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Finite element analysis and design of cold-formed steel built-up closed section columns with web stiffeners

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ABSTRACT

This paper presents a numerical investigation and design of cold-formed steel built-up closed section columns with web stiffeners. A finite element model (FEM), considering the initial geometric imperfections and nonlinear material properties, was developed to simulate the structural behaviour of fixed-ended built-up closed section compression members. The comparison between the numerical results and the available test results show that this FEM can provide good predictions for both the ultimate strength and the failure modes of the test specimens. The verified FEM was used to conduct an extensive parametric study for the investigation on the structural behaviour of cold-formed steel built-up closed sections with web stiffeners. The parametric study was designed to investigate the effect of web stiffeners as well as to evaluate the current design method. The column strengths obtained from the finite element analysis and the test results were compared with the design strengths calculated using the direct strength method in the North American Specification and the Australian/New Zealand Standard for cold-formed steel structures. Design curves modified from the current direct strength method are proposed for flexural, local and distortional buckling. The reliability analysis was used to assess the current design rules and the modified design curves. It is shown that the modified direct strength method is generally conservative and reliable for the design of cold-formed steel built-up closed section compression members.

1. Introduction

A cold-formed steel built-up closed section, formed by connecting two or more single sections together, is becoming a favorable choice in lightweight steel constructions due to its excellent performance to resist against torsional and flexural buckling. Whittle and Ramseyer [1], Reyes and Guzman [2] and Lee et al. [3] reported the test results of cold-formed steel built-up box-shaped sections. Georgieva et al. [4] and Lu et al. [5] investigated the performance of built-up columns formed by lipped Z-shaped sections and lipped channel sections, respectively. Compression tests of multi-limbs built-up sections were conducted by Liao et al. [6] and Liu and Zhou [7]. However, limited literature was found on the investigation of built-up sections with web stiffeners, where Young and Chen [8] and Zhang and Young [9] tested the built-up sections with longitudinal stiffeners at the web location. There is a need to further investigate the effect of web stiffener on cold-formed steel built-up closed sections.

Due to its high efficiency and low cost, finite element analysis (FEA) is a powerful method to explore the failure mechanism and to predict the ultimate strength of cold-formed steel structural members. To achieve an accurate prediction, a finite element model (FEM) should be carefully developed and verified against test results, in which the geometric and material nonlinearities of the specimens need to be well considered. The FEA has been successfully used to predict structural performance of cold-formed steel members and the results have been reported by quite a number of researchers, such as Young and Yan [10], Young [11], Nguyen et al. [12] and Aghoury et al. [13] for single sections as well as Zhang and Young [14], Dabaon et al. [15] and Aghoury et al. [16] for built-up section columns. To ensure its reliability and accuracy, in this study, a FEM was developed and verified against experimental results of cold-formed steel built-up closed section compression members with web stiffeners.

The main objectives of this study are to investigate the behaviour of cold-formed steel built-up closed section compression members with inward and outward web stiffeners and to propose design curves for such kind of structural components. The verified FEM was used to conduct a parametric study on the influence of inward and outward web stiffeners on the column strengths of cold-formed steel built-up closed sections. In the parametric study, the built-up sections were designed with variable inward stiffeners or outward stiffeners in the

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Notation

The following symbols are used in this paper:

