Experimental and numerical studies of laser-welded stainless steel channel sections under combined compression and major axis bending moment

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Abstract

This paper presents an in-depth experimental and numerical investigation into the behaviour of laser-welded stainless steel channel sections under combined compression and bending moment about the major axis. Two laser-welded austenitic stainless steel plain channel sections were considered in the experimental investigation, and for each channel section, four eccentrically loaded stub column tests were conducted under various initial loading eccentricities. The experimental results were then adopted in a numerical investigation for the validation of finite element models, by means of which parametric studies were conducted to generate further structural performance data over a wider range of cross-section sizes and initial loading eccentricities. Both the obtained experimental and numerical results were carefully analysed and then used to evaluate the accuracy of the current codified design rules for welded stainless steel channel sections under combined compression and major axis bending. The evaluation results generally revealed that the codified design rules yield excessively

conservative and scattered resistance predictions, owing to the neglect of the favourable material strain hardening of stainless steel and the beneficial stress redistribution within channel sections under combined loading. An improved design approach has been proposed through extension of the deformation-based continuous strength method (CSM) to the case of laser-welded stainless steel channel sections under combined compression and major axis bending. Quantitative evaluation of the new design approach was made through comparing the predicted resistances against the experimental and numerical failure loads, with the results revealing that the new design approach yields a much higher level of design accuracy and consistency than the current codified design rules. Finally, statistical analyses have been conducted to confirm the reliability of the new design approach according to EN 1990.

Keywords: Austenitic stainless steel; Channel sections; Continuous strength method; Eccentrically loaded stub column tests; International design codes; Laser-welded; New design proposal; Numerical modelling; Reliability analysis

1. Introduction

Stainless steel is gaining increasing use in a range of civil and offshore engineering applications, owing principally to its favourable mechanical properties (e.g., high strength, exceptional ductility and good fire resistance) and to its excellent durability, low maintenance cost during the service life of the structure and very high recycling rate after use, which are consistent with the current concern on sustainable construction. Research into stainless steel channel section members has been conducted previously, and a brief review of the key experimental studies is provided herein. Kuwamura [1] and Zhang et al. [2] carried out a series of compression tests on cold-formed austenitic stainless steel channel section stub columns and investigated their

local buckling behaviour and cross-section compression resistances. Theofanous et al. [3] and Zhang et al. [2] respectively performed bending tests on laterally restrained laser-welded and cold-formed austenitic stainless steel channel section beams to study their in-plane flexural behaviour and resistances, while laterally unrestrained beam tests on cold-formed austenitic stainless steel channel sections were carried out by Niu et al. [4], with their distortional–global interactive buckling behaviour and resistances examined. Lecce and Rasmussen [5], Becque and Rasmussen [6] and Rossi et al. [7] conducted a series of compression tests on cold-formed ferritic stainless steel channel section columns with varying member lengths and cross-section sizes, and studied their distortional, local–overall and distortional–overall buckling behaviour, respectively. It is worth noting that previous studies [1–7] focused mainly on cold-formed and welded stainless steel channel section members under isolated loadings (pure compression and pure bending), while there have been no investigations into their structural behaviour under combined compression and bending moment. This has prompted research carried out by the authors, to examine the local and global buckling behaviour of stainless steel channel section members subjected to combined loading. The local buckling behaviour of laser-welded austenitic stainless steel channel section stub columns under combined compression and minor axis bending moment has been studied by Liang et al. [8,9], based on tests and numerical modelling, while their behaviour under combined compression and major axis bending moment is experimentally and numerically investigated in the present paper.

In this paper, an experimental programme, including compression tests on eight laser-welded austenitic stainless steel channel section stub columns loaded at various eccentricities to the major axis, was firstly carried out. This was followed by a numerical modelling programme, where finite element models were initially developed to simulate the test results, and then employed to perform parametric studies to extend the current test data pool over a wider range

of cross-section sizes and initial loading eccentricities. The obtained test and numerical data were carefully analysed to develop a comprehensive understanding of the structural performance of laser-welded stainless steel channel sections under combined compression and major axis bending, and used to evaluate the accuracy of the relevant design provisions given in the European code EN 1993-1-4 [10] and American design guide AISC 27 [11]. An improved design approach was also proposed through extension of the deformation-based continuous strength method (CSM) [12–15] to the case of laser-welded stainless steel channel sections under combined compression and major axis bending, and the accuracy and reliability of the new design approach were assessed, based on the test and numerical data.

2. Experimental programme

2.1 General

Given that there have been no existing test data on laser-welded stainless steel channel section stub columns under combined compression and major axis bending, an experimental programme was firstly conducted to obtain a test data pool. Two channel sections were adopted in the experimental programme: C 40×40×5×5 and C 100×50×6×9, which were fabricated by laser-welding from hot-rolled EN 1.4307 and EN 1.4404 austenitic stainless steel plates, respectively. Laser-welding is a novel production method, which employs powerful lasers to locally melt and fuse together individual metallic plates into complete structural sections, without the use of filler material. Therefore, the two adopted laser-welded stainless steel channel sections comprise plated elements with sharp corners. Moreover, the heat input is kept to a minimum during laser-welding, thus resulting in very small heat affected zones, low thermal distortions and low residual stresses [3]. Both of the two adopted laser-welded stainless

steel channel sections are classified as Class 1, according to the slenderness limits prescribed in EN 1993-1-4 [10]. Overall, the experimental programme comprised material tensile coupon tests, initial local geometric imperfection measurements and eight eccentrically loaded stub column (combined loading) tests.

