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Behaviour of structural stainless steel cross-sections under combined loading – Part II: Numerical modelling and design approach

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ABSTRACT

In parallel with the experimental study described in the companion paper (Zhao et al., submitted for publication), a numerical modelling programme has been carried out to investigate further the structural behaviour of stainless steel cross-sections under combined loading. The numerical models, which were developed using the finite element (FE) package ABAQUS, were initially validated against the experiments, showing the capability of the FE models to replicate the key test results, the full experimental load–deformation histories and the observed local buckling failure modes. Upon validation of the FE models, parametric studies were conducted to generate additional structural performance data over a wide range of cross-section slenderness and combinations of loading. The experimental and numerical results were then compared with the design capacity predictions from the current European Standard EN 1993-1-4 (2006) and American Specification SEI/ASCE-8 (2002) for stainless steel structures. The comparisons revealed that the current design standards can significantly under-estimate the resistance of stainless steel cross-sections subjected to combined loading; this under-prediction of capacity can be primarily attributed to the lack of consideration of strain hardening of the material under load. The Continuous Strength Method (CSM) is a deformation-based design approach that accounts for strain hardening and has been shown to provide accurate predictions of cross-sectional resistance under compression and bending, acting in isolation. In the present paper, proposals are made to extend the scope of the CSM to the case of combined loading. Comparisons between the CSM design proposals and the test and FE results indicated a high level of accuracy and consistency in the predictions. The reliability of the proposals was confirmed by means of statistical analyses according to EN 1990 (2002).

1. Introduction

Recent years have witnessed increasing interest in the use of cold-formed stainless steel tubular sections in a variety of engineering applications owing to their durability and appearance, combined with excellent mechanical properties. Although a number of established structural design codes for stainless steel exist, previous studies [1–8] have highlighted limitations and undue conservatism in some of their provisions. This has prompted research aimed at broadening the scope and enhancing the efficiency of these codes. A brief review of the key studies relevant to the context of the present paper follows. At cross-sectional level, existing design codes [9,10] generally utilise traditional methods for the treatment of structural stainless steel cross-sections, namely section classification and the effective width concept. More recent design codes and guidance [11,12] have included more advanced design methods, including the Continuous Strength Method (CSM) for the design of stocky stainless steel cross-sections [11] and the Direct Strength Method (DSM) for slender cross-sections and members [12]. The underpinning research for the CSM was reported in [13–16], while the DSM developments were described by [17–19]. At member level, the European provisions for stainless steel member design mirror those for carbon steel but with different imperfection factors to reflect the particular characteristics of stainless steel. The American Specification SEI/ASCE-8 (2002) [10] utilises the tangent stiffness in the design of stainless steel members, which yields accurate capacity predictions, but needs iterative calculations. Revised buckling curves, covering both flexural and lateral torsional instabilities, were proposed in [20–22]. With regards to beam-column design, both EN 1993-1-4 (2006) [9] and SEI/ASCE-8 (2002) [10] employ interaction formulae, with the end

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points being the member capacities under the individual loading conditions. Revised interaction formulae have been proposed by Greiner and Kettler [23], Lopes et al. [24] and Huang and Young [25].

The focus of the present paper is the assessment of existing codified approaches and the development of new efficient methods for the design of stainless steel cross-sections under combined loading, based on the experimental results from the companion paper [26] and numerical simulations conducted herein. The numerical modelling programme was carried out initially to replicate the test results reported in the companion paper [26]. Upon validation of the FE models, parametric studies were performed to expand the available results over a wider range of cross-section slenderness. The experimental and numerical results were then compared against the strength predictions determined according to EN 1993-1-4 (2006) [9] and SEI/ASCE-8 (2002) [10], enabling the accuracy of each codified method to be assessed. Finally, the accuracy of the deformation-based CSM was assessed for combined loading, with both a simplified and more complex treatment examined.

2. Numerical modelling

2.1. Introduction

In conjunction with the experimental study described in the companion paper [26], a numerical modelling programme was performed using the general-purpose finite element analysis package ABAQUS [27]. The aims of the numerical investigations were initially to replicate the full experimental load–deformation histories and to assess the sensitivity of the FE models to various input parameters, and subsequently to conduct parametric studies to generate further structural performance data to supplement the experimental results.

