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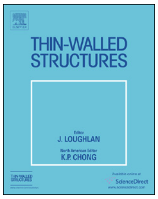

THIN-WALLED STRUCTURES

Flexural behaviour of axially and rotationally restrained cold-formed steel beams subjected to fire

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ABSTRACT

This paper presents the results of a wide-ranging experimental research carried on the flexural behaviour of cold-formed steel beams subjected to fire. The main purpose of this work was to evaluate the influence of different cross-sections, especially of compound cold-formed steel sections, the axial restraint to the thermal elongation of the beam and the rotational stiffness of the beam supports. The results showed above all that the critical temperature of a cold-formed steel beam might be strongly affected by the stiffness of the surrounding structure depending on the relation between its stiffness and the stiffness of the beam.

1. Introduction

The fire resistance of cold-formed steel (CFS) beams has been studied over the last decades [1–3]. However, the great majority of them have been performed on single members (composed of just one CFS profile), on unrestrained members and have been based on steady-state tests, in opposition to this research work and some studies of heavier hot-rolled steel members [4–8]. Note that most of them are related to columns, in spite of the fact that from the authors' view this issue may be more relevant in horizontal members, such as beams and slabs, i.e., members designed at ambient temperature for flexural loading conditions and not for compression axial forces. It is interesting to note that some of these studies concluded that the axial restraint is not such a severe phenomenon [5,7] in opposition to other ones [4,6]. However, Correia et al. [7] stated that the detrimental effect of the restraint to thermal elongation was cancelled by the beneficial effect of the rotational restraint provided by the surrounding structure. On the other hand, Valente and Neves [4] and Ali and O'Connor [6] are very clear about this issue. Valente and Neves [4] concluded that axial restraint reduces, in general the critical temperature of steel columns, while rotational restraint increases it. They observed that the fire design situation, proposed in the ENV1993-1.2:1995 [9], of column with fixed ends and no axial restraint, is acceptable only for less slender columns and in the cases where the surrounding structure provides high rotational restraining. Furthermore, when axial restraint was high and the rotational restraint was low, the real critical temperature of steel columns may be much lower than the critical temperature calculated according to the simplifications proposed in the ENV1993-1.2:1995 [9]. Is was still noticed that adding rotational restraint has a relatively minor effect on the value of generated restraint forces but failure temperatures can be greatly increased under the same load. The generated forces can increase the total imposed load to dangerous levels which may exceed the column's design load and the rotationally restrained columns normally present no sudden drop in the generated restraint forces [6]. When it comes to beams, it is worth mentioning that the connections (which introduce rotational restraint to the beam) can enhance their fire resistance by reducing some of the mid-span moment during most of the time when temperature is rising, despite the possibility of local flange buckling in the beam. Another main feature to take here into account is the effect of catenary action, but it seems it is more pronounced in cases with lower load levels and higher axial restraint [8]. However, it must be remembered that this one only becomes obvious at large deflections. So the structural failure criterion should need to be formulated to define the fire limit state for beams, when there is no intrinsic need to limit deflections.

In what concerns to CFS members with restrained thermal elongation, there has been a lack of studies in this field. Anyway, it is essential to highlight that CFS members may behave quite differently from hot-rolled steel members, since the latter are mostly found in class 1 or 2 cross-sections, while the former are class 3 or 4, according to EN1993-1.1:2004 [10]. This is due to the high slenderness of the cross-section's walls (high ratio width/thickness of the wall) and the low torsional stiffness (much lower than the flexural stiffness), and to the fact that in many of these cross-sections, the shear centre does not coincide with the centre of gravity and the great majority of the cross-sections are open and either mono symmetric or completely asymmetric. Consequently,

