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Structural performance of cold-formed lean duplex stainless steel columns

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ABSTRACT

The structural performance of cold-formed lean duplex stainless steel columns was investigated. A wide range of finite element analysis on square and rectangular hollow sections and other available data, with a total number of 259 specimens, were considered. An accurate finite element model has been created to simulate the pin-ended cold-formed lean duplex stainless steel columns. Extensive parametric study was carried out using the validated finite element model. The column strengths predicted from the parametric study together with the available data are compared with the design strengths calculated from various existing design rules for cold-formed stainless steel structures. It is shown that the existing design rules, except for the ASCE Specification as well as the stub column and full area approach, are conservative. Modifications are proposed for the AS/NZS Standard, EC3 Code, and direct strength method. Reliability analysis was performed to assess the existing and modified design rules. It is also shown that the modified design rules are able to provide a more accurate and reliable predictions for lean duplex stainless steel columns. In this study, it is suggested that the modified design rules in the AS/NZS Standard and the modified direct strength method to be used in designing cold-formed lean duplex stainless steel columns.

1. Introduction

Cold-formed stainless steel structures have been increasingly used, due to its high corrosion resistance, aesthetic appearance, ease of construction, and maintenance of structures. The high cost of stainless steel material is one of the main drawbacks for its application in construction projects. In recent years, a relatively new type of lean duplex stainless steel of grade EN 1.4162 (LDX 2101) with high strength and low Nickel content has been developed. The structural and economic advantages of lean duplex stainless steel offer great potential for the use of its material by structural engineers.

Previous researches on the design of column members were mainly focused on austenitic stainless steel grades EN 1.4301 (AISI 304) and EN 1.4401 (AISI 316) as well as ferritic stainless steel grade EN 1.4003 and duplex stainless steel grade EN 1.4462. However, investigation on column members of lean duplex stainless steel is very limited. Young and Hartono [1] conducted tests on austenitic stainless steel grade EN 1.4301 circular hollow section columns, and compared the test results with the existing design rules. It is shown that the current specifications are unconservative in designing compressive members. The design rules proposed by Rasmussen and Hancock [2] and Rasmussen and Rondal [3] are conservative and more reliable than the existing specifications for square hollow section (SHS) and circular hollow section (CHS) columns. Gardner [4] investigated the design of column and beam members of austenitic stainless steel. A new design approach which offers better prediction has been proposed. Young [5] and Young and Lui [6] studied the material properties and structural behaviour of duplex stainless steel grade EN 1.4462 SHS and rectangular hollow section (RHS) columns. It is shown that the current specifications are generally conservative. Theofanous and Gardner [7] carried out experimental and numerical investigations on stub columns and pin-ended columns of lean duplex stainless steel SHS and RHS columns. It is suggested that the class 3 limit ($c/t\varepsilon$) be relaxed from 30.7 to 37.0, and a new effective width equation has been proposed. Huang and Young [8 and 9] conducted a series of stub and pin-ended column tests on lean duplex stainless steel SHS and RHS. It was found that the existing design specifications are generally conservative for column members. A new design approach using stub column properties and full cross-sectional area to calculate compression capacity has been recommended.

The objective of this paper is to study the structural performance of cold-formed lean duplex stainless steel columns. A total number of 259 data, including the numerical results obtained from the parametric study in this paper and the available experimental and numerical data, were compared with the existing American Specification [10], Australian/New Zealand Standard [11], European Code [12] as well as the design rules proposed by Theofanous and Gardner [7] based on European Code, direct strength method (DSM), and the stub column and full area approach proposed by Huang and Young [9]. It should be noted that the lean duplex stainless steel is currently

