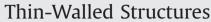
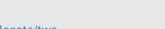
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# Structural performance of cold-formed lean duplex stainless steel columns



THIN-WALLED STRUCTURES

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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.

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#### 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		$P_{DSM}^{\#}$	unfactored design strengths calculated using the pro-
			posed design rules for direct strength method
A	full area	$P_{EC3}^{\#}$	unfactored design strengths calculated using the pro-
A <sub>e</sub>	effective area		posed design rules for the European Code
B	overall width of specimen	$P^*_{ASCE}$	unfactored design strengths calculated using material
b <sub>eff</sub>	effective width in European Code		properties obtained from stub column tests and full
C <sub>p</sub>	correction factor		area for American Specification
c c	flat width of specimen	P <sup>*</sup> <sub>AS/NZS</sub>	unfactored design strengths calculated using material
D	overall depth of specimen	10/1120	properties obtained from stub column tests and full
E <sub>o</sub>	initial Young's modulus		area for Australian/New Zealand Standard
$E_t$	tangent modulus	$P_{EC3}^*$	unfactored design strengths calculated using material
e	eccentricity or ratio of yield stress to initial Young's	LCJ	properties obtained from stub column tests and full
	modulus		area for European Code
Fm	mean value of fabrication factor	$r_y$	radius of gyration about minor axis
$f_n$	buckling stress in Australian/New Zealand Standard	t	thickness of specimen
$\int_{y}^{n}$	yield stress (0.2% proof stress) in Australian/New	$V_F$	coefficient of variation of fabrication factor
Jy	Zealand Standard and European Code	$V_m$	coefficient of variation of material factor
k	effective length factor	$V_p$	coefficient of variation of test and finite element to
L	length of specimen	• p	design predictions
$l_e$	effective length of specimen	α	coefficient of buckling stress in Australian/New Zeal-
$M_m$	mean value of material factor	01	and Standard or imperfection factor in European Code
n	Ramberg–Osgood parameter	β	coefficient of buckling stress in Australian/New Zeal-
P <sub>ASCE</sub>	unfactored design strengths (nominal strength) by	P	and Standard
I ASCE	American Specification	$\beta_0$	reliability index
D	unfactored design strengths (nominal strength) by	$\beta_1$	reliability index
P <sub>AS/NZS</sub>	American Specification	$\chi$	reduction factor for members in compression in
P <sub>crl</sub>	critical elastic local buckling load	λ	European Code
P <sub>DSM</sub>	the nominal member capacity of a member in	ε	material factor in European Code
<sup>1</sup> DSM	compression	$\phi_0$	resistance factor
D	unfactored design strengths by European Code	$\phi_1^{\phi_0}$	resistance factor
P <sub>EC3</sub> P <sub>T&amp;G</sub>	unfactored design strengths calculated by design rules	$\lambda^{\gamma_1}$	slenderness factor in American Specification and Aus-
I T&G	in Theofanous and Gardner [7]		tralian/New Zealand Standard
D	experimental ultimate load (test strength)	$\lambda_c$	non-dimensional slenderness to determine $P_{ne}$
$P_{Exp}$ $P_{FEA}$	ultimate load calculated from finite element analysis	$\lambda_l$	coefficient of buckling stress in Australian/New Zeal-
	mean value of test and finite element to design	101	and Standard or the non-dimensional slenderness to
$P_m$	predictions		determine $P_{nl}$
D	nominal member capacity of a member in compres-	$\lambda_{0}$	coefficient of buckling stress in Australian/New Zeal-
Pne	sion for flexural, torsional or flexural-torsional	100	and Standard
	buckling	$\overline{\lambda}_{o}$	limiting slenderness in European Code
D	nominal member capacity of a member in compres-	$\frac{\lambda_0}{\lambda_p}$	element slenderness in European Code
$P_{nl}$	sion for local buckling	$\varepsilon_f$	tensile strain after fracture based on gauge length
	ultimate strength of test or finite element specimens	$c_f$	of 25 mm
$P_u$	the nominal yield capacity of the member in	ρ	reduction factor in effective width calculation
$P_y$	compression	$\sigma_u^{ ho}$	static ultimate tensile strength
$P_{AS/NZS}^{\#}$	unfactored design strengths calculated using the pro-	$\sigma_{u}$	static 0.2% tensile proof stress
PAS/NZS	posed design rules for Australian/New Zealand	00.2	state 0.2% tensile proof stress
	· · · · · · · · · · · · · · · · · · ·		
	Standard		

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  $\times$  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

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