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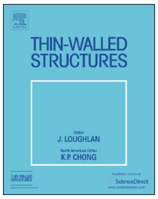

Flexural behaviour of beams made of cold-formed steel sigma-shaped sections at ambient and fire conditions

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ABSTRACT

This article reports a series of flexural tests at ambient and fire conditions on simply supported cold-formed steel beams made of one or two sigma-shaped profiles. It was assessed the critical temperature and time as well as the effect of the stiffeners on the beams under different restraining conditions, including no restraints, partial axial and beam supports rotational thermal restraints. The results showed that beams with web stiffeners may have different structural response in fire depending on the section shape. The beams without web stiffeners and not axially restrained presented the best structural behaviour under fire conditions.

1. Introduction

One of the greatest advantages of cold-formed steel (CFS) members is that they can be easily shaped and sized to meet any particular design requirement. They are usually formed in channel (U) sections, lipped channel (C) sections, zed (Z) sections and omega (Ω) sections as well as most studies in this field are concerned with these sections [1–4]. Nevertheless, finding the optimum or minimum weight beam is the challenging problem considering the complex and highly nonlinear constraints that govern their design. The low torsional stiffness, the low flexural rigidity about the minor axis, the high slenderness and the geometric imperfections are some of the main causes for their high susceptibility to buckling phenomena [5]. It is well known that beams made of CFS sections and subjected to bending moment may exhibit local, distortional [6] and global buckling. Beyond them, interactive buckling modes between or among the above ones are the most frequently in the CFS flexural members [7]. Understanding and dealing with these phenomena has been the central focus of recent research efforts [8,9]. In order to eliminate, or at least minimise, the local and distortional buckling phenomenon [10], edge and intermediate stiffeners are becoming used in CFS members at the expense of a little extra material. Note that the edge stiffeners used must have adequate rigidity to prevent out-of-plane deflections of the edge and the intermediate stiffeners to prevent out-of-plane deflections in the plate element in the region of the stiffener, thus allowing that under uniform compression this area of the section becomes fully stressed. Also, the yield strength of steel can be strengthened by forming edge and intermediate stiffeners in the sections due to the manufacturing process. The changes in the mechanical properties due to cold-working process are caused mainly by three phenomena: strain hardening, strain aging and the Bauschinger effect [11]. On the other hand, sections with more bends may reduce the distance between the centroid and shear centre of the cross-section introducing a lower torsional moment [12], as it may happen between the C and sigma (∑) sections.

Another interesting point is that when it comes to fire, the fire resistance of this kind of members is quite compromised due to the combination of the high thermal conductivity of steel and the high section factor of these structural members (small wall thickness) both of which lead to a rapid rise in steel temperature in a fire and consequently the deterioration of steel mechanical properties. As well as that it is expected that the rigidity of these stiffeners and the strengthening of steel in these regions decrease when the CFS members are exposed to high temperatures [13]. It is still worth mentioning that the structural behaviour of CFS members with stiffeners was rarely studied before by other authors at ambient temperature [10,14] and that there has been a lack of studies in this field at high temperatures, especially in CFS

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Notation

A_S	effective cross-sectional area of the edge stiffener
CFS	cold-formed steel
CV	coefficient of variation
E	longitudinal modulus of elasticity
I_S	second moment of effective area of the edge stiffener
K	spring stiffness of the edge stiffener per unit length
L	beam span
M	bending moment
M_sa	bending moment about the strong axis of the cross-section
M_wa	bending moment about the weak axis of the cross-section
$M_{b,Rd}$	design value of the resistant buckling moment
M_{cr}	critical elastic moment for lateral-torsional buckling
M_{Rd}	section moment capacity about the strong axis
N_A	axial restraining forces generated in the beam
P	applied load on the beam
P_0	initial applied load on the beam
P_{max}	maximum loadbearing capacity of the beam
b_n	width of the flange based on the centreline dimensions of the cross-section
d	vertical displacement of the beam at mid-span
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_r	rotational stiffness of the beam supports
$k_{r,b}$	rotational stiffness of the beam
k_σ	plate local buckling factor
t_{cr}	critical time of the beam
t_n	nominal thickness of the cross-section
t_{N_max}	time when the maximum restraining force in the beam is reached
β	lateral rotation of the beam at mid-span
$\overline{\theta}_B$	mean beam temperature
θ_{cr}	critical temperature of the beam
θ_{N_max}	beam temperature when the maximum restraining force is reached
θ_S	steel temperature
$\overline{\lambda}_{LT}$	non-dimensional slenderness for lateral-torsional buckling
μ	mean value
ν	Poisson's ratio
σ	standard deviation
$\sigma_{cr,d}$	critical elastic distortional buckling stress
$\sigma_{cr,l}$	critical elastic local buckling stress
φ	rotation of the beam supports
φ_{RS}	rotation of the roller support
φ_{PS}	rotation of the pinned support