2.2 Material tensile coupon tests and initial local geometric imperfection measurements

Tensile coupon tests were carried out to obtain the material properties of the two laser-welded stainless steel channel sections. The detailed setup and procedures for the tensile coupon tests were described by Theofanous et al. [3], while only a brief summary is reported herein. For each cross-section size, four longitudinal coupons were extracted from the middle portions of the flanges and the web (see Fig. 1), and tested under displacement control, with the applied strain rates conforming to the requirements of EN ISO 6892-1 [16] and AS 1391 [17]. The key average material properties measured for both laser-welded stainless steel channel sections are presented in Table 1, in which E is the Young's modulus, $\sigma_{0.2}$ is the 0.2% proof stress, $\sigma_{1.0}$ is the 1.0% proof stress, σ_u is the ultimate tensile strength, ε_u is the strain at the ultimate tensile strength, ε_f is the fracture strain, and n and $n'_{0.2,1.0}$ are the strain hardening exponents used in the Ramberg–Osgood (R–O) material model [18–22]. It is worth noting that channel section C 100×50×6×9 was laser-welded from dissimilar plates, and the identifiers of the coupons cut from the flanges and web are suffixed with ‘F’ and ‘W’, respectively.

Initial local geometric imperfection measurements were not performed specifically for each specimen, but conducted over a representative 600 mm length of each channel section size [3], following the test setup and procedures recommended by Schafer and Peköz [23]. For each constituent plate element of the channel section, the initial local geometric imperfections were

measured along the two edge lines and the centreline, with the magnitude taken as the largest derivation from a linear regression surface fitted to the measured data points [3,8]. Table 2 reports the maximum measured initial local geometric imperfection magnitudes of the two flanges and web, respectively denoted as ω_{f1} , ω_{f2} and ω_w , while the initial local geometric imperfection magnitude of the channel section (and thus the corresponding specimens) ω_0 was taken as the maximum of ω_{f1} , ω_{f2} and ω_w .

2.3 Eccentrically loaded stub column tests

For each cross-section, four eccentrically loaded stub column tests were carried out about the major axis, aimed at investigating the behaviour and resistances of laser-welded stainless steel channel sections under combined compression and major axis bending. The initial loading eccentricities were designed to vary between 8 mm and 45 mm, which led to a range of bending moment-to-axial load ratios being considered. The nominal length of each eccentrically loaded stub column specimen was selected in accordance with the guidelines of Ziemian [24] to be short enough to preclude global buckling but still long enough to include a representative pattern of initial local geometric imperfections and residual stresses. Table 3 presents the measured geometric properties of the specimens, where L is the member length, h and b_f are respectively the outer web and flange widths of the channel section (see Fig. 1), and t_w and t_f are the thicknesses of the web and flange, respectively.

Upon measurements of the geometric properties, the ends of each specimen were milled flat and then welded with end plates. The end plates, drilled with holes, were eccentrically bolted to the knife-edge devices of the testing machine, allowing the end sections of the specimens to rotate freely about the major axis. During testing, the applied eccentric load induced the

combined actions of compression load and bending moment about the major axis at the specimen ends. Fig. 2 depicts the setup for the eccentrically loaded stub column tests, where inclinometers are placed at each end of the specimen to record the end rotations, one LVDT is located at the mid-height of the specimen along the buckling direction to measure the lateral deflection and thus the second-order bending moment, and two pairs of strain gauges are attached to the extreme fibres of the flanges of the channel section (with the detailed locations shown in Fig. 1) at mid-height to determine the maximum and minimum longitudinal strains. The measured mid-height lateral deflections and longitudinal strains were employed to calculate the actual initial loading eccentricities, following the procedures and formulae described by the authors in previous studies of eccentrically loaded stainless steel columns [8,25–27].

The calculated (actual) initial loading eccentricity e_0 , together with the key experimental results, for each eccentrically loaded stub column specimen are reported in Table 4, where N_u is the failure load, e' is the measured mid-height lateral deflection at the failure load, $M_u = N_u(e_0 + e')$ is the failure moment at the mid-height of the specimen, and ϕ_u is the end rotation at the failure load. Figs 3(a) and 3(b) depict the load–end rotation curves for the C 40×40×5×5 and C 100×50×6×9 stub column specimens under combined compression and bending moment about the major axis, respectively, while Fig. 4 shows the local buckling failure mode of a typical eccentrically loaded stub column specimen C 100×50×6×9-2A.

3. Numerical modelling

3.1 General

In parallel with the experimental program, a numerical modelling programme was performed using the nonlinear finite element analysis package ABAQUS [28]. Finite element (FE) models were firstly developed to simulate the full experimental load–deformation histories and failure modes, and then used to conduct parametric studies to generate further structural performance data over a wider range of cross-section sizes and initial loading eccentricities.

