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Material and local buckling response of ferritic stainless steel sections

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ABSTRACT

An investigation into the material response and local buckling behaviour of ferritic stainless steel structural cross-sections is presented in this paper. Particular attention is given to the strain hardening characteristics and ductility since these differ most markedly from the more common austenitic and duplex stainless steel grades. Based on collated stress-strain data on ferritic stainless steel, key aspects of the material model given in Annex C of EN 1993-1-4 [1] were evaluated and found to require adjustment. Proposed modifications are presented herein.

The local buckling behaviour of ferritic stainless steel sections in compression and bending was examined numerically, using the finite element (FE) package ABAQUS. The studied section types were cold-formed square hollow sections (SHS), rectangular hollow sections (RHS) and channels, as well as welded I-sections. The models were first validated against experimental data collected from the literature, after which parametric studies were performed to generate data over a wide range of section geometries and slendernesses. The obtained numerical results, together with existing experimental data from the literature were used to assess the applicability of the slenderness limits and effective width formulae set out in EN 1993-1-4 [1] to ferritic stainless steel sections.

The comparisons of the generated FE results for ferritic stainless steel with the design provisions of EN 1993-1-4 [1], highlighted, in line with other stainless steel grades, the inherent conservatism associated with the use of the 0.2% proof stress as the limiting design stress. To overcome this, the continuous strength method (CSM) was developed as an alternative design approach to exploit the deformation capacity and strain hardening potential of stocky cross-sections. An extension of the method to ferritic stainless steels, including the specification of a revised strain hardening slope for the CSM material model, is proposed herein. Comparisons with test and FE data showed that the CSM predictions are more accurate and consistent than existing provisions thus leading to significant material savings and hence more efficient structural design.

1. Introduction

Stainless steels fall into five main categories, depending on their microstructure: ferritic, austenitic, martensitic, duplex and precipitation hardening. To date, the austenitic and duplex grades have been the most widely used in construction and have received the most attention from structural engineering researchers. Ferritic stainless steels differ from the austenitic and duplex grades in that they contain no nickel, hence their cost is lower and more stable. The key alloying element remains chromium which gives the material the ability to resist corrosion. In terms of mechanical properties, ferritic stainless steels have higher mechanical strengths than the austenitics in the annealed condition, and display a less rounded stress-strain response with lower ultimate-to-yield strength ratios. In general, ferritic stainless steels possess many of the advantages that the austenitics have over carbon steel but at a lower material cost, making them a more economic and sustainable alternative for a number of structural applications.

Despite the fact that the European structural design guidance for stainless steels, EN 1993-1-4 [1], includes three ferritic grades (1.4003, 1.4016 and 1.4512) the applicability of all aspects of the code to ferritic stainless steels is yet to be fully validated. With the benefit of a far greater pool of experimental data [2–11] than was available when EN 1993-1-4 [1] was published, and through the use of carefully validated finite element models, the applicability of the code to ferritic stainless steel is examined herein. In particular, focus is given to the material model given in Annex C of EN 1993-1-4 [1] and the slenderness limits and effective width formulations used for cross-section design. For the latter, the revised slenderness limits and effective width formulae proposed by Gardner and Theofanous [12] are also assessed. Finally, the continuous strength method,

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which is a deformation-based design approach that allows for the beneficial influence of strain hardening, is extended to cover ferritic stainless steel.

2. Material response

2.1. Material modelling

The nonlinear stress-strain response of metallic materials such as stainless steel and aluminium has traditionally been represented by Hill's [13] modified version of the Ramberg-Osgood material model [14]. During recent years, structural applications of these materials have increased and therefore, so has the need to provide practising engineers and researchers with more accurate models to replicate their material response. The current material model presented in Annex C of EN 1993-1-4 [1] is based on Rasmussen's modification [15] of the two-stage Ramberg-Osgood model presented by Mirambell and Real [16] and described in Eq. (1), where E is the Young's modulus, $E_{0.2}$ is the tangent modulus at the 0.2% proof stress $\sigma_{0.2}$, $\varepsilon_{0.2}$ is the total strain at the 0.2% proof stress, σ_u is the ultimate tensile stress with its corresponding ultimate strain ε_u and n and m are strain hardening exponents. Rasmussen [15] also proposed predictive expressions for some components of the model, reducing the number of required input parameters from six [16] to three. These predictive expressions, for m, ε_u and σ_u, are given by Eqs. (2)–(4), respectively.

