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Design rules for stainless steel welded I-columns based on experimental and numerical studies

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ABSTRACT

Stainless steel is characterised by its nonlinear stress-strain behaviour with significant strain hardening, although current design codes treat it as an elastic, perfectly plastic material like carbon steel. The continuous strength method (CSM) is a newly developed strain based design approach which was proposed for nonlinear metallic materials. With recent developments, CSM can be used to predict the cross-section resistance for stocky and slender sections, and CSM design rules have recently been proposed for predicting the buckling resistance of cold-formed RHS and SHS columns. Welded sections, however, could behave differently from cold-formed sections due to the presence of residual stresses. Despite offering more economic options in many design cases, research on stainless steel welded sections is very limited to date. In this study, the behaviour of stainless steel welded I-sections was investigated through a test program, and the investigation was complemented by finite element (FE) modelling. The test program covered tensile coupon tests, residual stress and initial geometric imperfection measurements, stub column tests and flexural buckling tests of pin-ended long columns. FE models were developed for both major and minor axis buckling based on test results, and the verified FE modelling technique was used to investigate the effects of cross-section slenderness λ_p, section height-to-width ratio H/Band the ratio of flange thickness-to-web thickness t_f/t_w on column curves of welded I-sections. Buckling formulas for welded I-columns were eventually proposed following the same philosophy recently adopted by the authors for cold-formed hollow section columns. The imperfection parameter was recalibrated appropriately to incorporate special features of welded I-sections. Two sets of equations were proposed to tackle the observed variation in buckling behaviour against major and minor axis buckling. Buckling resistance predictions obtained from the proposed method were deemed reliable showing good accuracy and consistency with test and FE results.

1. Introduction

Welded sections are often used to meet the high load bearing capacity required for buildings and bridges as this type of sections can be fabricated to meet the exact design requirements, and may yield more economic design solution for a structure. During the last decade, research on structural stainless steel was mainly focused on cold-formed sections due largely to their easy availability. Limited number of studies were conducted on welded sections, and very few design codes [1,2] have design guidelines for welded sections. In recent years, a number of research projects were reported on stainless steel welded sections. Kuwamura [3], Saliba and Gardner [4] and Yuan et al. [5] studied the local buckling behaviour of stainless steel welded I-sections. Real et al. [6], Saliba and Gardner [7], Hassanein [8] and Fortan et al. [9] studied the shear response of stainless steel plate girders. Wang et al. [10] and Yang et al. [11] investigated the lateral torsional buckling of stainless steel welded I-section beams. Yuan et al. [12] measured the residual stresses of welded box sections and I-sections, and observed that the magnitudes and the distribution of longitudinal residual stresses of stainless steel welded sections were different from those observed in carbon steel welded sections. They also proposed a model for residual stress distribution in stainless steel welded sections. Investigation on the compression resistance of stainless steel welded sections is scarce. Recently, Yuan et al. [13] studied the local-overall interactive buckling of welded box sections by testing eight specimens. Yuan et al. [14] also tested welded I-section columns produced from austenitic and duplex grades of stainless steel to study a similar behaviour. They also performed numerical analysis, and observed that residual stresses significantly affect the buckling resistance of welded I-section columns. Yang et al. [15] tested stainless steel welded I-section columns for

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flexural buckling, and showed that EN 1993-1-4 [1] and AS/NZS 4673 [16] predictions were conservative for predicting the buckling resistance of stainless steel welded I-columns, and ASCE 8-02 [17] predictions were very scattered. It should, however, be noted that AS/NZS 4673 and ASCE 8-02 design rules are proposed for cold-formed stainless steel structures. Recently, Gardner et al. [18] investigated the behaviour of laser welded stainless steel columns for local buckling and flexural buckling, and observed that the carrying capacity of laser welded sections were higher than the conventionally welded sections due to lower residual stress magnitudes. It is evident that there is significant lack of test data for appropriate understanding of the behaviour of stainless steel welded sections, and current design standards produce conservative or erroneous predictions for the buckling resistance of welded sections. This paper aims to fill up the knowledge gaps through an experimental program, and proposes design formulations for stainless steel welded I-section columns based on comprehensive numerical analysis.

Current design codes [1,16,17] treat stainless steel like carbon steel ignoring its nonlinear behaviour and, hence, its strain hardening benefits are not fully exploited. For nonlinear metallic materials like stainless steel, a new design technique named the Continuous Strength Method (CSM) [19,20] was proposed. CSM is a strain based design method that incorporates material nonlinearity, exploits strain hardening and incorporates element interactions in predicting resistances at the cross-section level. With the recent development of CSM [21,22], cross-section capacity for both stocky and slender cross-sections can be predicted through simple formulas using a bilinear material model and without calculating effective cross-sectional properties. Therefore, there is a clear scope for using CSM philosophies for predicting the buckling resistance of columns.