beams. Some of the main conclusions from the published works on beams until now suggest that the design methods given in EN1993-1.2 [15] are over-conservative for all the temperatures, excepted for cold-formed steel beams with very high slenderness values [16]. With regard to the maximum temperature in cold-formed steel members, EN1993-1.2 has recommended a limit of 350 °C, which also seems to be overly conservative [17,18].

This article therefore intends to bring a better understanding about these issues. So, this article attempts to address a special and detailed study in depth on the structural behaviour of CFS beams made of one or two sigma-shaped profiles at ambient and fire conditions, based on the results of a large programme of experimental tests. The main objectives of these tests at ambient temperatures were to assess the ultimate loadbearing capacity of the beams, to observe the stress distribution over the beams' cross-section and to provide a reference for the fire tests. On the other hand, the major purposes of these tests under fire conditions were to assess the critical temperature and time of the studied beams as well as to observe the effect of the stiffeners on beams as the rigidity of these stiffeners and the strengthening of steel in these regions decrease with increasing temperature. Other important goals of this research work were also to investigate the influence of the axial restraint to the thermal elongation of the beam and the rotational stiffness of the beam supports on the parameters mentioned before. Moreover, both tests at ambient temperature and under fire conditions were carried out in order to compare the failure modes, the post-buckling response of these two kinds of beams and still their experimental results with the predictions from currently European design rules [15,19,20,21].

Finally, this research is a continuation of a previous investigation on CFS beams under fire conditions [18] and intends to provide extra experimental data for future numerical studies. The experimental and numerical results will be then the basis of an analytical study for the development of simplified calculation methods for fire design of CFS beams with and without web stiffeners.

2. Experimental tests

2.1. Specimens

The specimens consisted of CFS beams made of one or two sigma-shaped profiles (Fig. 1). The cross-sections of these sigma profiles were 255 mm tall, 70 mm wide and 2.5 mm thick. The inside bend radius and the length of the edge stiffeners were 2 and 25 mm, respectively. In addition, bent angles of 90° and 120° were respectively employed in the outer and inner corners of the profiles' web. These sections were manufactured from sheet steel pre-galvanised with a standard (Z275) zinc coating thickness of 0.04 mm (275 g/m^2) [19] by cold rolling at the company ELASTRON

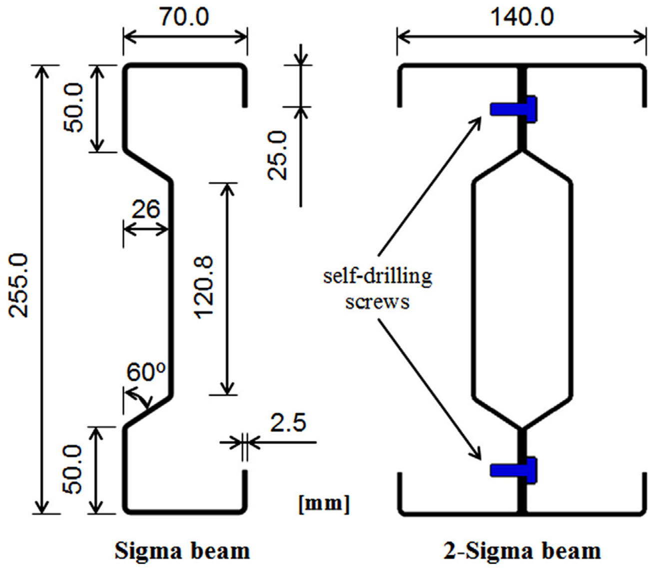

Fig. 1. Scheme of the cross-sections of the tested beams.