Engineering Structures 67 (2014) 62–76

Contents lists available at ScienceDirect

Engineering Structures

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

Local–overall interactive buckling of welded stainless steel box section compression members

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ARTICLE INFO

Article history:
Received 21 November 2013
Revised 20 February 2014
Accepted 20 February 2014
Available online 21 March 2014

Keywords:
Box sections
Design
Experiments
Interaction
Local buckling
Numerical modelling
Overall buckling
Stainless steel
Structures
Welded columns

ABSTRACT

The interaction between local and overall buckling of welded stainless steel columns has been investigated experimentally and numerically in this study. Eight stainless steel box section compression members were fabricated from slender hot-rolled plates. The material properties and welding residual stress patterns in the test specimens had been obtained previously. Initial geometric imperfections, both local and global, were accurately measured prior to the tests. The test specimens were axially loaded between two pin-ended supports, and both local plate buckling and overall flexural buckling featured visibly in the observed failure modes. Finite element (FE) models were also set up using the ABAQUS software package to conduct numerical simulations, which were initially validated by means of comparison with the experimental data. Using the validated FE models, parametric studies were carried out to assess the influence of the key input parameters, such as the residual stresses, the material strain hardening exponent and non-dimensional proof stress, geometric imperfections and slenderness ratios. Existing design methods, including the design provisions of Eurocode 3 Part 1.4, the design proposal of Rasmussen and Rondal, the direct strength method (DSM) for cold-formed carbon steel and two revisions thereof, were all evaluated against the obtained test and numerical results. It was revealed that the EN 1993-1-4 buckling curves, which do not differ with grade, provide reasonable average strength predictions, but tend to slightly overpredict the local–overall buckling resistances of welded austenitic stainless steel members and slightly underestimate those of duplex stainless steel members. Furthermore, the three considered DSM design curves, all of which were developed on the basis of structural performance data from cold-formed sections, provide generally unconservative strength predictions for welded stainless steel sections. Based on the generated data points, modifications to the current EN 1993-1-4 provisions and the DSM have been proposed, which offer more accurate strength predictions for local–overall interactive buckling resistances of welded stainless steel box section columns.

1. Introduction

Stainless steels are being increasingly used in structural applications, particularly those in which the key durability benefits of the material can be exploited [1]. The majority of the previous research on structural stainless steel has focused on the behaviour of cold-formed sections. However, heavier load bearing applications require larger, typically welded sections, for which there is a growing trend. Hence, a study of the behaviour of welded stainless steel box columns, with an emphasis on local–overall interaction buckling [2–4] is the focus of the present paper.

Compression tests on structural stainless steel elements, aimed at studying either overall buckling [5–8] or local buckling [9–11], have been conducted by many researchers. Interactive buckling of stainless steel members, involving local and global modes, has been studied less extensively, though the following recent investigations have been carried out on cold-formed sections. Young and Lui [12] tested twenty-four cold-formed duplex stainless steel SHS and RHS columns, five of which were reported to fail by interactive buckling. Becque and Rasmussen [13–15] carried out experimental and numerical research on cold-formed stainless steel lipped channel columns and I-section columns and developed design provisions to account for the local–overall interaction buckling effects, while Rossi et al. [16,17] studied combined distortional and overall flexural–torsional buckling of cold-formed stainless steel sections. In addition, Gonçalves and Camotim [18] used the generalised

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http://dx.doi.org/10.1016/j.engstruct.2014.02.012
0141-0296/

beam theory to analyse the local and global buckling of stainless steel columns. Experiments on welded stainless steel columns, featuring interactive buckling, are scarce. Hence, the present paper involves testing of such members, and assesses the applicability of existing methods to their design.

Interactive buckling tests on a total of eight welded stainless steel columns with box sections were conducted in this study, exploring the local–overall buckling behaviour and resistances. The material properties, initial geometric imperfections, both local and global, and welding residual stresses were all measured prior to the tests. The test specimens were axially loaded with pin-ended boundary conditions. The test results were used to validate FE models, which were subsequently used to carry out systematic parametric studies. The obtained test and numerical results are then used to evaluate the current design provisions of EN 1993-1-4 [19], the DSM for carbon steel [20,21] and two revised versions thereof proposed by Becque et al. [15] and Huang and Young [22] for stainless steel. This study also forms part of the fundamental work to underpin the development of the first Chinese design code for structural stainless steel.

