Thin-Walled Structures 95 (2015) 196–207

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Cross-sectional flexural capacity of cold-formed laterally-restrained steel rectangular hollow flange beams

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ARTICLE INFO

Article history:
Received 20 April 2015
Received in revised form
25 June 2015
Accepted 26 June 2015
Available online 17 July 2015

Keywords:
Cold-formed steel profiles
Rectangular hollow flange beams
Flexural capacity
Experimental tests
Numerical modelling

ABSTRACT

This paper presents the results of a comprehensive experimental-numerical study aimed at determining the flexural performance of cold-formed laterally-restrained steel rectangular hollow flange beams (RHFBs). Two RHFBs of different dimensions were considered as representative of typical secondary beams in small steel-framed houses. Results of the experimental study that consisted of (i) material characterisation and (ii) tests on full-scale specimens are thoroughly presented. Moreover, a numerical work was performed in order to develop a model able to reproduce the experimental outcomes and used to expand the available findings over a wider slenderness range through parametric studies.

1. Introduction

The use of cold-formed steel sections in small houses is well established in North America and Australia but in Europe their exploitation is mainly limited to secondary elements of steel roof systems. Nowadays, even in Europe the use of such profiles is growing fast. Cold-formed steel sections are very sensitive to buckling phenomena—both local and global—because they are generally thin-walled profiles so that they can easily undergo cold working processing. Therefore, a lot of research has been addressed to understand their behaviour under compressive stresses owing to axial and/or flexural loads, see for instance review articles on numerical and experimental findings [1–4]. Nevertheless, their use as secondary beams often entails fully laterally-restrained conditions of the flange in compression owing to a steel sheeting that prevents lateral torsional buckling (LTB). Hence, the knowledge of the bending moment capacity of the section represents a key information [5]. In order to enhance bending moment performance, the use of hollow flange sections is tempting because most of the mass is located away from the strong section axis. Moreover, hollow flange sections also provide torsional stiffness. Thus, RHFBs can be a potential alternative to C- and Z-sections as well as to small hot-rolled sections thanks to: (i) enhanced flexural behaviour associated with reduced weight; (ii) ease of producing doubly symmetric geometry and (iii) fast production times. Related research works were mainly devoted to the analysis of rectangular hollow flanges of channel sections [6–10] and to triangular hollow flanges of doubly symmetric I sections [11–13]. Numerical studies on symmetric rectangular hollow flange sections have been recently performed [14–18]. However, there is a lack of experimental testing on such profiles. On these premises, an experimental test programme on cold-formed steel RHFBs was planned in order to investigate their flexural performance by determining the section bending moment capacity. Furthermore, the experimental part is enriched by a numerical study with the following objectives: (i) to calibrate a finite element model capable of reproducing the experimental evidences; (ii) to perform a parametric analysis with the aim to broaden the results in terms of bending capacity to a wider range of slenderness ratios of the tube flanges; (iii) to assess whether the prediction of the Eurocode EN1993 is adequate for such a cross section; and (iv) to evaluate how the Direct Strength Method (DSM) [2] estimates the flexural behaviour of RHFB cross sections.

The paper is articulated as follows: Section 2 describes in detail the experimental programme and the geometry of the specimens; Section 3 provides insight into the characterisation of the material properties; Section 4 presents and discusses the outcomes of the tests on the full-scale specimens; Section 5 introduces the numerical modelling and analyses the results of the model calibration; Section 6 describes the parametric studies, whereas Section 7 draws the conclusions and future perspectives.

2. Experimental programme

The whole experimental programme was performed at the Laboratory of Structures and Materials Testing of the University of

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http://dx.doi.org/10.1016/j.tws.2015.06.018
0263-8231/

Trento. In detail, it was characterised by the following:

- 25 tensile tests on flat strips and on round corners of material coupons extracted from the specimens. The objective was to measure the actual tensile properties and to estimate the hardening induced by the cold working processing; and
- 6 static monotonic tests on RHFBs.

2.1. Specimen properties

The section dimensions of the specimens were selected to be of common use in structural applications such as either purlins or secondary beams in small steel-framed houses. In detail, the section geometry is depicted in Fig. 1. The nominal dimensions of the specimen sections are reported in Table 1. Both sections were overall classified as Class 4 according to EN1993-1-1 [19] considering an S235 steel grade: tube plates of Class 4 and web plate of Class 3.

