Engineering Structures 151 (2017) 422–431

Contents lists available at ScienceDirect

Engineering Structures

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

Design of stainless steel continuous beams with tubular cross-sections

I. Arrayago [*], E. Real, E. Mirambell

Department of Civil and Environmental Engineering, Universitat Politècnica de Catalunya – BarcelonaTech, Jordi Girona 1-3, C1 Building (Room 207), Barcelona 08034, Spain

ARTICLE INFO

Article history:
Received 6 February 2017
Revised 18 July 2017
Accepted 20 August 2017

Keywords:
Continuous beam
Continuous Strength Method
Direct Strength Method
Global plastic design
Stainless steel

ABSTRACT

This paper presents a comprehensive study on the application of global plastic design methods, not currently allowed in European specification provisions, to stainless steel rectangular and square hollow section continuous beams. The analysis of experimental and numerical continuous beam strengths highlighted that ultimate capacity predictions calculated based on global elastic analysis result in a considerable conservatism due to strain hardening and bending moment redistribution effects. Alternatively, the assessment and reliability analyses of the traditional plastic design methods demonstrated that the Class 1 cross-section limit provided in the European specification can be safely applied for the partial safety factor γ_{M0} currently provided. However, the analysis evidenced that including bending moment redistribution in capacity predictions is not enough since strain hardening effects play an important role when stocky cross-sections are analysed. Thus, the Continuous Strength Method for indeterminate structures was also assessed and it was found to provide accurate capacity predictions for all analysed stainless steel grades. Finally, an alternative Direct Strength Method design approach is proposed for stainless steel continuous beams based on the Direct Strength Method bending capacity. The proposed method, statistically validated, accounts for strain hardening effects and moment redistribution and provides the best resistance predictions among the different design methods considered.

1. Introduction

It is widely recognized that the behaviour of stainless steel is considerably different from that exhibited by structural carbon steel, with a nonlinear stress-strain response even for low strain levels. Carbon steel presents an elastic region with a clearly defined yield point, usually followed by a yield plateau. In opposition to this elastic-perfectly plastic material, stainless steels present a nonlinear stress-strain response where no clearly defined yield point is identified, which is conventionally determined as the proof stress for a 0.2% offset strain. In addition to the improved corrosion resistance against carbon steels, stainless steels exhibit considerable strain hardening and high ductility, with strains at fracture reaching 40–60% for the most ductile austenitic grades. However, the behaviour of stainless steel grades has been assumed to be similar to that exhibited by carbon steel in the different existing standards (e.g. EN1993-1-4 [1], AS/NZS4673 [2], SEI/ASCE 8-02 [3]), usually leading to overconservative design provisions.

Development of efficient design guidance for stainless steel structures is key for the increased use of this corrosion-resistant material by considering both its nonlinear behaviour and strain hardening effects into resistance predicting expressions, together with the moment redistribution in indeterminate structures. Research efforts have mainly focused on the resistance prediction of stainless steel cross-sections and members, where different methods accounting for strain hardening effects have been proposed. The Continuous Strength Method (CSM) developed for austenitic and duplex stainless steels by Afshan and Gardner [4] and adapted to ferritics by Bock et al. [5]; and the Direct Strength Method (DSM) approach that considers strain hardening effects proposed by Rossi and Rasmussen [6] and Arrayago et al. [7].

Although no plastic design is allowed for stainless steel structures in EN1993-1-4 [1], various research works analysed the bending moment redistribution capacity of stainless steel structures and the applicability of plastic design methods, provided that stainless steel indeterminate structures with stocky cross-sections possess high deformation capacity prior to collapse. This paper presents the assessment of the different global plastic design approaches based on extensive experimental and numerical databases, where the accuracy and reliability of these approaches are investigated. The traditional plastic design method given in EN1993-1-1 [8] and the alternative Continuous Strength Method (CSM) for indeterminate structures (Gardner et al. [9] and Theofanous et al. [10]) have been considered in the analysis. This paper also presents a new Direct Strength Method (DSM) approach for

---

[*] Corresponding author.
E-mail address: itsaso.arrayago@upc.edu (I. Arrayago).

http://dx.doi.org/10.1016/j.engstruct.2017.08.047
0141-0296/

stainless steel continuous beams based on the DSM bending capacity approach, which accounts for both strain hardening effects and the bending moment redistribution capacity of the beams, and the reliability of the method is demonstrated by means of statistical analyses.

2. Gathered experimental data and FE ultimate strengths

The different analyses and proposals presented in this paper are based on an extensive strength database comprising both experimental and numerical results for several stainless steel grades. This section first presents the collated experimental database and offers all the relevant information regarding the finite element model validation and the conducted parametric studies.

