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Behaviour and design of cold-formed lean duplex stainless steel lipped channel columns

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ABSTRACT

This paper presents a numerical investigation on the behaviour and design of lean duplex stainless steel (LDSS) lipped channel columns subjected to axial compression. Numerical models were developed using general purpose finite element (FE) package ABAQUS, and have been verified using experimental data available in the literature. Developed FE models included material nonlinearities as well as initial geometric imperfections. A comprehensive parametric study has been carried out covering a wide range of slenderness with different cross section geometries for the considered lipped channel columns. Column resistances obtained from the numerical study were used to assess the performance of the current Direct Strength Method (DSM) guidelines when applied for cold-formed LDSS columns; obtained comparisons showed considerable conservatism. A modified design method for LDSS lipped channels is proposed herein following DSM techniques, which provides considerably more accurate predictions for the considered cold-formed columns. Reliability of the proposed design equations is also presented showing a good agreement with both experimentally and numerically obtained results.

1. Introduction

Stainless steel offers many highly desirable properties including corrosion resistance, aesthetic appearance, recyclability, improved performance in fire, negligible maintenance cost and durability that make it an attractive construction material, especially in coastal regions of high corrosion. Austenitic grades with nickel content of 8–11% were typically more common in early applications but the increasing price of nickel with associated volatility makes it a difficult choice in the construction sector. Recent development of low nickel stainless steel alloys such as Lean Duplex Stainless Steel (LDSS) promises to be a viable alternative to its expensive counterparts. LDSS such as grade EN 1.4162 in particular, has a low nickel content of ~1.5%, and an increased strength compared to conventional austenitic and ferritic stainless steels, making it a potentially attractive material for use in construction. Appropriate use of this material will reduce life cycle costs and will allow achieving sustainable solutions for structural applications.

Considerable research has been carried out in the area of structural stainless steel during the last few decades. However, stainless steel research is primarily focused on hollow sections produced from austenitic and duplex grades due to their easy availability. Limited experimental evidence is currently available for open cross-sections, especially for those produced from LDSS. Liu and Young [1], and Gardner and Nethercot [2] performed tests on cold-formed hollow section columns produced from austenitic stainless steels. Ellobody and Young [3] investigated the structural performance of high strength stainless steel members. Young and Wing-Man Lui [4,5] experimentally investigated the behaviour of cold-formed high strength stainless square and rectangular hollow section columns produced from duplex and high strength austenitic stainless steel. Ashraf et al. [6–8] reported comprehensive investigations on FE modelling for different stainless steel cross section types, and proposed a generalized design method based on the deformation capacity of cross sections. Gardner and Ashraf [9] proposed a design approach that is suitable for nonlinear metallic materials, and is based on an accurate material model applicable for stresses greater than 0.2% proof strains. Becque et al. [10–12] proposed Direct Strength formulations to predict the strength of ferritic and authentic steel columns based on experimental and numerical evidences.SHS and RHS columns produced from LDSS were experimentally and numerically investigated by Theofanous and Gardner [13–14]. Huang and Young [15] also conducted tests on SHS and RHS members produced from LDSS. FE investigations for LDSS hollow section columns with various cross-section types i.e. square, L-, T-, and +-shaped sections were recently reported by

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Nomenclature

A	cross-sectional area (mm^2)
b_f	breadth of flange of lipped channel section
b_l	breadth of lip of lipped channel section
b_w	breadth of web of lipped channel section
E_o	initial Young's modulus
E_t	tangent modulus
L	length of specimen
L_e	effective length of specimen
n	exponent in Ramberg–Osgood expression
P_{crl}	critical elastic local buckling load (kN)
P_{crd}	critical elastic distortional buckling load (kN)
P_{cre}	critical elastic Euler's buckling load (kN)
P_{EXP}	Experimental failure load (kN)
P_{FEA}	ultimate load calculated from the FE analysis (kN)
P_{nl}	nominal member capacity of a member in compression for local buckling (kN)
P_{nd}	nominal member capacity of a member in compression for distortional buckling (kN)
P_{ne}	nominal member capacity of a member in compression for flexural, torsional and flexural/torsional buckling (kN)
$P_{\acute{y}}$	yield capacity of the member in compression (kN)
$P_{n,DSM}$	unfactored design strength calculated by Direct Strength Method (kN)
$P_{n,Bec}$	unfactored design strength calculated by design rules in Becque [11] (kN)
$P_{n,Pro}$	unfactored design strength calculated using the proposed design rule for Direct Strength Method (kN)
r_i	inner corner radius of specimen
r_o	outer corner radius of specimen
t	thickness of lipped channel section
λ_l	local buckling slenderness
λ_d	distortional buckling slenderness
λ_c	overall buckling slenderness
λ_s	cross-sectional slenderness
λ_o	overall slenderness
σ_{cr}	elastic critical buckling stress of the section
$\sigma_{0.2}$	static 0.2% tensile proof stress
σ_u	static ultimate tensile strength
β	reliability index
ϕ	resistance factor

