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Fire design methodologies for cold-formed steel beams made with open and closed cross-sections

Luís Laím[a], João Paulo C. Rodrigues[b,*]

[a] ISISE, Department of Civil Engineering, University of Coimbra, Portugal
[b] LAETA, Department of Civil Engineering, University of Coimbra, Portugal

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ABSTRACT

This paper focuses on developing a simplified fire design methodology for single and built-up cold-formed steel beams based on the European guidelines. Open and closed cross-sections made with (lipped and unlipped) channel sections were selected for this research work. Existing experimental tests and shell finite element analysis using an advanced commercial program were used as the basis for the novel study conducted herein. Numerical results were then compared with predictions from available European fire design rules and appropriate recommendations are made. Such design rules were found to be unsafe or over-conservative depending on the relative slenderness and serviceability load of the beams. Comparisons with numerical moment capacities also demonstrated good precision of the new fire design methodology. The results obtained by this methodology may have an average error of half of those obtained by using the available European design curves.

1. Introduction

The interest on using and developing simple fire design methods for cold-formed steel (CFS) members is growing, due to the increased usage of this structural typology. CFS structural members are increasingly used in residential, industrial and commercial buildings due to their better qualities over other construction materials such as concrete, wood and hot-rolled steel [1]. Different CFS sectional configurations can be produced economically by cold forming process and consequently favourable strength-to-weight ratios can be obtained. As this type of member is usually classified as class four cross-section, according to EN 1993-1-1:2004 [2] and has much lower strength and stiffness than hot-rolled steel members, CFS members can fail by a variety of buckling modes including global, local and distortional buckling and their interactions [3–6]. This is why, the strength calculations of CFS members may be highly complex depending on the purpose of its use. For the design of flexural members at ambient temperature the Effective Width Method (EWM) and the Direct Strength Method (DSM) [7] may be applied. The EWM, available in the EN 1993-1-3:2004 [8] and introduced by Von Kármán et al. [9], performs a reduction of the plates for the prediction of the local buckling strength. On the other hand, Eurocode considers the distortional buckling strength by using a reduced thickness in the edge stiffener and/or distorted part of the compression flange.

However, when it comes to fire, design rules for CFS members are generally based on past research on hot-rolled steel members and they are up to now inadequate for this type of members [10–12]. According to Kankanamge and Mahendran [10], EN 1993-1-2:2005 [13] predictions were found to be over-conservative for high temperatures except for beams with very high slenderness. EN 1993-1-3:2004 [8] design method with buckling curve 'b' was found to be over-conservative or unsafe for some temperatures and slenderness ratios. Actually, Kankanamge and Mahendran [10] have already proposed a new fire design methodology for CFS lipped channel beams subjected to lateral-torsional buckling, based on modified AS/NZS4600 [14] design rules [15]. The proposed formulae is an adaptation of the ambient temperature design method by replacing the mechanical properties at ambient temperature with the respective reduction factors depending on the temperature ($E = k_{E,\theta} \cdot E_{20}$, $f_y = k_{y,\theta} \cdot f_{y,20}$) and using the $f_{p,\theta}/f_{y,\theta}$ factor for taking into account the non-linearity in the stress-strain curve of steel. However, this design method did not provide accurate load-bearing capacity predictions for the full range of temperatures and slenderness ratios [10]. Other new simplified fire design rules were proposed [11] but they were specifically developed for CFS floor systems.

Still, there is an urgent need to study the structural behaviour of CFS members in case of fire due to the lack of suitable design specifications [12,16]. As already mentioned, the design methods established in EN 1993-1-2:2005 [13] can be applied to such members according to its Annex E, but respectively replacing the area of the member cross-

* Corresponding author.
E-mail address: jpaulocr@dec.uc.pt (J.P.C. Rodrigues).