3.2 Development of FE models

The four-noded doubly curved shell element with reduced integration, S4R [28], has been successfully employed in previous numerical modelling of stainless steel channel section structural members [2,8,15,29], and was thus also employed herein. With regard to the element size, the length along the longitudinal direction of each FE model was set equal to the minimum of the measured flange and web thicknesses of the corresponding channel section, while the element widths along the centreline of the cross-section depended on the widths of the strips in the applied residual stress distribution pattern; specifically, an element width equal to the minimum of the measured flange and web thicknesses was adopted in the peak (constant) tensile and compressive residual stress regions of the modelled channel section, while a finer mesh of three elements was assigned to the transition regions. In the present numerical modelling, the residual stresses for laser-welded stainless steel internal and outstand plate elements were determined from the predictive model of Gardner et al. [30]. The distribution pattern defined by the predictive model is shown in Fig. 5, while Table 5 reports the distribution

parameters a , b , c and d ; the peak tensile residual stresses in the flange and web (σ_{ft} and σ_{wt} , respectively) are equal to half of the corresponding material 0.2% proof stresses, while the peak compressive residual stresses in the flange and web (σ_{fc} and σ_{wc} , respectively) are determined based on each constituent plate element being in self-equilibrium. Fig. 6 depicts the mesh size and residual stresses adopted in the FE models for the C 100×50×6×9 specimens. Regarding the material modelling of stainless steel, the measured engineering stress–strain curves were firstly converted into the true stress–plastic strain curves, before inputting into ABAQUS [28].

The end section of each eccentrically loaded stub column FE model was coupled to a reference point, which was located eccentrically to the major axis, with the eccentricity equal to the corresponding actual initial loading eccentricity (see Table 4), and also offset longitudinally from the end section by 87 mm – the distance from the specimen end to the tip of the knife-edge in the tests. The reference point at the loaded end was set free to rotate about the major axis and translate in the longitudinal direction, while the other reference point was only allowed to rotate about the major axis, in order to simulate the pin-ended boundary conditions provided by the knife-edges in the eccentrically loaded stub column tests. Initial local geometric imperfections were incorporated into the developed FE models in the form of the lowest elastic local buckling mode shape under the applied loading condition, obtained from a prior elastic eigenvalue buckling analysis [28]. Three local imperfection magnitudes, including the measured magnitude ω_0 , 1/100 of the maximum of the measured web and flange thickness of the channel section, and the imperfection magnitude calculated from the modified Dawson and Walker (D&W) model $\omega_{D\&W}$ [31,32], were adopted to factor the obtained initial local geometric imperfection distribution, in order to examine the sensitivity of the developed FE models to various imperfection magnitudes and seek the most suitable imperfection magnitudes to be employed in the parametric studies. Upon incorporation of the initial local geometric

imperfections into the FE models, materially and geometrically nonlinear analyses, using the static modified Riks method [28], were conducted to derive the failure loads, load–deformation histories and failure modes.

3.3 Validation of FE models

The accuracy of the developed FE models was assessed through comparisons of the numerically derived failure loads, load–end rotation curves and local buckling failure modes with those observed from the eccentrically loaded stub column tests. Table 6 reports the ratios of numerical to experimental failure loads; good agreement was generally obtained for all the three considered local imperfection magnitudes, indicating that the failure loads of laser-welded stainless steel non-slender channel section stub columns under major axis combined loading were relatively insensitive to local imperfection magnitudes. Comparisons between the experimental and numerical load–end rotation curves for the two series of eccentrically loaded stub column specimens are displayed in Fig. 7, where the initial stiffnesses, the general shapes and the post-ultimate responses of the experimental load–end rotation curves are well captured by their numerical counterparts. Good agreement between the experimental and numerical local buckling failure modes was also obtained, as illustrated in Fig. 4. To conclude, the developed FE models are capable of simulating the experimental responses of the laser-welded stainless steel channel section stub column specimens under combined compression and bending moment about the major axis, and are thus considered to be validated and suitable for conducting parametric studies.

3.4 Parametric studies

Upon validation of the FE models, a series of parametric studies was carried out to generate further structural performance data over a wider range of cross-section sizes and initial loading eccentricities. In the parametric studies, the measured material properties of the laser-welded stainless steel channel section C 40×40×5×5 were used; the initial local geometric imperfection magnitudes, calculated from the modified Dawson and Walker model [31,32], led to the best agreement between the test and numerical failure loads in the validation study, and were also adopted in the parametric studies. Residual stresses were determined from the predictive model of Gardner et al. [30] (see Fig. 5 and Table 5), and incorporated into the FE models. In terms of the geometric dimensions of the modelled channel sections, the outer web widths were set equal to 150 mm, while the outer flange widths were varied between 50 mm and 150 mm, which resulted in a wide spectrum of cross-section aspect ratios from 1.0 to 3.0. The thicknesses of the web and flanges ranged from 6 mm to 20 mm, and the resulting modelled channel sections covered all four cross-section classes, according to the slenderness limits in EN 1993-1-4 [10]. The length of each FE model was set to be equal to three times its mean outer dimensions. The initial loading eccentricities were varied between 5 mm and 770 mm, enabling a broad range of loading combinations to be considered. In total, 220 parametric study results were generated, including 80 for Class 1 sections, 80 for Class 2 sections, 40 for Class 3 sections and 40 for Class 4 sections.

4. Evaluation of current international design codes

4.1 General

In this section, the design provisions for welded stainless steel channel sections under combined compression and bending moment about the major axis, as given in the European code EN 1993-1-4 [10] and American design guide AISC 27 [11], are firstly described and discussed. Then, the accuracy of each design code is evaluated by comparing the test and numerical failure loads N_u against the predicted failure loads $N_{u,pred}$, with the mean ratio of $N_u/N_{u,pred}$ and the corresponding coefficient of variation (COV) listed in Table 7. A value of $N_u/N_{u,pred}$ larger than unity indicates a safe failure load prediction. Note that all the calculations made herein are based on the measured (or modelled) material and geometric properties, and all partial factors are set to be equal to unity, leading to unfactored failure load predictions being compared.