The buckling resistance of stainless steel columns are normally calculated following two different approaches: tangential stiffness method and Perry formulas. SEI/ASCE8-02 [17] and AS/NZS 4673 [16] codes use the tangential stiffness method, which recognises material nonlinearity through an iterative process to calculate the instantaneous tangent modulus but does not consider geometric imperfections of the member. This method is not applicable for welded sections as there is no provision of considering residual stresses for welded sections. On the other hand, Eurocode [1] follows Perry curves, which is a direct method specifying separate curves for different types of cross-sections based on an imperfection parameter but the technique does not incorporate material nonlinearity. Through numerical analysis, Rasmussen and Rondal [23] showed that different column curves are necessary to predict the buckling resistance of different grades of stainless steel as their nonlinearity varies significantly between grades. Hradil et al. [24] tried to include the material nonlinearity in Perry curves by defining transformed slenderness but their suggested procedure uses tangent modulus, which is iterative. Shu et al. [25] proposed two base curves and some complicated transfer formulas for hollow sections which could be used to develop multiple curves from two base curves to cover different grades of stainless steel. All of the aforementioned methods use effective areas for slender cross-sections. Huang and Young [26] proposed a method using full cross section area with material properties taken from stub column tests to predict the column capacity. Recently Ahmed and Ashraf [27] proposed new buckling formulas for predicting the buckling capacity of cold-formed stainless steel RHS and SHS columns following CSM. This proposal successfully incorporated all the characteristics of stainless steel through simple equations. However, the behaviour of welded sections is different from cold-formed sections due to the presence of residual stresses [13–15]. Further investigations are required to investigate the suitability of the proposed CSM based technique for stainless steel welded sections.

In this study, the structural behaviour of stainless steel welded I-columns are investigated through a comprehensive test program as well as FE analysis. The test program included material test, initial geometric imperfection and residual stress measurements, stub column tests and flexural buckling tests on austenitic grade stainless steel welded I-sections. Based on the results obtained from this test program, nonlinear FE models were developed and verified, and a comprehensive parametric study was carried out to identify the influential key parameters onthe flexural buckling of welded I-columns. Design formulas were developed using test and FE results for welded I section columns, and finally, the performance of the proposed CSM flexural buckling formulas was verified and compared with other standards.

2. Test program

A test program was conducted to investigate the structural behaviour of stainless steel welded I-sections produced from 316L austenitic grade stainless steel. Flanges and webs were connected by Tungsten Inert Gas (TIG) welding. Most of the recent studies used shielded metal arc welding (SMAW) for fabricating welded sections [5,13–15]. But compared to SMAW, TIG welding offers better quality and precision. TIG welding is aesthetically good with smaller seam size, and the thermal distortion is also significantly low for TIG welded members. Material properties of the considered stainless steel were determined through tensile coupon tests. Three stub column tests were performed to examine the local buckling behaviour of stainless steel welded I-sections. To examine the buckling behaviour of the welded members, 16 long columns were tested. Prior to the test, local and global geometric imperfections were measured. In addition, residual stresses of two representative members were also determined by sectioning method. Details of the test program are described in the following sections. Designation system adopted for the considered specimens are as follows: "I D × B × t_f × t_w − L", where I stands for I-section, D is the nominal depth of the section, B is the nominal width of the section, t_f is the nominal flange thickness, t_w is the nominal web thickness and L is the nominal length of column.

3. Tensile coupon test

Tensile coupon tests were performed to evaluate accurate material properties for the plate materials used to fabricate the considered I-sections. Plates of five different thicknesses were used for different cross-sections, and plate thicknesses varied from 2 to 6 mm. Five coupons, each representing a specific thickness, were cut from 200 × 200 mm plates taken from the same batch as the welded I-columns. Tensile coupons were produced according to EN ISO 6892-1 [28], and all tensile coupons were necked in the middle. Submersible wire cutting technology was used to prepare the test coupons to minimise heat effects during the cutting process. All tensile coupon tests were performed using a Shimadzu Z100 kN electromechanical universal testing machine (UTM), and video extensometer was used to measure the longitudinal strain over a specified gauge length. A linear electrical resistance strain gauge was also attached to the face of each tensile coupon to record more accurate measurements for the initial elastic part of stress-strain curves. In the tests, strain rate was maintained at 0.001/s throughout the test. The plastic strain at fractures was also measured over a gauge length of $5.65\sqrt{A_c}$, where A_c is the cross-sectional area of the coupon.

Key material parameters such as Young's modulus E, 0.2% proof stress $\sigma_{0.2}$ and ultimate tensile stress σ_u, strain corresponding to the ultimate tensile stress ε_u, and plastic strain at fracture $\varepsilon_{pl,f}$ were extracted from the recorded stress-strain curves. The best-fit Young's modulus E was calculated based on the strain gauge measurements. Compound Ramberg–Osgood nonlinearity parameters n and m were also calculated from the strain gauge data. Results obtained from all tested coupons are summarised in Table 1. Stress-strain curves are shown in Fig. 1.