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Design of cold-formed stainless steel circular hollow section columns using direct strength method

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ABSTRACT

Cold-formed stainless steel circular hollow section (CHS) columns have been increasingly used in construction, due to its aesthetic appearance, long life-span and good ductility. It is shown that direct strength method (DSM) is capable of predicting cold-formed steel column strengths accurately. However, the DSM is developed for cold-formed steel sections with plate rather than curved elements, and thus its applicability for cold-formed stainless steel CHS is worth investigating. This paper presents a numerical investigation of cold-formed stainless steel CHS columns. A non-linear finite element model was developed and verified against column tests. Extensive parametric study of cold-formed duplex, lean duplex and ferritic stainless steel CHS columns has been performed to obtain column strengths. A total of 273 experimental and numerical cold-formed stainless steel CHS column strengths, which are obtained from previous researches and parametric study obtained from this study, are compared with the design strengths predicted by the current DSM. Reliability analysis was performed to evaluate the reliability of the design rules. It is shown that the current DSM provides unconservative and not reliable prediction for cold-formed stainless steel CHS columns. Therefore, modified DSM is proposed for cold-formed stainless steel CHS columns. It is shown that the modified design rule is more accurate than the current DSM, and the modified design rule is considered to be reliable.

1. Introduction

Cold-formed stainless steel has many advantages in construction applications, such as ease to construct, shiny appearance, long life span, relatively low maintenance cost, and better ductility compared with carbon steel. Therefore, it has been increasingly used in construction projects. Specifications [1–3] have been developed to facilitate engineers in designing stainless steel structural members. A wide range of experimental and numerical investigation on cold-formed stainless steel circular hollow section (CHS) columns has been conducted by previous researchers, including Young and Hartono [4], Ellobody and Young [5], Young and Ellobody [6], Talja [7], Gardner and Nethercot [8], Rasmussen and Hancock [9], and Bardi and Kyriakides [10]. Various types of austenitic and duplex stainless steel materials have been covered in previous investigation. Details of the previous experimental and numerical analysis are presented in Section 2 of this paper. The existing design rules, including American Specification [1], Australian/New Zealand Standard [2], European Code [3] as well as design rules proposed by Rasmussen and Hancock [9] and Rasmussen and Rondal [11], have been examined for designing stainless steel CHS section columns.

However, the direct strength method (DSM) proposed by Schafer and Pekoz [12] has not been examined for cold-formed stainless steel circular hollow section columns in previous research. The direct strength method has shown to be able to accurately predict compressive strengths of cold-formed steel columns, and it has been adopted by the North American Specification (AISI) [13,14] for cold-formed steel structures. Direct strength method predicts the design strengths by calculating the nominal strengths of compressive members subjected to flexural, local and distortional buckling, and then takes the minimum value of these nominal strengths as the design strength. Full cross-sectional area, instead of effective area, is used in the direct strength method. Thus, the calculation procedure of direct strength method is relatively convenient compared with the traditional effective method. It should be noted that the current direct strength method in AISI [13,14] does not covers circular hollow section or stainless steel material. Zhu and Young [15] performed experimental and numerical analysis on aluminum circular hollow section columns, and compared the test and numerical results with design values calculated by the current direct strength method in AISI [13,14]. It is shown that the current direct strength method generally provides conservative prediction for the

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Nomenclature

A	cross-sectional area
D	diameter of specimen
E_o	initial Young's modulus
e_{exp}	axial displacement at ultimate load obtained from experimental program
e_{FEA}	axial displacement at ultimate load obtained from finite element analysis
F_m	mean value of fabrication factor
f_{ol}	elastic local buckling stress
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_{crl}	elastic local buckling load
P_{DSM}	design strengths calculated using direct strength method
P_{exp}	column strength obtained from experimental program
P_{FEA}	column strength obtained from finite element analysis
P_{ne}	nominal member capacity of a member in compression for flexural buckling
P_{nl}	nominal member capacity of a member in compression for local buckling
P_u	compressive capacity of column members
P_y	the nominal yield capacity of the member in compression
P^*_{DSM}	design strengths calculated using modified direct strength method
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	reliability index
ε	tensile strain
$\varepsilon_{true,pl}$	plastic true strain
ϕ	resistance factor
λ_c	non-dimensional slenderness to determine P_{ne}
λ_l	non-dimensional slenderness to determine P_{nl}
σ	tensile stress or normal stress
σ_{true}	true stress
σ_u	static tensile strength
$\sigma_{0.2}$	static 0.2% tensile proof stress

aluminum non-welded columns of circular hollow sections. Design equation is proposed for aluminum alloy circular hollow section columns with transverse welds at the ends of the columns. Becque et al. [16] and Huang and Young [17] examined the direct strength method [13,14] for designing stainless steel columns, and the modified direct strength method was proposed. However, the specimens in experimental and numerical program [16,17] are rectangular and square hollow sections, but not circular hollow section. Therefore, there is a lack of investigation to examine the suitability of direct strength method for stainless steel circular hollow section columns.