4.2 EN 1993-1-4 (EC3)

The European code for the design of stainless steel structures EN 1993-1-4 [10] employs the same design provisions for cross-section resistances as those given in the carbon steel design code EN 1993-1-1 [33]. For welded stainless steel channel sections under combined compression and major axis bending moment, a linear interaction formula is used, as given by Eq. (1), in which $N_{u,EC3}$ is the design failure load, $M_{u,y,EC3}=N_{u,EC3}(e_0+e')$ is the design failure moment about the major axis, equal to the product of the design failure load $N_{u,EC3}$ and the sum of the initial loading eccentricity e_0 and the generated mid-height lateral deflection e' at failure, $N_{EC3,Rd}$ is the cross-section compression resistance and given by Eq. (2), and $M_{EC3,y,Rd}$ is the

cross-section bending moment resistance about the major axis and given by Eq. (3). The values of $N_{EC3,Rd}$ and $M_{EC3,y,Rd}$ depend on the cross-section class. Specifically, for Class 1 and 2 channel sections, $N_{EC3,Rd}$ is equal to the yield load, defined as the product of the gross cross-sectional area A and the 0.2% proof stress $\sigma_{0.2}$, and $M_{EC3,y,Rd}$ is taken as the plastic moment capacity $M_{pl,y} = W_{pl,y} \sigma_{0.2}$, in which $W_{pl,y}$ is the plastic section modulus about the major axis. For Class 3 channel sections, $N_{EC3,Rd}$ remains equal to the cross-section yield load, while $M_{EC3,y,Rd}$ is given by the elastic moment capacity $M_{el,y}$, equal to the elastic section modulus about the major axis $W_{el,y}$ multiplied by the 0.2% proof stress $\sigma_{0.2}$. For Class 4 channel sections, the effective cross-section area A_{eff} and modulus $W_{eff,y}$ are employed in place of the gross cross-section properties for the calculation of $N_{EC3,Rd}$ and $M_{EC3,y,Rd}$.

$$\frac{N_{u,EC3}}{N_{EC3,Rd}} + \frac{M_{u,y,EC3}}{M_{EC3,y,Rd}} \leq 1 \quad (1)$$

$$N_{EC3,Rd} = \begin{cases} A\sigma_{0.2}, & \text{for Class 1, 2 and 3 stainless steel channel sections} \\ A_{eff}\sigma_{0.2}, & \text{for Class 4 stainless steel channel sections} \end{cases} \quad (2)$$

$$M_{EC3,y,Rd} = \begin{cases} W_{pl,y}\sigma_{0.2} & \text{for Class 1 and 2 stainless steel channel sections} \\ W_{el,y}\sigma_{0.2} & \text{for Class 3 stainless steel channel sections} \\ W_{eff,y}\sigma_{0.2} & \text{for Class 4 stainless steel channel sections} \end{cases} \quad (3)$$

The accuracy of the European code EN 1993-1-4 [10] was assessed through comparisons of the test and numerical failure loads with the design failure loads from Eq. (1). The results of the assessment are presented in Table 7, showing that the mean ratio of $N_u/N_{u,EC3}$ is equal to 1.49 with the corresponding COV of 0.10. The rather high level of conservatism and scatter can also be seen from Fig. 8, where the test and numerical results, normalised by the respective yield loads and plastic moment capacities and arranged by cross-section classes, are plotted together with the average (since the ratios of $W_{el,y}/W_{pl,y}$ and $W_{eff,y}/W_{pl,y}$ vary between channel sections) codified linear design interaction curves. The comparisons results indicated that the

conservatism increases as the cross-sections become stockier (i.e. moving from Class 4 to Class 1). The conservative and scattered EC3 failure load predictions stem principally from the use of linear design interaction curves, which ignore the favourable spread of plasticity and stress redistribution within channel sections under major axis combined loading, and from the inaccurate compression and bending end points of the linear design interaction curves, which are limited to the cross-section yield load and plastic (or elastic and effective) moment capacity, without considering the pronounced strain hardening exhibited by stainless steel.

4.3 AISC 27 (AISC)

The American design guide AISC 27 [11] employs a bi-linear interaction curve for the design of welded stainless steel channel sections under combined compression and bending moment about the major axis, as defined by Eqs (4) and (5), where $N_{u,AISC}$ is the design failure load, $M_{u,y,AISC}=N_{u,AISC} (e_0+e')$ is the design failure moment about the major axis, $N_{c,AISC}$ is the cross-section compression resistance and calculated according to Chapter 5 of AISC 27 [11], and $M_{cy,AISC}$ is the cross-section bending moment resistance about the major axis and determined according to Chapter 6 of AISC 27 [11]. Note that AISC 27 [11] employs the same slenderness limits for cross-section classification as EN 1993-1-4 [10], but with different rules for the calculation of cross-section compression and bending moment resistances. With regard to non-slender channel sections (corresponding to Class 1, 2 and 3 channel sections defined in EN 1993-1-4 [10]), $N_{c,AISC}$ is taken as the cross-section yield load $A\sigma_{0.2}$, while for slender channel sections (corresponding to Class 4 channel sections defined in EN 1993-1-4 [10]), $N_{c,AISC}$ is given as the product of the reduced yield stress $Q_a Q_s \sigma_{0.2}$ and the gross cross-section area A , i.e. $N_{c,AISC}=Q_a Q_s \sigma_{0.2} A$, where Q_a and Q_s are the reduction factors for slender stiffened (web) and unstiffened (flange) plate elements, respectively, and calculated according to Chapter 5 of