2.1. Collected experimental data

The number of available tests on hollow section stainless steel continuous beams is very limited: while Theofanous et al. [10] and Real and Mirambell [11] reported 14 continuous beam test results on the most common austenitic stainless steel EN1.4301 grade, Arrayago and Real [12] provided experimental data on ferritic EN1.4003 alloy two span continuous beams.

2.2. FE model validation and parametric studies

In addition to the available experimental database, parametric studies based on finite element (FE) modelling have been performed in order to provide a comprehensive assessment of the global plastic design methods. These FE models procured ultimate strengths of continuous beams with stocky cross-sections by testing virtual specimens with cross-sections not covered by the existing experimental programmes. This section presents the validation of the FE models for ferritic stainless steel Rectangular and Square Hollow Section (RHS and SHS) continuous beams over two span configurations based on the experimental results conducted by the authors and reported in [12] and also summarizes the conducted parametric studies. The configuration of the reference tests reported in [12] is shown in Fig. 1. 3200 mm long beams were tested under a five-point bending configuration over two 1500 mm long spans, each subjected to a concentrated midspan load.

All FE models were performed by the general purpose software Abaqus [13], where the mid-surface of the cross-sections was modelled by four-node shell elements with reduced integration S4R, widely used for cold-formed stainless steel elements, and the nonlinear behaviour was investigated by conducting modified Riks analyses. Loading and boundary conditions adopted in the two span continuous beam tests described in [12] were considered in the models, where regions corresponding to support and loading sections stiffened during the tests by wooden blocks were modelled as kinematic coupling interaction. The bottom faces of the support and loading regions were forced to move as a rigid body referred to their centre points, where the boundary conditions were defined. The longitudinal displacement of the middle support of the two span continuous beams was restrained, while end supports were free to move longitudinally, and loads were introduced as imposed vertical displacements.

The suitability of the developed FE models for representing the behaviour of ferritic stainless steel continuous tubular beams is demonstrated in Table 1 for RHS and SHS cross-sections bending around their major (Mj) and minor (Mi) axes. The numerical (FE)-to-experimental (exp) ratios of the ultimate loads $F_{u,FE}/F_{u,exp}$ and the corresponding midspan deflections $d_{u,FE}/d_{u,exp}$ are presented for the continuous beam tests reported in Arrayago and Real [12], together with the mean values and coefficients of variation (COV).

In the model validation, two different material definitions were considered. Initially, the measured material properties of the flat and corner regions of the cross-sections were assigned, where corner material definitions were extended also to the adjacent flat parts by a length equal to two times the thickness of the element, as assumed in Theofanous and Gardner [14]. Residual stresses were not explicitly introduced in the models since according to [15] the stress-strain curves obtained from coupon tests already include the bending residual stresses, and the membrane residual stresses were assumed to be negligible. In addition, the weighted average material properties were also considered in FE models, where the same behaviour was assigned to the entire cross-section in order to evaluate the accuracy of this simplification for further FE analyses. These weighted average material properties were calculated by assigning the value of the corresponding material parameter to the flat or corner regions, which were then weighted according to the area of the considered region compared to the total area of the cross-section. The material parameters describing the behaviour of flat parts, corner parts and weighted average behaviour can be found in the original publication [12].

Experimental load-midspan deflection curves were also compared to the corresponding FE results considering different constitutive laws in flat and corner regions (FE) and the weighted average material behaviour in the entire cross-section (FE, average material). Fig. 2 presents the comparison between experimental and FE results for the $80 \times 40 \times 4 - \mathrm{Mj}$ and $60 \times 60 \times 3$ specimens as an example of the typical validation curves obtained for continuous beams. Results in Table 1 and Fig. 2 demonstrate that the results derived from the numerical analyses are in good agreement with the considered experimental results for ferritic stainless steel beams when measured material properties are adopted, but also when the weighted average material is considered. Thus, this

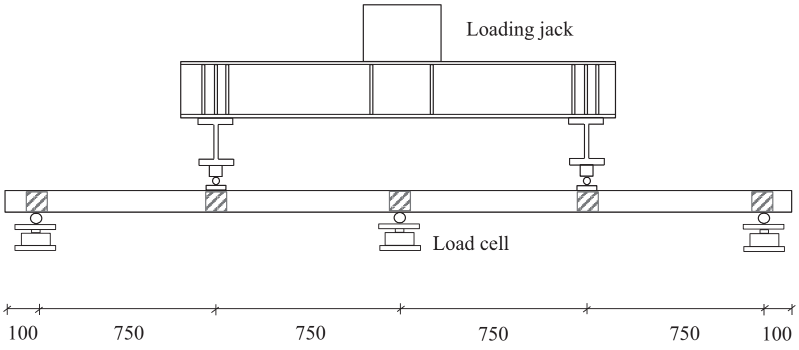

Fig. 1. Schematic diagram of the test setup for the continuous beam tests. Dimensions in mm.