2. Material properties and test specimens

Two stainless steel alloys – austenitic grade EN 1.4301 and duplex grade EN 1.4462, were examined in this study. The material properties were obtained from tensile and compressive coupon tests, which were reported in a previous study [23]. Table 1 lists the material properties of the 6.00 mm plates, from which all of the test specimens were fabricated, while the full recorded stress–strain curves are plotted in Fig. 1. It can be seen that the austenitic EN 1.4301 alloy exhibits more considerable strain-hardening behaviour while the duplex EN 1.4462 alloy is of higher strength.

The measured average geometric dimensions of the test specimens are tabulated in Table 2, in which λ_{pf} and λ_{pw} are local element slendernesses for the flanges and the webs, respectively and λ_c is the non-dimensional global member slenderness; each of these is defined as the square root of the ratio of the yield to elastic buckling stress of the element or member. Other symbols are defined in Fig. 2. The cross-sections of the test specimens were designed to be of slender proportions, and hence susceptible to local plate buckling. The nominal outer sectional dimensions ranged from 180 mm to 400 mm, covering a wide range of plate width-to-thickness ratios from 28.0 to 64.7. Three cross-sectional aspect ratios h/b_f of 1.0, 1.5 and 2.0 were included. The effective length (L_e) of the columns was taken as the geometric length (L) plus the depth of the two pinned ends (2×190 mm = 380 mm). The slenderness ratio (L_e/r_y) of the test specimens varied from 40.7 to 57.0, which corresponds to columns of intermediate slenderness. All the web plates were machined to create beveled edges for butt welds. The test specimens were fabricated from hot-rolled plates by means of shielded metal arc welding (SMAW) and the weld size was designed to be 5 mm. All the constitutive plates of the test specimens studied in this paper were cut parallel to the longitudinal coil direction. Both ends of each test specimen were fitted with two 20 mm thick carbon steel end plates.

3. Determination of initial imperfections and residual stresses

Prior to testing, the initial global and local imperfections, together with the residual stresses, in the test specimens were measured, as described in the following sub-sections.

3.1. Global geometric imperfections

By means of an optical theodolite and a calibrated vernier caliper, the initial global geometric imperfections were measured [24]. A schematic view and field photo of the measurement setup are shown in Fig. 3. On the basis of a virtual straight line generated from the theodolite, five cross-sections – the mid-length section, two quarter point sections and two end sections, were measured along each column specimen for determining the amplitude of the initial global curvature. Due to the restriction of the end plates, the two end sections were moved 50 mm away from the end plates. The maximum deviation from a straight line between the two ends of the members was taken as the global imperfection amplitude, $v_0 = \max(v_1, v_2, v_3)$. Based on the described method, the global geometric imperfections were measured and are summarised in Table 3. It can be observed that the overall geometric imperfections of the test specimens are generally small, with the maximum amplitude reaching only $L/2000$.

3.2. Local geometric imperfections

The local imperfections of the test specimens were measured using the tool [20] shown in Fig. 4, which involved a digital linearly-varying displacement transducer (LVDT), driven by a calibrated electric guideway at a constant rate (2 mm/s), recording positional data across the section and corresponding time points. Three cross-sections – the mid-length cross-section and two quarter point cross-sections were measured for each constitutive plate. The local imperfection amplitude (w_0) for each specimen was taken as the maximum value among the three cross-sections. The measured results are summarised in Table 3.

3.3. Residual stress patterns

Residual stress measurements were taken on additional samples fabricated in parallel with the test specimens and using the same welding process. Measurements were taken by means of the sectioning method. Based on the ECCS predictive model [25] for welded carbon steel sections, a new predictive model for determining the residual stresses in welded stainless steel box sections was proposed [26]. The basic distribution pattern is shown in Fig. 5, while Table 4 lists the key parameters of the newly proposed model, which shows lower peak tensile residual stresses, narrower peak tension zones but wider transition zones, compared with the existing models for carbon steel structural sections.

Table 1
Measured material properties from hot-rolled coil used to fabricate structural sections.

Grade	t (mm)	Direction	E_0 (MPa)	$\sigma_{0.01}$ (MPa)	$\sigma_{0.2}$ (MPa)	$\sigma_{1.0}$ (MPa)	σ_u (MPa)	ε_f (%)	n
1.4301	6.00	LT	188,600	186.3	312.6	354.4	695.7	60.6	5.8
		LC	182,300	177.2	281.5	347.3	–	–	6.5
1.4462	6.00	LT	193,200	404.4	605.6	665.0	797.9	34.6	7.4
		LC	191,900	360.6	553.0	667.4	–	–	7.0

LT: longitudinal tension, LC: longitudinal compression.