where n_y and n_z are components of the vector normal to the boundary in the plane of the cross-section. The right hand side of Eq. (5) is dependent on the type of boundary condition. Since the beam is exposed to fire from three sides, there are two types of boundaries:

- Fire exposed boundaries where the heat flux is governed by:

$$q_b = -h_f(T + T_f) \tag{6}$$

- Unexposed boundary where the heat flux equation is given by:

$$q_b = -h_0(T + T_0) \tag{7}$$

where h_f and h_0 are heat transfer coefficient of the fire side and the cold side, respectively. T_f and T_0 are fire and cold side temperatures, respectively.

Generally, Eqs. (1) and (2) are simplified into one dimensional problem and then finite difference method is applied for solving the simplified equation. Eurocode 3 [4] presents incremental finite difference relations for solving Eq. (1) with adjustments made in order to compensate for the simplification. However, since the Eurocode relations are based on finite difference solution, the accuracy of the Eurocode relations is highly dependent on the size of the time increment; in addition, the analysis is complex and requires intensive use of spreadsheets calculations.

To overcome the above drawbacks and limitations in the current approaches, a simplified equation for predicting temperature in steel sections is derived. In order to simplify the partial differential Eq. (1), the following assumptions are made [5]:

- Steel temperature (due to the high conductivity of steel) has a uniform distribution, leading to $\nabla^2 T=0$. This is justified for individual thin steel plates used in structural members.
- The radiation problem can be approximately described as an equivalent convection problem. This is justified for protected steel members since the temperature at insulation outer surface is assumed to be equal to the fire temperature (T_f) [1,2,4]. For unprotected steel, it will be shown through comparison to test data and finite element results that this assumption, when coupled with assuming constant thermal properties for steel, generally leads to conservative results. This assumption is important in order to arrive at a simple handy expression for evaluating cross-sectional steel temperatures.
- Temperature in insulation material is assumed to be equal to an average of steel and fire temperatures, i.e., $(T_s+T_f)/m$, where $m=2$ for linear variation of temperature across the insulation material.
- Insulation is thin and applied as a contour protection around the perimeter of the steel section. Thus the volume of the insulation is computed as its thickness (t_p) multiplied by the heated perimeter (F_p) of the section, and
- The thermal parameters of steel and insulation materials are assumed to be constant over the temperature range.