Gruppo Manni, an Italian steelwork company, was a stakeholder of this experimental study, that can be considered as a feasibility study, and provided the specimens. However, since the machine for fabricating the RHFBs from a unique coil was not available yet, the specimens were built by welding two structural tubes—produced by cold rolling—to a cut flat plate that constitutes the web. This fact prevented to introduce an intermediate stiffener on the outermost flat elements that are part of the tubes, as illustrated in Fig. 1. This sort of detailing would be beneficial in order to reduce local buckling and crushing due to local effects of the flange in compression. Moreover, the way of producing the specimens was cause of higher imperfections relatively to those presumably expected if the appropriate cut machine had been used. In this respect, in agreement with the steelwork company, we convened to perform repeated tests—three for each section dimension—because some scatter in the results could appear. For instance, it was noticed increased imperfections owing to extensive welding between tubes and web plate and RHFB-240 profiles, endowed with smaller elements and thicknesses, were more prone to be affected by the production process. This aspect was observed in the tests and confirmed during the numerical calibration process presented later on in the paper.

Based on the previous considerations, a careful measurement of the actual geometric properties of thin-walled profiles is important because even small deviations from the nominal values could significantly affect their local and global behaviour. As a result, Table 2 collects the actual measurements of the section dimensions as well as the actual length of the specimen L. As expected, the actual values differ from the nominal ones and they are generally lower. Global imperfections were also measured even though they could not influence the behaviour of the beams during the tests because any possible global buckling mode was prevented. In any case, for sake of completeness, for all the specimens the global imperfections in the two principal axes were measured and they were less than L/2500. Only for the T01 RHFB-240 specimen a global imperfection about the weak axis of approximately L/1600 was found.

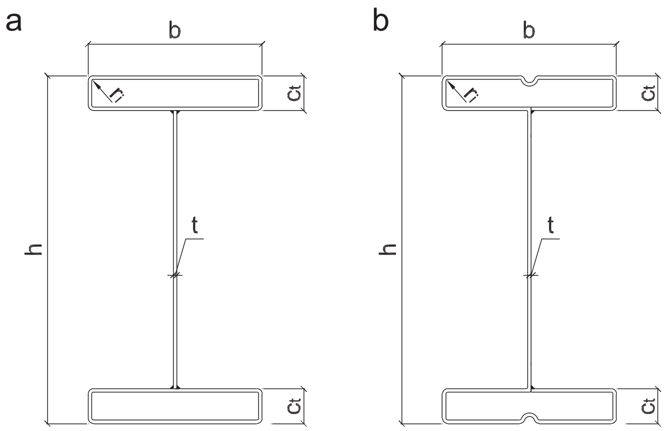

Fig. 1. Geometry of: (a) tested section and (b) optimised section.

Table 1
Nominal section dimensions of the specimens. Dimensions in mm.

	h_{nom}	b_{nom}	$c_{t,nom}$	t_{nom}	L_{nom}
RHFB-240	240	100	20	2.0	4500
RHFB-300	300	150	30	3.0	4500

Table 2
Measured section dimensions of the specimens. Dimensions in mm.

	h	b	c_t	t	r_i	L
T01 RHFB-240	235.2	100.0	19.8	1.92	1.75	4495
T02 RHFB-240	235.6	100.0	20.0	2.00	2.25	4495
T03 RHFB-240	235.3	99.9	19.7	2.01	2.50	4495
T04 RHFB-300	298.3	150.0	30.4	2.87	3.00	4498
T05 RHFB-300	296.8	150.1	30.0	2.86	3.50	4496
T06 RHFB-300	297.5	150.1	30.2	2.93	3.50	4498

It was difficult to precisely quantify local initial imperfections and consequently, they were not measured. Nevertheless and as already observed, RHFB-240 profiles were overall more affected by imperfections.

3. Material characterisation

A total of 25 tensile tests were carried out on material coupons extracted from the specimens. The tests were performed in accordance with EN ISO 6892-1 [20]. Both flats and corners were tested in order to establish the increase in yield strength owing to hardening induced by cold working and to obtain the stress–strain material relationships to be used in the numerical modelling. Corners were machined and tested to minimise eccentricities when loaded in the traction machine; in particular, the end parts were flattened. The yield strength f_y of steels used for structural applications classified according to EN10025-2 [21] is defined as the upper yield strength R_{eH}. Nevertheless, due to cold working, the corners undergo plastic deformation; thus, the yield point may not be well defined and the 0.2% proof strength ($R_{p0.2}$) is consequently provided. As highlighted in Table 3, a discrepancy among values of average yield strength between web and flange flats was observed, leading to so-called hybrid beams. This is particular

Table 3
Tensile properties of steel.

	avgf_y (MPa)	**COV**	**avgf_u (MPa)**	**COV**	**avgε_f (%)**	**COV**
RHFB-240						
Web	274.1	0.03	354.4	0.03	24.6	0.08
Tube flat	343.3	0.02	391.0	0.03	22.5	0.21
Tube corner	439.6	0.02	476.9	0.03	7.7	0.12
RHFB-300						
Web	258.5	0.01	355.6	0.00	25.6	0.09
Tube flat	394.8	0.02	438.1	0.02	25.8	0.16
Tube corner	512.2	0.06	551.8	0.07	10.6	0.06