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Nomenclature

A	full area
A_e	effective area
B	overall width of specimen
b_{eff}	effective width in European Code
C_p	correction factor
c	flat width of specimen
D	overall depth of specimen
E_o	initial Young's modulus
E_t	tangent modulus
e	eccentricity or ratio of yield stress to initial Young's modulus
F_m	mean value of fabrication factor
f_n	buckling stress in Australian/New Zealand Standard
f_y	yield stress (0.2% proof stress) in Australian/New Zealand Standard and European Code
k	effective length factor
L	length of specimen
l_e	effective length of specimen
M_m	mean value of material factor
n	Ramberg–Osgood parameter
P_{ASCE}	unfactored design strengths (nominal strength) by American Specification
$P_{AS/NZS}$	unfactored design strengths (nominal strength) by American Specification
P_{crl}	critical elastic local buckling load
P_{DSM}	the nominal member capacity of a member in compression
P_{EC3}	unfactored design strengths by European Code
$P_{T\&G}$	unfactored design strengths calculated by design rules in Theofanous and Gardner [7]
P_{Exp}	experimental ultimate load (test strength)
P_{FEA}	ultimate load calculated from finite element analysis
P_m	mean value of test and finite element to design predictions
P_{ne}	nominal member capacity of a member in compression for flexural, torsional or flexural–torsional buckling
P_{nl}	nominal member capacity of a member in compression for local buckling
P_u	ultimate strength of test or finite element specimens
P_y	the nominal yield capacity of the member in compression
$P^{\#}_{AS/NZS}$	unfactored design strengths calculated using the proposed design rules for Australian/New Zealand Standard
$P^{\#}_{DSM}$	unfactored design strengths calculated using the proposed design rules for direct strength method
$P^{\#}_{EC3}$	unfactored design strengths calculated using the proposed design rules for the European Code
P^{*}_{ASCE}	unfactored design strengths calculated using material properties obtained from stub column tests and full area for American Specification
$P^{*}_{AS/NZS}$	unfactored design strengths calculated using material properties obtained from stub column tests and full area for Australian/New Zealand Standard
P^{*}_{EC3}	unfactored design strengths calculated using material properties obtained from stub column tests and full area for European Code
r_y	radius of gyration about minor axis
t	thickness of specimen
V_F	coefficient of variation of fabrication factor
V_m	coefficient of variation of material factor
V_p	coefficient of variation of test and finite element to design predictions
α	coefficient of buckling stress in Australian/New Zealand Standard or imperfection factor in European Code
β	coefficient of buckling stress in Australian/New Zealand Standard
β_0	reliability index
β_1	reliability index
χ	reduction factor for members in compression in European Code
ε	material factor in European Code
ϕ_0	resistance factor
ϕ_1	resistance factor
λ	slenderness factor in American Specification and Australian/New Zealand Standard
λ_c	non-dimensional slenderness to determine P_{ne}
λ_l	coefficient of buckling stress in Australian/New Zealand Standard or the non-dimensional slenderness to determine P_{nl}
λ_o	coefficient of buckling stress in Australian/New Zealand Standard
$\overline{\lambda}_o$	limiting slenderness in European Code
$\overline{\lambda}_p$	element slenderness in European Code
ε_f	tensile strain after fracture based on gauge length of 25 mm
ρ	reduction factor in effective width calculation
σ_u	static ultimate tensile strength
$\sigma_{0.2}$	static 0.2% tensile proof stress

not covered by the ASCE [10], AS/NZS [11] and EC3 [12] specifications. Reliability analysis was performed on the existing design rules. Modifications are suggested for the design rules in the AS/NZS, EC3, and DSM. The modified AS/NZS and modified DSM are recommended to be used in designing lean duplex stainless steel columns, due to their accurate and reliable predictions as well as the relatively simple calculation procedure.

2. Finite element model for pin-ended columns

2.1. General

This section of the paper describes the finite element model by using the programme ABAQUS version 6.11 [13] to simulate the cold-formed lean duplex stainless steel pin-ended column tests conducted by Huang and Young [9]. The measured geometry, material properties, residual stresses, initial local and overall geometric imperfections of the test specimens were used in the finite element model (FEM).

2.2. Type of element and material modelling

A four-noded shell element with reduced integration S4R was used to model the SHS and RHS pin-ended columns. A mesh size of 10 mm × 10 mm (length by width) was adopted in the flat portions of the columns. A finer mesh was used at the corners of the sections to ensure the curvature is accurately modelled. The material modelling used in this study is identical to the FEM as described in Huang and Young [8]. The measured stress–strain curves of flat portions and corners of each section were included in the model. Multi-linear stress–strain curves were used, including