The purpose of this paper is firstly to investigate the behaviour of stainless steel circular hollow section columns by performing extensive parametric study using finite element analysis (FEA). The finite element model (FEM) is verified with the available test results. Secondly, the suitability of current DSM for stainless steel circular hollow section column is assessed by comparing the numerical strength with design strength. Thirdly, design rules for stainless steel circular hollow section columns are proposed based on the current DSM. Lastly, reliability analysis was performed to assess the reliability of these design rules.

2. Summary of available data

Extensive experimental and numerical investigation on stainless steel circular hollow section column has been performed by previous researchers. A total of 165 available experimental and numerical data of stainless steel circular hollow section columns are used in this study, as summarized in Table 1. The data pool covers four different types of austenitic stainless steel and two types of duplex stainless steel, as shown in Table 1. The type 304 austenitic stainless steel circular hollow section columns have been investigated by Young and Hartono [4], Ellobody and Young [5], Young and Ellobody [6] and Gardner and Nethercot [8]. The available type 304 austenitic stainless steel circular hollow section column specimens ranged from stocky to slender sections with slenderness (D/t) of 5–200, where D and t are diameter and thickness of section. Tests on other types of austenitic stainless steel (316L and 304L) were conducted by Talja [7] and Rasmussen and Hancock [9], respectively. The slenderness of these specimens ranged from 34 to 48.6. Finite element analysis was performed for duplex stainless steel (EN 1.4462). The sections of these specimens ranged from stocky to slender, with D/t of 5–62.5. Experimental analysis of duplex stainless steel (EN 1.4410) was performed on sections with D/t ranging from 22.9 to 54.7.

The relationship of P_u/P_{ne} and λ_l for the available data is shown in Fig. 1, where P_u is the experimental and numerical column strength, P_{ne} is the nominal member capacity and λ_l is the non-dimensional slenderness, as specified in the North American Specification [13]. It is shown that the slenderness of stainless steel CHS columns in previous researchers are smaller than 0.776 ($\lambda_l < 0.776$), while those with slenderness larger than 0.776 ($\lambda_l \geq 0.776$) are not available. It should be noted that the direct strength method predicts the column strength by considering the nominal member capacity for flexural buckling (P_{ne}) with $\lambda_l < 0.776$ and nominal member capacity for local buckling (P_{nl}) with $\lambda_l \geq 0.776$, and then take the minimum of P_{ne} and P_{nl} as the design strength. Therefore, the lacking of experimental and numerical data of stainless steel CHS columns with slenderness larger than 0.776 leads to difficulties in assessing the suitability of current DSM for stainless steel CHS columns. Therefore, the parametric study in this paper focuses on the columns with slenderness larger than 0.776, which is detailed in Section 3 of this paper. The relationship of P_u/P_y and λ_c for the available data is shown in Fig. 2, where P_y equals to yield stress of the material multiply by cross-sectional area, and λ_c is the non-dimensional slenderness to determine P_{ne}.

3. Finite element model

3.1. General

A non-linear finite element model (FEM) has been developed using

Table 1
Summary of available cold-formed stainless steel CHS column strengths.

Reference	Approach	Material	Type		# of data
			EN	ASTM	
Young and Hartono [4]	Tests	Austenitic	1.4301	304	16
Ellobody and Young [5]	FEA	Austenitic	1.4301	304	35
		Duplex	1.4462	S31803	35
Young and Ellobody [6]	FEA	Austenitic	1.4301	304	42
Talja [7]	Tests	Austenitic	1.4435	316L	5
			1.4541	321	4
Gardner and Nethercot [8]	Tests	Austenitic	1.4301	304	4
Rasmussen and Hancock [9]	Tests	Austenitic	1.4306	304L	6
Bardi and Kyriakides [10]	Tests	Duplex	1.4410	S32750	20
				Total	165