Patton and Singh [16–17].

The current research aims at investigating the buckling behaviour of LDSS fixed ended lipped channel sections under axial compression. An FE model was developed including material nonlinearities, strength enhancements due to cold-working at the corner regions, geometric nonlinearity and geometric imperfections. The performance of the developed model was verified against available experimental results, and the technique was subsequently used to carry out an extensive parametric study covering a wide range of member and section slenderness. Numerically generated column resistances were compared against those obtained using current guidelines proposed in the Direct Strength Method (DSM). Appropriate modifications are proposed for DSM to accurately predict the resistance of LDSS lipped channel columns.

2. Finite element modelling

LDSS is new type of stainless steel, and hence limited number of experimental evidences are currently available on hollow section columns produced from this new SS grade. The lack of tests on LDSS lipped columns prompted the current paper to adopt a two stage validation to justify the accuracy of the adopted FE modelling technique. Before using the developed FE models of LDSS lipped channel columns for parametric analysis, the modelling technique was validated against LDSS hollow sections followed by lipped channel sections produced from other SS grades. Initially, FE models were developed using ABAQUS [22] to simulate the cold-formed RHS LDSS column tests reported in [15]. The model was based on the centre line dimensions of the cross-section. 4 node doubly curved shell elements with reduced integration S4R were used in FE modelling. A uniform mesh of size 5 mm × 5 mm was adopted in the flat portions of the columns through convergence study, whilst smaller elements were used at corners to ensure accurate curvatures were achieved in the models. Linear Eigen value buckling analysis was followed by nonlinear analysis, where material nonlinearity or "plasticity" was included in the FEM. Three material models proposed for stainless steel by Rasmussen [19], Gardner and Ashraf [9], and Afshan and Gardner [20] were used initially to check their accuracy in predicting the load-deformation behaviour of SS members.Residual stresses were neglected in the model as it is reported to have negligible effect on the ultimate load and load-end shortening behaviour (Ellobody and Young, [3]). Tables 1 and 2 show the measured dimensions of tested specimens and material properties reported by Huang and Young [15] respectively. These results were used for initial verification. It is worth noting that nonlinear material models proposed by Rasmussen [19] and Gardner and Ashraf [9] require additional parameters, which were calculated using the guidelines reported by Quach et al. [21]. Enhanced material strength at corners for the considered press-braked sections were restricted to the corner regions following the recent FE modelling technique reported by Huang and Young [15], where material properties were adopted from tension coupon tests. It is, however, worth noting that Ashraf et al. [7] suggested extending the enhanced material properties up to 2t beyond the corner regions when the material properties were taken from compression coupon tests. As the current study uses tension coupon tests, Huang and Young's [15] suggested approach was adopted in the parametric analysis.

Reference points (RP1 and RP2) were created at the geometric centroid of the section to define appropriate boundary conditions at the ends of the column. Fig. 1(a) illustrates the validation model for RHS.

The column ends were constrained through multi point constraint (MPC) available in ABAQUS [21]. Except for the vertical translation, all degrees of freedom were restrained at the loaded end. This MPC acted as a rigid surface that was rigidly connected to the upper and lower ends of the column (Fig. 1b).

The reference points for the constraints were considered at the

Table 1
Tested column dimensions (Huang and Young [15]).

Specimen ID	Depth (D) (mm)	Width (B) (mm)	Thickness (t) (mm)	Outer radius (r_0) (mm)	Inner radius (r_i) (mm)	Length (L) (mm)	Area (A) mm^2
SC5L300	100.1	50.9	2.510	3.3	1.2	300.1	718.0
SC6L450	150.0	50.2	2.463	4.3	2.0	450.0	944.8