2.2. Basic modelling assumptions

The four-noded doubly curved shell element with reduced integration and finite membrane strain, S4R [27], was selected as the element type throughout the present numerical investigation, which has been shown to perform well in similar studies [4,5,28–30] concerning the modelling of thin-walled structures. An element size equal to the cross-section thickness was assigned to the flat parts of the modelled cross-sections, and a finer mesh of 5 elements was used in the corner regions to ensure that the curved geometry could be accurately represented. The two-stage Ramberg–Osgood (R–O) material model [31], which is an extension of the basic Ramberg–Osgood formulations [32,33] and followed developments by Mirambell and Real [34] and Rasmussen [35], was employed to represent the experimental stress–strain curves. Since ABAQUS requires the material properties to be defined in the format of true stress and log plastic strain, the measured engineering stress–strain curves were converted into the true stress–log plastic strain curves, by means of Eqs. (1) and (2), before inputting into ABAQUS

$$\sigma_{true} = \sigma_{nom}(1 + \varepsilon_{nom}) \tag{1}$$

$$\varepsilon_{ln}^{pl} = \ln(1 + \varepsilon_{nom}) - \frac{\sigma_{true}}{E} \tag{2}$$

in which σ_{true} is the true tress, ε_{ln}^{pl} is the logarithmic plastic strain, E is the Young's modulus, and σ_{nom} and ε_{nom} are the engineering stress and strain, respectively.

The examined cross-sections were produced by cold-rolling. This process induces plastic deformations, resulting in strength enhancements, which are most notable in the corner regions. It has been both experimentally [36,37] and numerically [28,38] verified that the high corner strength enhancements are not restricted only to the curved portions of the section, but also extend into the adjacent flat parts by a distance approximately equal to two times the cross-section thickness. This finding has been adopted in the present numerical study by assigning corner material properties to both of the aforementioned regions. Note that strength enhancements also arise in the flat regions of cold-rolled hollow sections, but these are already reflected in the stress–strain properties of the tested flat coupons.

Residual stresses are also introduced into the specimens during the production process, with a combination of through-thickness bending residual stresses due to cold-forming and membrane residual stresses from welding. For cold-rolled and seam-welded stainless steel tubular sections, Young and Lui [39], Cruise and Gardner [40], Jandera et al. [41] and Huang and Young [42] carried out careful residual stress measurements and concluded that the magnitude of the membrane residual stresses was small compared to that of the bending residual stresses. In addition, as highlighted in [39–41,43], the effect of the through-thickness bending residual stresses is inherently incorporated into the measured material properties, since the coupons straighten during tensile testing. Thus, explicit inclusion of residual stresses in the numerical models was deemed unnecessary.

FE models were created to simulate the tested concentrically and eccentrically loaded stub columns, and beams. The following end section boundary conditions were employed in the respective models: For the concentric stub columns, which had fixed ends, the nodes of each end cross-section were coupled to a concentric reference point, where all degrees of freedom were restrained at one end and all degrees of freedom except for longitudinal translation were fixed at the loaded end. For each combined loading stub column FE model, the end section was coupled with an eccentric reference point, allowing rotation about the axis of buckling at one end and the same rotation plus longitudinal translation at the loaded end, in order to simulate pin-ended boundary conditions. In addition, the eccentric reference point was offset longitudinally from the end section by a distance equal to the thickness of the welded end plate (25 mm) in order to accurately model the effective member length. Similar end section boundary conditions as those for the combined loading stub column FE models were applied to the four-point bending FE models, with the only difference being that the reference point was located at the mid-point of the bottom flange; these boundary conditions replicated the simply-supported conditions employed in the beam tests.

Initial local geometric imperfections exist in all thin-walled structural members and can influence the development of local buckling, the local level at which plasticity initiates, the ultimate load-carrying capacity and the post-ultimate response. Hence, it is necessary to include suitable geometric imperfections into the FE models in order to accurately replicate the observed experimental response. Previous numerical studies [28,38,44,45] have adopted an imperfection pattern along the member length in the form of the lowest buckling mode shape, which was determined by performing a prior elastic eigenvalue buckling analysis; this approach was also employed herein. Upon the incorporation of the initial geometric imperfection into the FE model, geometrically and materially nonlinear analyses were carried out, using the modified Riks method [27] to trace the full load–deformation response of the specimens, including the post-ultimate path. The sensitivity of the models to imperfections was examined by considering three different imperfection amplitudes. The three considered values were the maximum measured imperfection amplitude ω_0, as reported in the companion paper [26], 1/100 of the cross-section thickness and the imperfection amplitude $\omega_{D\&W}$ derived from the modified Dawson and Walker (D&W) predictive model [28,46], as given by Eq. (3), where $\sigma_{cr,\min}$ is the minimum elastic buckling

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