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Experimental and numerical investigation of cold-formed lean duplex stainless steel flexural members

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ABSTRACT

Experimental and numerical investigation of cold-formed lean duplex stainless steel flexural members is presented in this paper. The test specimens were cold-rolled from flat plates of lean duplex stainless steel with the nominal 0.2% proof stress of 450 MPa. Specimens of square and rectangular hollow sections subjected to both major and minor axes bending were tested. A finite element model has been created and verified against the test results using the material properties obtained from coupon tests. It is shown that the model can accurately predict the behaviour of lean duplex stainless steel flexural members. An extensive parametric study was carried out using the verified finite element model. The test and numerical results as well as the available data on lean duplex beams are compared with design strengths predicted by various existing design rules, such as the American Specification, Australian/New Zealand Standard, European Code and direct strength method for cold-formed stainless steel. Reliability analysis was performed to evaluate the reliability of the design rules. It is shown that these current design rules provide conservative predictions to the design strengths of lean duplex stainless steel flexural members. In this study, modified design rules on the American Specification, Australian/New Zealand Standard, European Code and direct strength method are proposed, which are shown to improve the accuracy of these design rules in a reliable manner.

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1. Introduction

Cold-formed stainless steel is gaining increasing applications as a construction material serving both architectural and structural needs. It provides aesthetic and modern shining appearance, superior corrosion resistance, longer service life with easy maintenance, and convenience in construction. Therefore, extensive research has been carried out on the structural performance of stainless steel structures. Design specifications for stainless steel structures were developed for various types of stainless steel, including ferritic, austenitic and duplex stainless steel. Nevertheless, the high cost of stainless steel material constrains its wider application. In recent years, a relatively new type of stainless steel, called lean duplex stainless steel of grade EN 1.4162 (LDX 2101), with structural and economical advantages was developed. It is becoming an attractive choice as a construction material due to its low cost compared to duplex stainless steel, and the strength of the material is comparable with duplex stainless steel. However, the lean duplex stainless steel is currently not covered in any design specification, and the investigation on such new material is also limited.

Theofanous and Gardner [1] carried out three-point bending tests on eight specimens and finite element analysis on 36 specimens of lean duplex stainless steel rectangular hollow section (RHS) and square hollow section (SHS). It was found that the European Code is overly conservative, while the Australian/New Zealand Standard and the American Specification provided more accurate prediction to the strengths of flexural members. The modified classification limits that proposed by Gardner and Theofanous [2] and the continuous strength method (CSM) provided better prediction to the flexural members. Huang and Young [3] investigated the material properties of lean duplex stainless steel by conducting coupon tests, stub column tests and measurement of residual stresses. Column tests were conducted on cold-formed lean duplex stainless steel members by Huang and Young [4]. It was found that the current design specifications are generally conservative for columns, and a new design approach of using stub column property and full cross-sectional area in calculation compression capacity has been recommended. Furthermore, finite element analysis on lean duplex stainless steel columns was also performed by Huang and Young [5]. A total number of 259 column strengths were compared with design values predicted by various design rules. It is shown that the existing design rules are generally conservative. Modifications are proposed for the AS/NZS Standard, EC3 Code and direct strength method in order to obtain a more accurate prediction

