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Numerical analysis on axially-and-rotationally restrained cold-formed steel beams subjected to fire

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ABSTRACT

A numerical parametric investigation into the response of axially and rotationally restrained compound cold-formed steel beams in fire has been carried out. A suitable finite element model was validated against experimental fire tests. Some parameters that could have influence on the behaviour of these beams were evaluated, such as the section geometry, initial applied load, slenderness and influence of the axial and rotational restraints. The results showed that the critical temperature of axially restrained beams may drop significantly (reaching a 50% reduction) and, beyond a certain value of axial or rotational restraint it may be no longer possible to change its fire resistance. Furthermore, it was still concluded that the methods established in EN1993-1.2:2004 are not appropriate for the fire design of these beams (reaching relative differences in the order of 20% and some predictions can be unsafe).

1. Introduction

The structural performance of cold-formed steel (CFS) members under fire conditions has increasingly been studied over the last years. However, the great majority of them have been performed on single sections (with just one profile) [1–3] and assumed that the internal forces and moments at supports of the members remain unchanged throughout the fire exposure [4,5]. The more or less rigid connection between a member and the other elements of a structure restrains the thermal elongation of that member and also the rotation of its ends. This rotational restraint, as well as the axial restraint, has an elastic nature and might influence the fire behaviour of the members under fire conditions, and therefore their critical temperature and fire resistance. The imposed axial restraint can generate substantial unforeseen forces in the members during fire adding another hazard that may cause an unpredictable structural failure, in contrast to the imposed rotational restraint, which might avoid a sudden failure [6]. Note that this subject has only been studied on hot-rolled steel members (class 1 or 2 cross-sections) [7–16]. Most of the conclusions from these works state that the fire resistance of identical compression members may be not significantly affected by the stiffness of the surrounding structure, due to the beneficial effect of the rotational restraint at their ends [7–11]. On the other hand, local buckling near the beam ends might reduce the stiffness of the restrained beam greatly, whereas the restraint stiffness affected greatly the value of the axial force in the restrained beams [12]. In addition, if catenary action might be developed (i.e., the connections are able to sustain increased tensile forces), the beams will be able to survive to very high temperatures without collapse [13]. Rotational restraint will also improve the fire response of restrained beams by reducing the mid-span bending moment in the beam [14]. Still note that the higher the end axial restraint stiffness or the lower the end rotational restraint, the larger the beam's catenary force is [15,16]. Hence, if large deflection is not a design concern and beam design is based on catenary action, it is safe to assume complete end axial restraint stiffness and zero end rotational restraint. However, this may be very different on CFS members because they are usually classified as class 3 or 4 cross-sections, according to EN1993-1.1:2004 [17], and have much lower rotational stiffness. Hence, their high susceptibility to buckling phenomena (including local, distortional, global buckling and their interactions) [18–20] may also cause an unpredictable structural failure, i.e., the degradation level of this type of beams may be already far too high even before the beam enters a catenary phase, especially for unbraced beams as it is the case study presented in this paper. As well as that connections in cold-formed steel structures are often only dimensioned not to fail in shear (i.e., the connections are not able to sustain increased tensile forces).

Studies in this research field (CFS members in fire) are mostly

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Notation

CFS	cold-formed steel
CV	coefficient of variation
FEA	finite element analysis
E	elastic modulus of steel
L	length of the member
LL	initial applied load level on the beams
$M_{b,Rd}$	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
N_A	axial restraining forces generated in the beam
P	applied load on the beams
P_0	initial applied load on a beam
d_L	lateral displacement of beam at mid-span
$f_{0.2p}$	0.2% yield strength of steel
$f_{0.5}$	0.5% yield strength of steel
f_p	proportional stress limit of steel
f_u	ultimate strength of steel
f_y	yield strength of steel
h	height of the cross-section
$k_{E,\theta}$	reduction factor for the modulus of elasticity of steel at temperature θ
k_a	axial restraining to the thermal elongation of the beam
$k_{a,b}$	axial stiffness of the beam
k_r	rotational stiffness of the beam supports
$k_{r,b}$	rotational stiffness of the beam
$k_{y,\theta}$	reduction factor for the yield strength of steel at temperature θ
t_n	nominal thickness of the cross-section
θ_B	mean beam temperature
θ_{cr}	critical temperature of the beam
θ_S	steel temperature
$\bar{\lambda}_{LT}$	non-dimensional slenderness for lateral-torsional buckling at ambient temperature
μ	mean value
σ	standard deviation