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Nomenclature

Notation

CFS	cold-formed steel
FEM	finite element model
FEA	finite element analysis
θ	temperature
θ_B	mean temperature of the beam
θ_{cr}	critical temperature of the beam
θ_S	steel temperature
L	length of the beam
LL	initial applied load level on the beams
h	height of the cross-section
t	nominal thickness of the cross-section or time of fire exposure
w	width of the flange plate of a C profile
d_v	vertical displacement of a beam at loading points
e	length of the edge stiffener of the cross-section
α	imperfection factor
σ	standard deviation
μ	mean value
E	modulus of elasticity of the steel at ambient temperature
E_θ	modulus of elasticity of the steel at temperature θ
$f_{p,\theta}$	proportional limit for the steel at temperature θ
f_y	yield strength of the steel at ambient temperature
$f_{y,\theta}$	yield strength of the steel at temperature θ
$k_{E,\theta}$	reduction factor for the modulus of elasticity of the steel at temperature θ
$k_{y,\theta}$	reduction factor for the 0.2% proof strength of the steel at temperature θ
k_a	axial restraining to the thermal elongation of the beam
k_r	rotational stiffness of the beam supports
$M_{b,fi,t,Rd}$	design buckling resistance moment at time t
$M_{b,Rd}$	design value of the resistant buckling moment at ambient temperature
M_{cr}	critical elastic moment for lateral-torsional buckling at ambient temperature
$M_{fi,\theta,Rd}$	design moment resistance of the cross-section for a uniform temperature θ
P_0	initial applied load on a beam
$P_{b,Rd}$	maximum load on a beam, corresponding to its design value of the resistant buckling moment at ambient temperature
W_{eff}	effective section modulus of a cross-sectional shape
W_y	section modulus of a cross-sectional shape
$\gamma_{M,fi}$	partial factor for the relevant material property in fire situation
$\bar{\lambda}_{LT}$	non-dimensional slenderness for lateral-torsional buckling at ambient temperature
$\bar{\lambda}_{LT,\theta}$	non-dimensional slenderness for lateral-torsional buckling at temperature θ
σ_{eng}	engineering stresses obtained from the tensile coupon tests
σ_{true}	true stresses taking into account the instantaneous or actual area of the specimen
ε_{eng}	engineering strains obtained from the tensile coupon tests
ε_{true}	true strains taking into account the instantaneous or actual area of the specimen

section and the section modulus by the effective area and effective section modulus, calculated as recommended in EN 1993-1-3:2004 [8] and EN 1993-1-5:2006 [17], i.e. based on the steel properties at ambient temperature. Besides, the steel yield strength should be set as the 0.2 percent proof strength. To further exacerbate this situation, EN 1993-1-2:2005 [13] still recommends a limit of 350 °C for the maximum temperature of members with class four cross-sections, which seems to be overly conservative [18–20].

Recent research experimental studies on unrestrained and restrained single and built-up CFS beams under both fire and flexural loading conditions have been performed by the authors [12,19]. Furthermore, the methods presented in EN 1993-1-2:2005 [13] both for the prediction of the temperature evolution on CFS members and for the estimation of their critical temperature were also used to compare with those experimental results. The results allowed to provide comprehensive time-deflection and time-temperature profiles for various CFS sections which can be widely used in structural numerical studies as input for evaluating other parameters not yet studied. Based on their study's findings, it was suggested that temperature evolution of sections calculated by the method established in EN1993-1.2:2005 [13] gives generally precise temperatures, but that the methods for the prediction of their structural fire behaviour should be revised and improved, as

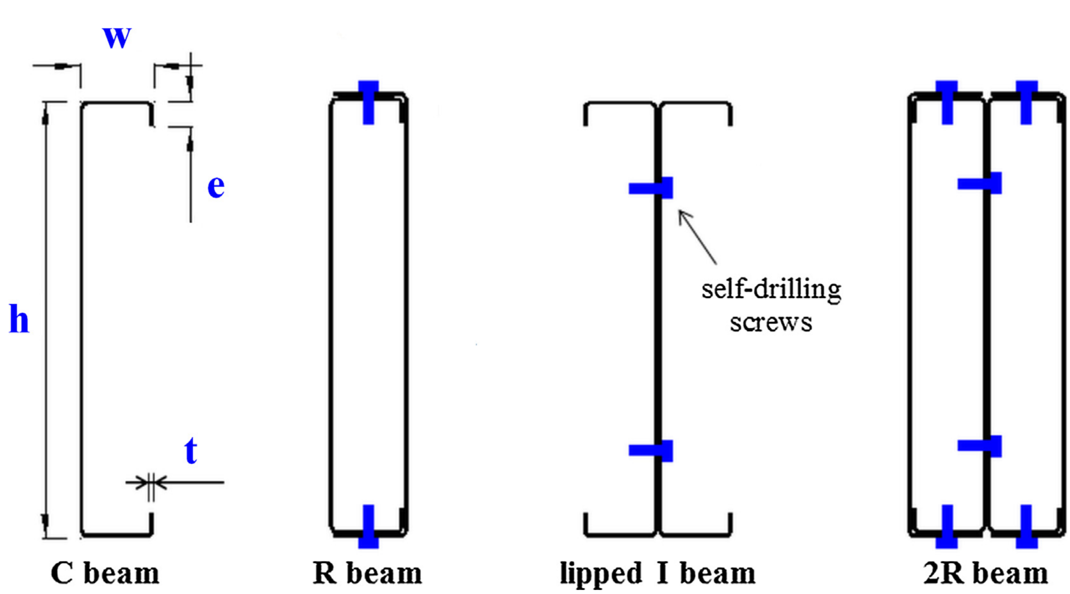

Fig. 1. Cross-sections of the studied beams.