AISC 27 [11]. The cross-section bending moment resistance $M_{cy,AISC}$ is determined in accordance with Chapter 6 of AISC 27 [11]. For compact channel sections (corresponding to Class 1 and 2 channel sections defined in EN 1993-1-4 [10]), AISC 27 [11] uses the plastic moment capacity $M_{pl,y}$ but with a upper limit of $1.6M_{el,y}$. For non-compact channel sections (corresponding to Class 3 channel sections defined in EN 1993-1-4 [10]), AISC 27 [11] accounts for partial plasticity in the determination of cross-section bending moment resistances, thus leading to higher resistances than the elastic moment capacities calculated from EN 1993-1-4 [10]. For slender channel sections (corresponding to Class 4 channel sections defined in EN 1993-1-4 [10]), AISC 27 [11] specifies the use of the elastic critical buckling moments as the design bending moment resistances, which are generally more conservative than the effective moment capacities calculated from EN 1993-1-4 [10].

$$\frac{N_{u,AISC}}{N_{c,AISC}} + \frac{8}{9} \frac{M_{u,y,AISC}}{M_{cy,AISC}} \leq 1, \quad \text{for } \frac{N_{u,AISC}}{N_{c,AISC}} \geq 0.2 \quad (4)$$

$$\frac{N_{u,AISC}}{2N_{c,AISC}} + \frac{M_{u,y,AISC}}{M_{cy,AISC}} \leq 1, \quad \text{for } \frac{N_{u,AISC}}{N_{c,AISC}} < 0.2 \quad (5)$$

The AISC predicted failure loads were evaluated through comparisons with the test and numerical failure loads. The mean ratio of $N_u/N_{u,AISC}$, as presented in Table 7, is equal to 1.40 with the COV equal to 0.09. The American design guide AISC 27 [11] was generally found to result in more accurate and consistent failure load predictions for laser-welded stainless steel channel sections under combined compression and major axis bending moment than the European code EN 1993-1-4 [10], owing principally to the use of a more efficient bi-linear design interaction curve. However, since AISC 27 [11] also ignores stain hardening in the design, the failure load predictions are still conservative and scattered.

5. New design approach

5.1 Development of new design approach

The codified design interaction curves for stainless steel channel sections under the combined compression and major axis bending moment, as prescribed in EN 1993-1-4 [10] and AISC 27 [11], suffer from having inaccurate shapes and end points; the shapes do not adequately take into account the favourable stress redistribution within channel sections subjected to combined loading, while the compression and bending end points of the design interaction curves are calculated based on the 0.2% proof stress without considering the favourable material strain hardening of stainless steel. Therefore, improved design approaches may be sought through the use of more accurate end points and then the development of more efficient nonlinear interaction curves, anchored to these new end points.

The continuous strength method (CSM) [12–15] is a deformation-based design approach that relates the cross-section resistance to its deformation capacity and uses a bi-linear material model to account for strain hardening. The method has been shown to result in a high level of accuracy and consistency in the prediction of stainless steel channel section resistances under isolated loading cases (i.e. pure compression and pure bending) [2,15], which are ideal to be used as the new end points. The application of the CSM firstly requires identification of the cross-section deformation capacity under the applied loading condition. This may be achieved through the use of the CSM base curves, which defines the relationship between the strain ratio $\varepsilon_{csm}/\varepsilon_y$ and the cross-section slenderness $\bar{\lambda}_p$, as given by Eqs (6) and (7) for non-slender [12] and slender [13] plated sections, respectively, where ε_{csm} is the maximum (limiting) strain that a cross-section can attain prior to failure by local buckling, $\varepsilon_y = \sigma_{0.2}/E$ is the yield strain, and $\bar{\lambda}_p$

is calculated as $\sqrt{\sigma_{0.2}/\sigma_{cr}}$, in which σ_{cr} is the elastic buckling stress of the full cross-section under the applied loading, and may be determined using the finite strip software CUFSM [34]. The CSM bi-linear (elastic, linear hardening) material model, featuring four material coefficients (C_1 , C_2 , C_3 and C_4), is then employed, which enables design stresses greater than the 0.2% proof stress to be achieved for cross-sections with strain ratios $\varepsilon_{csm}/\varepsilon_y$ greater than unity, as shown in Fig. 9. The CSM material coefficient C_1 is used to define a cut-off strain $C_1\varepsilon_u/\varepsilon_y$ to prevent over-predictions of strength from the linear hardening material model, with a value of 0.1 for austenitic stainless steel. The CSM material coefficient C_2 is employed in Eq. (8) to define the strain hardening slope E_{sh} , and is equal to 0.16 for austenitic stainless steel, while $\varepsilon_u = C_3(1 - \sigma_{0.2}/\sigma_u) + C_4$ is the predicted strain corresponding to the material ultimate strength, where C_3 and C_4 are respectively equal to 1.0 and 0.0 for austenitic stainless steel.