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Nomenclature

A_m	surface area of steel exposed to fire
CFS	cold-formed steel
L	beam span
$M_{b,fi,t,\mathrm{Rd}}$	design lateral-torsional buckling resistance moment of a laterally unrestrained beam in case of fire
$M_{b,\mathrm{Rd}}$	design value of the resistant buckling moment
M_{cr}	critical elastic moment for lateral-torsional buckling
M_{Rd}	section moment capacity about the major axis
P_0	initial applied load on a beam
V	volume of the section
W_y	appropriate section modulus
c_a	specific heat of steel
f_y	0.2% yield strength
h	height of the cross-section
k_a	axial restraining to the thermal elongation of the beam
$k_{a,b}$	axial stiffness of the beam
$k_{E,\theta}$	reduction factor for the modulus of elasticity of steel at temperature θ
k_r	rotational stiffness of the beam supports
$k_{r,b}$	rotational stiffness of the beam
k_{sh}	correction factor for the shadow effect
$k_{y,\theta}$	reduction factor for the 0.2% yield strength of steel at temperature θ
t_{cr}	critical time of the beam
$t_{N\_\max}$	time when the maximum restraining force in the beam is reached
$\dot{h}_{\mathrm{net}}$	net heat flux per unit area
$\Delta\theta_{a,t}$	the increase of the steel temperature during the time interval Δt
Δt	the time interval
Φ	configuration factor
α_c	coefficient of heat transfer by convection
$\gamma_{M,\mathrm{fi}}$	partial factor for the respective material property
ε_f	emissivity of the fire
ε_m	surface emissivity of the member
θ_{cr}	critical temperature of the beam
θ_g	gas temperature
θ_m	the steel temperature of the member
$\theta_{N\_\max}$	beam temperature when the maximum restraining force is reached
θ_r	effective radiation temperature of the fire environment
$\bar{\lambda}_{\mathrm{LT}}$	non-dimensional slenderness for lateral-torsional buckling
$\bar{\lambda}_{\mathrm{LT},\theta}$	non-dimensional slenderness for lateral-torsional buckling at temperature θ
μ	correction factor for the shadow effect, which depends on the section shape
ρ	unit mass of steel
σ	Stephan Boltzmann constant

these members may buckle at a stress level lower than the yield point of steel. It is therefore clear that cold-formed steel members are more susceptible to instability (local, distortional and global) than hot-rolled ones, and there are still many open questions to investigate. As it is an emerging technology and since a great variety of profiles with different geometric shapes can be easily produced, it is of the utmost importance that studies in this field should be undertaken. An exception to this is the research work done by Craveiro et al. [11], where it was found out that the level of axial and the associated rotational restraint may affect significantly the critical temperature of the CFS columns, especially for high values of stiffness and high initial load levels.

This paper therefore intends to fill the knowledge gap in this almost unexplored field and bring a better understanding about these issues. So, it is presented a parametric experimental investigation of axially and rotationally restrained CFS beams during fire. A new experimental system was developed for these tests where different degrees of axial and rotational restraint can be applied either separately or together to the test beams. The paper discusses the main outcomes of the research and demonstrates measurements of generated forces, temperatures and vertical displacements of the beams. The influence of the section geometry (involving open, closed, single and compound sections) was also studied. It also includes a comparison with the predictions from the currently available design rules (EN1993-1-2:2004 [12]). Another purpose of this experimental research is to provide valuable data for the validation of numerical models, which can be used to develop analytical guidance in the design of CFS beams subjected to fire.

2. Experimental investigation

2.1. Tested beams

The specimens consisted of beams made of one or more CFS profiles, namely, C (lipped channel), U (channel) and Sigma profiles (Fig. 1). These cross-sections were 250 mm tall and 43 mm wide for

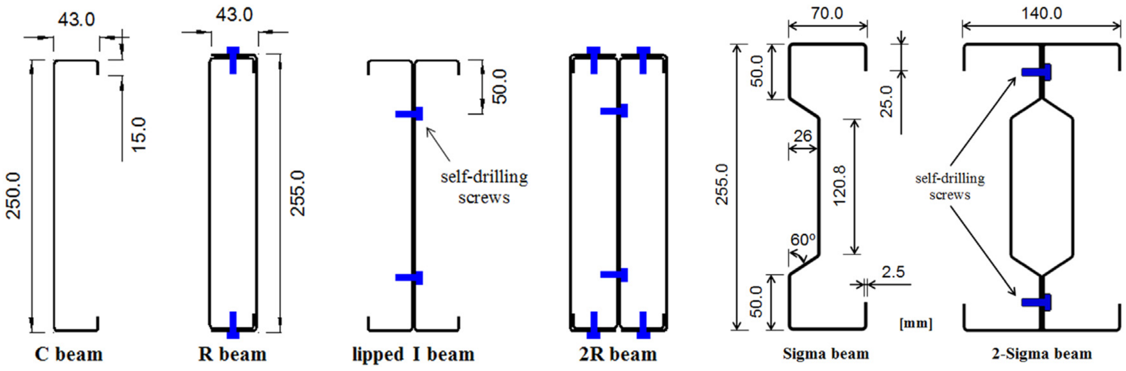

Fig. 1. Scheme of the cross-sections of the tested beams.