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Nomenclature

A	full area
B	overall width of the flange
b	flat width of the flange
b_e	effective width of compressive flange
C_y	compression strain factor in American Specification and Australian/New Zealand Standard
D	overall depth of the web
d	flat portion of the web
d_e	effective width of stress block in the compressive web
d_{e1}	portion of the effective width of compressive web in stress gradient
d_{e2}	portion of the effective width of compressive web in stress gradient
d_g	height of the stress gradient in the compression portion of the web in the modified approach by inelastic reserve capacity
d_w	depth of the compressed portion of the web
E_o	initial Young's modulus
e_y	yield strain in American Specification and Australian/New Zealand Standard
F_m	mean value of fabrication factor
f_y	yield strength
k	curvature
$k_{Exp,u}$	curvature corresponding to the experimental ultimate moment
$k_{FEA,u}$	curvature corresponding to the ultimate moment predicted by finite element analysis
k_{pl}	curvature corresponding to the plastic moment (M_{pl}) on the ascending branch of moment–curvature curve
k_u	curvature at ultimate moment
$\hat{k}_{pl}$	curvature corresponding to the plastic moment (M_{pl}) on the descending branch of moment–curvature curve
L	length of specimen
M_{crl}	critical elastic local buckling moment
M_{DSM}	unfactored design moment capacity predicted by the direct strength method
$M^{\#}_{DSM}$	unfactored design moment capacity predicted by the modified direct strength method
M_d	moment capacities predicted by design rules
M_{EC3}	unfactored design moment capacity predicted by the European Code
M_{Exp}	experimental ultimate moment (test moment capacity)
M_{FEA}	ultimate moment predicted by finite element analysis
M_{el}	elastic bending moment
$M^{\#}_{EC3}$	unfactored design moment capacity predicted by the modified European Code
$M_{G\&T}$	unfactored design moment capacity predicted by the modified European Code by Gardner and Theofanous
$M_{inelastic}$	unfactored design moment capacity predicted by the approach by inelastic reserve capacity in American Specification and Australian/New Zealand Standard
$M^{*}_{inelastic}$	unfactored design moment capacity predicted by the approach by inelastic reserve capacity for specimens with the ratio of the depth of the compressed portion of the web to its thickness exceeded the slenderness ratio
$M^{\#}_{inelastic}$	unfactored design moment capacity predicted by the modified approach by inelastic reserve capacity
M_m	mean value of material factor
M_{ne}	nominal flexural strength for lateral-torsional buckling in direct strength method
M_{nl}	nominal flexural strength for local buckling in direct strength method
M_{nd}	nominal flexural strength for distortional buckling in direct strength method
M_{pl}	plastic bending moment
M_u	experimental and numerical ultimate moments
M_y	yield moment
$M_{yielding}$	unfactored design moment capacity predicted by the approach by initiation of yielding in American Specification and Australian/New Zealand Standard
n	Ramberg–Osgood parameter
P_m	mean value of tested-to-predicted load ratio
R	rotational capacity
r	radius of the curved beam specimen between the LVDTs located at the two loading points
r_i	inner radius
r_o	outer radius
S_e	effective section modulus
S_f	gross section modulus
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 tested-to-predicted load ratio
β_0	reliability index
β_1	reliability index
ε	material factor in European Code
ε_f	tensile strain after fracture based on gauge length of 25 mm
ϕ_0	resistance factor
ϕ_1	resistance factor
λ_l	slenderness ratio in American Specification, Australian/New Zealand Standard and direct strength method
$\overline{\lambda}_p$	element slenderness in European Code
ρ	value in calculating effective area in American Specification, Australian/New Zealand Standard and European Code
$\sigma_{0.2}$	0.2% tensile proof stress
σ_u	tensile strength

for the cold-formed lean duplex stainless steel columns. Saliba and Gardner [6] performed experimental and numerical investigation on the structural behaviour of lean duplex stainless steel welded I-sections. The investigation included coupon tests, stub column tests and bending tests as well as parametric study on welded I-sections using finite element analysis. The experimental and numerical data were compared with design predictions by European Code for stainless steel and continuous strength method (CSM). It is shown that the current Class limits in the European Code can be relaxed. In addition, the continuous strength method is shown to provide better prediction than the current European Code prediction.

The objective of this study is mainly to investigate the structural performance of cold-formed lean duplex stainless steel flexural members. A series of bending tests and a wide range of parametric study on lean duplex stainless steel flexural members were carried out. The 180 numerical and experimental data obtained from this study and previous research [1] were compared with design predictions by the American Specification (ASCE) [7], Australian/New Zealand Standard (AS/NZS) [8], European Code (EC3) [9], the design rule proposed by Gardner and Theofanous [2], the direct strength method (DSM) described in the North American Specification (AISI) [10] and continuous strength method (CSM) presented in Saliba and Gardner [6]. Reliability analysis

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