of a numerical nature. Some of them concluded that the increase of the magnitude of the local imperfections may lead to a relatively straightforward decrease of initial stiffness of the member and that, on the other hand, the magnitude of global imperfections may have more influence on the ultimate load of the member. For instance, Kaitila [21] observed that the compressive ultimate load of a C column may be reduced by 5.1% when the global imperfection magnitude increases from L/1000 to L/500 and may also be reduced by 3.9% when the local imperfection magnitude increases from h/200 to h/100 at 600 °C. Nevertheless, the failure by distortional buckling may still be further affected by the initial geometric imperfections. Ranawaka and Mahendran [22] noted that the maximum load capacity of a C column may be reduced by 20 and 30% when the distortional imperfection magnitude increases from zero to $2t_n$ at 20 °C and 500 °C, respectively. In addition, it seems that the design method given in EN1993-1.2:2004 [23] is over-conservative for all the temperatures excepted for CFS beams with very high slenderness values [24]. With regard to the maximum temperature in CFS members with class 4 cross-sections, EN1993-1.2:2004 [23] has required a limit of 350 °C, which also seems to be overly conservative [25,26]. Therefore, there is a long trek to go in the clarification of this behaviour before developing simplified calculation methods that can be used in fire design.

In what concerns to the residual stresses of CFS members, it is important to remember that coiling, uncoiling, cold bending to shape, and straightening of the formed member lead to a complicated set of initial stresses and strains in the cross-section [27,28]. It is also noticed that both residual stress and cold-work of forming effect (where the yield stress of the material in the corners is increased above the virgin yield stress) should not be modelled independent of one another because they are derived from the same process. However, this effect in the corners is generally small since the corners are usually just a small proportion of the overall cross-sectional area [22]. These residual stresses vary across the steel sheet thickness as membrane (constant) and bending (linear variation) components, in opposition to the hot-rolled members. The membrane residual stresses are reasonably small and can be ignored. As well as that, Ranawaka and Mahendran [22] observed in their study that the influence of flexural residual stress in a press-braked C-section was negligible. This may occur because the members may buckle at a stress level lower than the yield point of steel and the residual stresses decrease with increasing temperature. Hence, members with high values of steel yield strength and/or low values of the steel sheet thickness are little sensitive to residual stresses and, on the other hand, in those cases, the own residual stresses also have the tendency to be low [29]. This is why the residual stresses in CFS members are not often considered in the numerical simulations, especially at elevated temperatures [22].

The mesh density is another important parameter to take into account in numerical analysis. For example, an approximately 40 mm mesh size yields a 9% higher load capacity than an approximately 10 mm mesh size in case of the S4 element [30]. It is noticed that this element is doubly-curved, a four-node (4), quadrilateral and stress/displacement shell element. It is also essential to stress that, for distortional buckling, the lip itself of C sections undergoes bending and at least four linear elements or two quadratic elements are required to provide reasonable accuracy [31].

In order to acquire new knowledge to this scientific field, this paper intends to present a numerical parametric study on the structural behaviour of cold-formed galvanised steel beams under combined bending and fire conditions. Therefore, a suitable finite element model was first developed to compare with experimental results. Consequently, it is described in detail in this paper all parameters, considerations and assumptions took into account in a three-dimensional nonlinear finite element model to predict the behaviour of CFS beams in fire, such as, the beams previously tested in Laboratory by the authors [32]. After verifying the developed finite element model against the experimental results, it was performed a parametric study outside the bounds of the original experimental tests, concentrating particularly on variation in slenderness of the beams, level of initial applied load on the beams and stiffness of the surrounding structure. It is aimed to see how far the axial and rotational restraint at beam supports can affect the structural performance of the beams in case of fire. Finally, this paper is a continuation of previous works [20,32], which make it possible a better understanding of how the surrounding structure affects a CFS beam when is subjected to fire. Nevertheless, in the near future, these studies will be the basis of an analytical study for the development of simplified calculation methods for fire design of axially and rotationally CFS beams.