Ag	gross cross-sectional area
b_f	width of flange
b_w	width of web
C_p	correction factor in reliability analysis
C_ϕ	calibration coefficient in reliability analysis
d	depth of the web stiffener
E	Young's modulus
e	axial shortening
F_{crd}	elastic distortional buckling stress of cross section
F_{crl}	elastic local buckling stress of cross section
F_{EXP}	axial compressive stress obtained by experiment
F_{FEA}	axial compressive stress obtained by finite element analysis
F_m	mean value of fabrication factor
f_y	yield stress is taken as the static 0.2% proof stress
H	the height of the cross-section for built-up closed section
K	effective length factor
L	length of column specimen
l^*	side length of artificial stiffener
M_m	mean value of material factor
P	axial load
P_{crd}	critical elastic distortional column buckling load
P_{cre}	critical elastic column buckling load in flexural buckling
P_{crl}	critical elastic local column buckling load
$P_{DSM\text{-}pro1}$	nominal axial strength calculated using current direct strength method and rational design calculation for elastic buckling stress
$P_{DSM\text{-}pro2}$	nominal axial strength calculated using the modified direct strength method and rational design calculation for elastic buckling stress
$P_{DSM\text{-}s}$	nominal axial strength calculated using direct strength method that assumes the built-up section as two independent single sections
$P_{DSM\text{-}2t}$	nominal axial strength calculated using direct strength method that assumes the built-up section as rigidly connected section
P_{EXP}	ultimate load obtained by experiment
P_{FEA}	ultimate load obtained by finite element analysis
P_m	mean value of tested-to-predicted load ratios
P_n	nominal axial strength
P_{nd}	nominal axial strength for distortional buckling
P_{ne}	nominal axial strength for flexural buckling
P_{nl}	nominal axial strength for local buckling
P_u	column strength
P_y	squash load
r	radius of gyration of full unreduced cross section about axis of buckling
r_i	inside corner radius at flanges of specimen
t	nominal plate 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 ratios
V_Q	coefficient of variation of load effect
w_1,w_2, w_3,w_4	dimensions of web stiffeners
β	reliability index (safety index)
ε	engineering strain
ε_f	elongation (tensile strain) after fracture
ε_{true}^{pl}	true plastic strain
ϕ_c	resistance (capacity) factor for compression member
λ_c, λ_d, λ_l	non-dimensional slenderness used in direct strength method
σ	engineering stress
$\sigma_{0.2}$	static 0.2% tensile proof stress
σ_{true}	true stress
σ_u	static ultimate tensile strength

webs of the sections. The results obtained from the parametric study and test specimens were compared with the design strengths calculated by the current direct strength method. Design curves that modified from the current direct strength method are proposed for cold-formed steel built-up closed section compression members. In addition, the reliability of the current design rules and modified design curves were evaluated using reliability analysis.

2. Summary of experimental investigation

2.1. General

The built-up closed sections with inward or outward stiffeners at the webs were tested, and detailed in Zhang and Young [17]. The test specimens were first brake-pressed from high strength steel zinc-coated grades G500 and G550 structural steel sheets, and then connected together to form a built-up closed section by self-tapping screws, as shown in Figs. 1 and 2. The nominal plate thicknesses of the specimens were 0.48 and 1.0 mm, and the nominal screw spacing along the longitudinal direction was 100 mm. The specimens had column lengths ranged from 300 to 3200 mm and tested between fixed ends. The specimens were divided into four groups, which were labelled as VT0.48, VT1.0, OT0.48 and OT1.0, so that the sectional configuration and nominal plate thicknesses can be easily identified. Table 1 shows the nominal cross-section dimensions for Series VT0.48, VT1.0, OT0.48 and OT1.0, using the nomenclature defined in Figs. 1 and 2.

The test specimens were labelled to clarify its test series and column length. For examples, the labels "VT1.0L2000" and "OT0.48L800R" define the specimens as follows: the first letter indicates the cross-section shape, where the letter "V" refers to V-shaped inward web stiffeners and the letter "O" refers to O-shaped outward web stiffeners. The

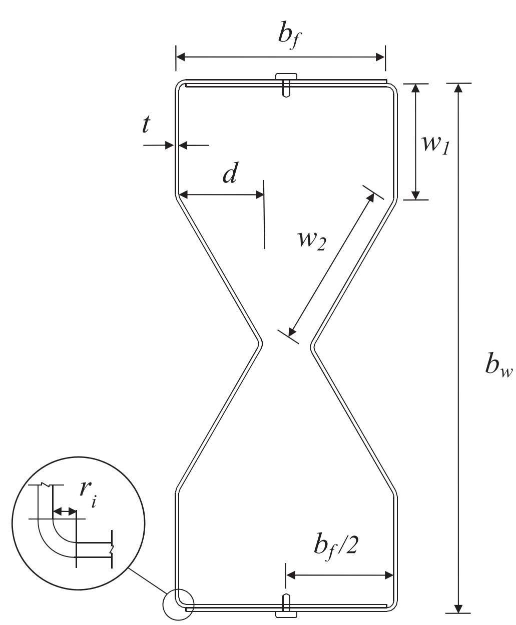

Fig. 1. Definition of symbols for built-up closed section with inward web stiffeners (V-section).