$$\frac{\varepsilon_{csm}}{\varepsilon_y} = \frac{0.25}{\bar{\lambda}_p^{3.6}} \text{ but } \leq \min\left(15, \frac{C_1\varepsilon_u}{\varepsilon_y}\right), \text{ for } \bar{\lambda}_p \leq 0.68 \quad (6)$$

$$\frac{\varepsilon_{csm}}{\varepsilon_y} = \left(1 - \frac{0.222}{\bar{\lambda}_p^{1.050}}\right) \frac{1}{\bar{\lambda}_p^{1.050}}, \text{ for } \bar{\lambda}_p > 0.68 \quad (7)$$

$$E_{sh} = \frac{\sigma_u - \sigma_{0.2}}{C_2\varepsilon_u - \varepsilon_y} \quad (8)$$

Upon determination of the limiting strain ε_{csm} and the strain hardening modulus E_{sh} , the CSM design stress σ_{csm} can be calculated from Eq. (9), while the CSM cross-section compression resistance $N_{csm,Rd}$ is given as the product of the CSM design stress σ_{csm} and the gross cross-section area A , as given by Eq. (10). On the basis of the assumption of a linearly-varying through-depth strain distribution and the CSM elastic, linear hardening material model, the CSM cross-section bending moment resistance $M_{csm,Rd}$ was firstly derived through integration of the CSM design stress distribution throughout the cross-section depth, and then transformed

into a simplified design formula, as given by Eq. (11) [12–15], where α is the CSM bending coefficient, related to cross-section shape, aspect ratio and axis of bending; for channel sections in bending about the major axis, α is taken as 2.0, and $M_{pl}=M_{pl,y}$ and $M_{el}=M_{el,y}$.

$$\sigma_{csm} = \begin{cases} \sigma_{0.2} + E_{sh} (\varepsilon_{csm} - \varepsilon_y), & \text{for } \varepsilon_{csm} \geq \varepsilon_y \\ E\varepsilon_{csm}, & \text{for } \varepsilon_{csm} < \varepsilon_y \end{cases} \quad (9)$$

$$N_{csm,Rd} = A\sigma_{csm} \quad (10)$$

$$M_{csm,Rd} = \begin{cases} M_{pl} \left[1 + \frac{E_{sh}}{E} \frac{W_{el}}{W_{pl}} \left(\frac{\varepsilon_{csm}}{\varepsilon_y} - 1 \right) - \left(1 - \frac{W_{el}}{W_{pl}} \right) / \left(\frac{\varepsilon_{csm}}{\varepsilon_y} \right)^\alpha \right], & \text{for } \bar{\lambda}_p \leq 0.68 \\ \frac{\varepsilon_{csm}}{\varepsilon_y} M_{el}, & \text{for } \bar{\lambda}_p > 0.68 \end{cases} \quad (11)$$

The experimental and numerical results are normalised by the CSM cross-section compression and bending moment resistances, and shown in Fig. 10, where the normalised data points may now be seen to follow a much tighter trend in comparison to the rather scattered data points when normalised by the yield load and plastic moment capacity in Fig. 8. Therefore, the use of the CSM cross-section compression and bending moment resistances as the end points of the design interaction curves can substantially reduce the scatter and conservatism of the failure load predictions. The next step towards developing improved design approaches for stainless steel channel sections under combined compression and major axis bending moment now lies in the employment of efficient nonlinear interaction curves, anchored to these CSM end points.

For channel sections subjected to combined compression and major axis bending moment, the theoretical plastic interaction formula is similar to that for I-sections under the same combination of loading. A bi-linear approximation to the plastic interaction is given by Eq. (12) [33], where $N_{u,p}$ is the design compression load, $M_{u,y,p}=N_{u,p}(e_0+e')$ is the design bending

moment about the major axis, $M_{pl,y}$ is the plastic moment capacity about the major axis, $M_{R,pl,y}$ is the corresponding reduced plastic moment capacity due to the existence of the compression load $N_{u,p}$, and a_w is the ratio of the web area to the gross area of the cross-section, with an upper limit of 0.5.

$$M_{u,y,p} \leq M_{R,pl,y} = M_{pl,y} \frac{(1 - N_{u,p} / A\sigma_{0.2})}{(1 - 0.5a_w)} \leq M_{pl,y} \quad (12)$$

Considering that the normalised test and numerical data points in Fig. 10 generally display a bi-linear trend, it is proposed to adopt the bi-linear interaction curve given by Eq. (12), but with the CSM cross-section compression and bending moment resistances replacing the yield load and plastic moment capacity as the end points, for the design of stainless steel channel sections under combined compression and major axis bending moment. Note that the bi-linear interaction curve with the EC3 end points (i.e. yield load and plastic moment capacity) is also recommended for Class 1 and 2 stainless steel channel sections. A transition is defined at a cross-section slenderness $\bar{\lambda}_p$ equal to 0.60 (corresponding to a strain ratio $\varepsilon_{csm}/\varepsilon_y$ of 1.6), beyond which a linear design interaction curve is used to ensure compatibility with the increasingly elastic end points as the cross-section slenderness approaches $\bar{\lambda}_p = 0.68$ (corresponding to a strain ratio $\varepsilon_{csm}/\varepsilon_y$ of 1.0), where the CSM cross-section compression and bending moment resistances are equal to the yield load $A\sigma_{0.2}$ and elastic moment capacity $M_{el,y}$. The proposed bi-linear and linear design interaction curves for stainless steel channel sections under combined compression and major axis bending moment are defined by Eqs (13) and (14), respectively, where $N_{u,csm}$ is the design compression load, $M_{u,y,csm} = N_{u,csm}(e_0 + e')$ is the design bending moment about the major axis, $M_{csm,y,Rd}$ is the CSM cross-section bending moment resistance about the major axis, calculated from Eq. (11), and $M_{R,csm,y,Rd}$ is the corresponding reduced CSM cross-section bending moment resistance due to the existence of the compression

load $N_{u,csm}$. The proposed bi-linear and linear design interaction curves are plotted in Fig. 10, and shown to accurately represent the distribution of the test and numerical data points.