$$\varepsilon = \begin{cases} \frac{\sigma}{E} + 0.002\left(\frac{\sigma}{\sigma_{0.2}}\right) & \text{for } \sigma \le \sigma_{0.2} \\ \frac{\sigma-\sigma_{0.2}}{E_{0.2}} + \varepsilon_u\left(\frac{\sigma-\sigma_{0.2}}{\sigma_u-\sigma_{0.2}}\right)^m + \varepsilon_{0.2} & \text{for } \sigma > \sigma_{0.2} \end{cases} \quad (1)$$

$$m = 1 + 3.5\frac{\sigma_{0.2}}{\sigma_u} \quad (2)$$

$$\varepsilon_u = 1 - \frac{\sigma_{0.2}}{\sigma_u} \quad (3)$$

$$\frac{\sigma_{0.2}}{\sigma_u} = \begin{cases} 0.2 + 185(\sigma_{0.2}/E) & \text{for austenitic and duplex alloys} \\ \frac{0.2+185(\sigma_{0.2}/E)}{1-0.0375(n-5)} & \text{for all alloys} \end{cases} \quad (4)$$

Rasmussen [15] noted that the accuracy of the predictive model for ε_u (Eq. (3)) may require further assessment because "it was not clear if the ultimate strain quoted in the references were the uniform elongation at the ultimate tensile strength, as was assumed, or the total strain after fracture including local elongation in the area of necking". A reassessment of Eq. (3) was carried out in [7], where the accuracy of the predictive expression was confirmed for austenitic and duplex stainless steel, but the predictions were found to be less accurate for ferritic stainless steel. A proposed revision to Eq. (3) was made in [5] based on test data on ferritic stainless steel sheet material. In light of further available experimental data on a broader range of products, a revised expression is proposed herein.

2.2. Collection of experimental data

The results from a total of 135 material tests on ferritic stainless steel [2–9], where the strain at the ultimate tensile stress ε_u was recorded, have been gathered. Additionally, 128 material tests conducted on austenitic stainless steel [5,7,17–22], 20 on duplex [5,7,20,23] and 20 on lean duplex [7,24] have also been considered for comparison purposes. A summary of the sources of the test data, the number of results, the product types and the material grades is provided in Table 1. Note that the collected experimental data includes results on sheet material as well as material extracted from the flat and corner regions of SHS, RHS, CHS (circular hollow sections) and I-sections.

Table 1
Summary of the available stainless steel material data.

Source	Austenitic	Ferritic	Duplex	Lean duplex
[2]	–	60 sheets	–	–
[3]		2 flat parts (SHS) 1 flat part (RHS)	–	–
[4]	–	4 sheets	–	–
[5]	14 sheets	14 sheets	14 sheets	–
[6]	–	9 sheets	–	–
[7]	10 flat parts (SHS) 4 flat parts (RHS) 10 corners (SHS) 4 corners (RHS) 5 welds (SHS) 2 welds (RHS)	7 flat parts (SHS) 2 flat parts (RHS) 4 welds (SHS) 1 welds (RHS)	2 CHS	2 flat parts (SHS) 1 weld (SHS) 2 corners (SHS)
[8]	–	8 flat parts (SHS) 8 flat parts (RHS) 2 corners (SHS) 2 corners (RHS)	–	–
[9]	–	6 CHS 5 welded I-sections	–	–
[17]	28 flat parts (SHS) 26 flat parts (RHS) 3 corners (SHS) 2 corners (RHS)	–	–	–
[18]	2 flat parts (SHS) 1 CHS 1 corner (SHS)	–	–	–
[19]	2 flat parts (SHS) 4 flat parts (RHS)	–	–	–
[20]	2 sheets	–	1 sheet	–
[21]	1 flat parts (SHS) 1 flat part (RHS)	–	–	–
[22]	6 sheet	–	–	–
[23]	–	–	3 sheet	–
[24]	–	–	–	11 flat parts (SHS) 4 flat parts (RHS)
Total	128	135	20	20

2.3. Assessment of the predictive expression for ε_u

The collected test data are compared with the existing EN 1993-1-4 predictive model (Eq. (3)) in Fig. 1, which shows a graph of ultimate strain ε_u against $\sigma_{0.2}/\sigma_u$. The comparison reveals good agreement between the predictive model and the austenitic, duplex