$$M_{u,y,csm} \leq M_{R,csm,y,Rd} = M_{csm,y,Rd} \frac{(1 - N_{u,csm} / N_{csm,Rd})}{(1 - 0.5a_w)} \leq M_{csm,y,Rd}, \text{ for } \bar{\lambda}_p \leq 0.60 \quad (13)$$

$$\frac{N_{u,csm}}{N_{csm,Rd}} + \frac{M_{u,y,csm}}{M_{csm,y,Rd}} \leq 1, \quad \text{for } \bar{\lambda}_p > 0.60 \quad (14)$$

The accuracy of the new CSM-based design approach was assessed by comparing the test and numerical failure loads against the predicted failure loads. As reported in Table 7, the mean $N_u/N_{u,csm}$ ratio is equal to 1.13 with the COV of 0.05, indicating that the new CSM-based design approach yields significantly more accurate and consistent failure load predictions for laser-welded stainless steel channel sections under combined compression and major axis bending moment than the current design codes. The improved accuracy and consistency of the new CSM-based design approach can also be seen in Figs 11 and 12, where the failure loads predicted from the new design proposal and existing design codes are plotted against the test and numerical failure loads.

5.2 Reliability analysis

In this section, the reliability of the new design proposal was evaluated through statistical analyses, according to the requirements of EN 1990 [35]. In the present reliability analyses, the material over-strength ratio for austenitic stainless steel was taken as 1.3 with the COV of 0.06, while the COV of the geometric properties of stainless steel cross-sections was taken equal to 0.050, as recommended by Afshan et al. [36]. The key statistical parameters, calculated based on a total of 228 test and numerical data, are summarised in Table 8, where $k_{d,n}$ is the design (ultimate limit state) fractile factor, b is the mean ratio of test and numerical resistances to

design model resistances, V_δ is the COV of the test and numerical resistances relative to the resistance model, V_r is the combined COV incorporating both model and basic variable uncertainties, and γ_{M0} is the partial safety factor for stainless steel cross-section resistance. As reported in Table 8, the resulting partial safety factor for the new design proposal is equal to 0.9, which is less than the currently adopted value of 1.1 in EN 1993-1-4 [10], thus demonstrating that the new design proposal for laser-welded stainless steel channel sections under combined compression and major axis bending moment satisfies the reliability requirements of EN 1990 [35].

5.3 Summary

Overall, EN 1993-1-4 [10] yields the highest level of conservatism and scatter in the prediction of failure loads for laser-welded stainless steel channel sections under combined compression and major axis bending moment, due to the use of a linear design interaction curve anchored to conservative compression and bending end points determined without considering strain hardening of stainless steel. AISC 27 [11] adopts a bi-linear design interaction curve, and leads to improved failure load predictions than EN 1993-1-4 [10]. The new design proposal employs an efficient bi-linear design interaction curve with the CSM cross-section compression and bending moment resistances as the end points, and has been shown to result in more accurate and consistent failure load predictions than the current design codes. Comparisons of the test results against the proposed and codified design interaction curves are shown in Fig. 13, which also highlight the improved accuracy and consistency of the new CSM-based design approach.

6. Conclusions

A comprehensive experimental and numerical modelling programme has been conducted to investigate the structural performance of laser-welded stainless steel channel sections under combined compression and major axis bending moment. A total of eight eccentrically loaded stub column tests on two channel section sizes was conducted. The test results were used in a numerical modelling programme for the validation of FE models, which were then employed to conduct a series of parametric studies to extend the current test data pool over a broader range of cross-section sizes and initial loading eccentricities. Analysis of the experimental and numerical results allowed the current codified design provisions for welded stainless steel channel sections under combined compression and major axis bending moment given in EN 1993-1-4 [10] and AISC [11] to be assessed. Generally, both the considered codified design methods were found to yield unduly conservative and scattered failure load predictions, principally due to the adoption of conservative design interaction curves and the use of conservative compression and bending end points. An improved design approach was then proposed through the use of a bi-linear interaction curve, anchored to more accurate end points determined from the continuous strength method (CSM) [12–15], which rationally exploits strain hardening in the determination of cross-section compression and bending resistances. The new CSM-based design approach was shown to yield significantly improved failure load predictions for laser-welded stainless steel channel sections under combined compression and major axis bending moment. The reliability of the new design proposal was confirmed by means of statistical analyses according to EN 1990 [35].

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Fig. 1. Notations and locations of tensile coupons and strain gauges.

Fig. 2. Eccentrically loaded stub column test setup.

Fig. 3. Load–end rotation curves for eccentrically loaded stub column tests.

Fig. 4. Experimental and numerical failure modes for specimen C 100×50×6×9-2A.

Fig. 5. Residual stress distribution pattern for laser-welded stainless steel channel sections.

Fig. 6. Typical residual stress distribution and amplitudes (in MPa) in FE models for C 100×50×6×9 specimens (positive values indicate tensile residual stresses while negative values indicate compressive residual stresses).

Fig. 7. Experimental and numerical load–end rotation curves for eccentrically loaded stub column tests.

Fig. 8. Eccentrically loaded stub column test and numerical results normalised by cross-section yield loads and plastic moment capacities.

Fig. 9. CSM elastic, linear hardening material model.

Fig. 10. Eccentrically loaded stub column test and numerical results normalised by CSM cross-section compression and bending moment resistances.

Fig. 11. Comparison of test and numerical failure loads with predicted failure loads from EN 1993-1-4 [10] and CSM-based design approach.

Fig. 12. Comparison of test and numerical failure loads with predicted failure loads from AISC 27 [11] and CSM-based design approach.

(a) C 40x40x5x5 specimens.

(b) C 100x50x6x9 specimens.

Fig. 13. Comparison of test results with proposed and codified design interaction curves.

Table 1 Summary of key average measured material properties [3].

Cross-section	E	$\sigma_{0.2}$	$\sigma_{1.0}$	σ_u	ε_u	ε_f	R-O exponents	
	(GPa)	(MPa)	(MPa)	(MPa)	(%)	(%)	n	$n'_{0.2,1.0}$
C 40×40×5×5	190	292	383	659	57	69	4.8	3.5
C 100×50×6×9-W	185	258	340	576	49	64	3.7	3.3
C 100×50×6×9-F	196	275	337	604	51	67	5.8	2.5

Table 2 Measured initial local geometric imperfection magnitudes [3].

Cross-section	ω_{f1}	ω_{f2}	ω_w	ω_0
	(mm)	(mm)	(mm)	(mm)
C 40×40×5×5	0.48	0.29	0.30	0.48
C 100×50×6×9	0.38	0.21	0.13	0.38

Table 3 Measured geometric properties of eccentrically loaded stub column specimens.

Cross-section	Specimen ID	L	h	b_f	t_w	t_f
		(mm)	(mm)	(mm)	(mm)	(mm)
C 40×40×5×5	1A	120.1	40.02	40.02	4.59	4.81
	1B	120.3	39.94	40.00	4.62	4.80
	1C	119.5	40.05	39.99	4.60	4.79
	1D	120.4	39.98	39.96	4.65	4.83
C 100×50×6×9	2A	300.2	100.35	49.56	5.94	8.75
	2B	299.5	100.33	49.47	5.96	8.81
	2C	300.1	100.31	49.50	5.95	8.78
	2D	300.0	100.36	49.49	5.95	8.83

Table 4 Summary of eccentrically loaded stub column test results.

Cross-section	Specimen ID	e_0	N_u	e'	M_u	ϕ_u
		(mm)	(kN)	(mm)	(kNm)	(deg)
C 40×40×5×5	1A	13.0	107.2	2.9	1.7	1.4
	1B	28.1	78.6	3.7	2.5	1.8
	1C	40.5	57.4	4.1	2.6	1.9
	1D	43.6	55.4	4.1	2.6	2.1
C 100×50×6×9	2A	8.9	391.7	6.1	5.9	1.9
	2B	10.9	380.1	6.3	6.5	2.0
	2C	18.3	339.0	6.8	8.5	2.3
	2D	27.5	295.1	7.6	10.4	2.5

Table 5 Distribution parameters in residual stress model for laser-welded stainless steel channel sections

[30].

Parameter	a	b	c	d
	$0.2b_f$	$0.075b_f + 0.5t_w$	$0.0375h_w$	$0.1h_w$

Table 6 Comparison of FE failure loads with test failure loads for varying initial local geometric imperfection magnitudes.

Cross-section	Specimen ID	e_0 (mm)	FE N_u /Test N_u		
			ω_0	$t/100$	$\omega_{D\&W}$
C 40×40×5×5	1A	13.0	0.97	1.00	1.00
	1B	28.1	0.89	0.92	0.92
	1C	40.5	0.95	0.98	0.98
	1D	43.6	0.93	0.96	0.96
C 100×50×6×9	2A	8.9	0.98	0.99	0.99
	2B	10.9	0.98	0.98	0.99
	2C	18.3	0.98	0.99	0.99
	2D	27.5	0.99	1.00	1.00
Mean			0.96	0.98	0.98
COV			0.04	0.03	0.03

Table 7 Comparisons of test and FE failure loads with predicted failure loads.

No. of test data: 8	$N_u/N_{u,EC3}$	$N_u/N_{u,AISC}$	$N_u/N_{u,csm}$
No. of numerical data: 220			
Mean	1.49	1.40	1.13
COV	0.10	0.09	0.05

Table 8 Reliability analysis results calculated according to EN 1990 [35].

No. of test and numerical data	$k_{d,n}$	b	V_δ	V_r	γ_{M0}
228	3.133	1.146	0.051	0.093	0.90

Table 1 Summary of key average measured material properties [3].

Cross-section	E	$\sigma_{0.2}$	$\sigma_{1.0}$	σ_u	ε_u	ε_f	R-O exponents	
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	1D	120.4	39.98	39.96	4.65	4.83
C 100×50×6×9	2A	300.2	100.35	49.56	5.94	8.75
	2B	299.5	100.33	49.47	5.96	8.81
	2C	300.1	100.31	49.50	5.95	8.78
	2D	300.0	100.36	49.49	5.95	8.83

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	2C	18.3	339.0	6.8	8.5	2.3
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Parameter	a	b	c	d
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	1D	43.6	0.93	0.96	0.96
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	2B	10.9	0.98	0.98	0.99
	2C	18.3	0.98	0.99	0.99
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