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Numerical investigation and design of aluminum alloy circular hollow section columns

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ABSTRACT

This paper presents a numerical investigation of aluminum alloy circular hollow section non-welded and welded columns using finite element analysis. A non-linear finite element model was developed and verified against fixed-ended column tests. The column specimens were extruded from heat-treated aluminum alloys of 6063-T5 and 6061-T6, and the ends of the columns were transversely welded to aluminum end plates for the welded columns. The non-welded columns without welding of end plates were also investigated. The welded columns were modeled by dividing the column into different portions along the column length, so that the heat-affected zone softening at both ends of the welded columns was included in the simulation. The initial local geometric imperfections of the columns were measured in this study. Geometric and material non-linearities were incorporated in the finite element model. The verified finite element model was used for a parametric study of fixed-ended aluminum alloy circular hollow section columns. A comparison of the column strengths predicted by the finite element analysis and the design strengths calculated using the current American, Australian/New Zealand and European specifications for aluminum structures was presented. The column strengths were also compared with the design strengths predicted by the direct strength method, which was developed for cold-formed carbon steel members. Design rules were proposed for aluminum alloy circular hollow section columns with transverse welds at the ends of the columns. Reliability analysis was performed to evaluate the reliability of the design rules.

1. Introduction

Aluminum members are being used increasingly in structural applications. The current American Aluminum Design Manual [1], Australian/New Zealand Standard [2] and European Code [3] for aluminum structures provide design rules for compression members. Schafer and Peköz [4] developed a new design method called the direct strength method (DSM) for cold-formed steel structures. The test data used in the development of column design for DSM were based on concentrically loaded pin-ended cold-formed steel column for certain cross sections and geometric limits [5,6]. The DSM has been adopted by the North American Specification [7,8] for cold-formed steel structures. Zhu and Young [9,10] showed that the DSM with some modification can be used in the design of aluminum alloy square hollow section (SHS) and rectangular hollow section (RHS) columns. For the purpose of obtaining accordant design rules of different cross-sections, the DSM was used in this study for the design of aluminum alloy circular hollow section (CHS) columns.

One disadvantage in using aluminum as a structural material is that heat-treated aluminum alloys could suffer loss of strength in a localized region when welding is involved, and this is known as heat-affected zone (HAZ) softening. Previous research [11,12] indicated that welds have significant effect on column strength. The test program presented by Zhu and Young [13] showed that transverse welds at the ends of the CHS columns reduce the column strength for nearly 46%. In addition, it was also shown that the design rules in the current American, Australian/New Zealand and European specifications are generally quite conservative for aluminum alloy welded columns of circular hollow sections [13]. Hence, it is necessary to obtain accurate design rules for aluminum alloy columns containing transverse welds.

Finite element analysis (FEA) has been widely used in structural design. Compared with physical experiments, FEA is relatively inexpensive and time efficient, especially when a parametric study of cross-section geometry is involved. In addition, FEA is more convenient for investigation involving geometric imperfections of structural members, whereas this could be difficult to investigate through physical tests. Although FEA is a useful and powerful tool for structural analysis and design, it is important to obtain an accurate and reliable finite element model (FEM) prior to a parametric study of FEA to be

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Nomenclature

A	gross cross-section area
COV	coefficient of variation
D	overall diameter of CHS
DL	dead load
E	Young's modulus
e	axial shortening
FEA	finite element analysis
FEM	finite element model
F_m	mean value of fabrication factor
f_y	material yield strength
k_c	coefficient in the AS/NZS Standard
L	length of specimen
LL	live load
l_e	column effective length
M_m	mean value of material factor
P	axial load
P_{AA}	unfactored design strength for American Aluminum Design Manual
$P_{AS/NZS}$	unfactored design strength for Australian/New Zealand Standard
P_{cre}	critical elastic buckling load in flexural buckling, $\pi^2 EA/(l_e/r)^2$
P_{crl}	critical elastic local column buckling load
P_{DSM}	column strength calculated using the direct strength method
$P_{DSM\text{-}W}$	welded column strength calculated using the proposed design rules
P_{EC9}	unfactored design strength for Eurocode 9
P_{Exp}	experimental ultimate load of column
P_{FEA}	ultimate load predicted by FEA
P_{FEA15}	ultimate load predicted by FEA using 15 mm heat-affected zone extension for welded column
P_{FEA20}	ultimate load predicted by FEA using 20 mm heat-affected zone extension for welded column
P_m	mean value of tested-to-predicted load ratio
P_{ne}	nominal axial strength for flexural buckling
P_{nl}	nominal axial strength for local buckling
P_u	column strength
P_y	yield strength of the section ($f_y A$)
r	radius of gyration of gross cross-section about the minor y-axis of buckling
t	thickness of section
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
z	longitudinal coordinates
α_1	factor in the proposed design equation due to welding $(1.3(D/t)^{-0.19})$
α_2	factor in the proposed design equation due to welding $(0.6(x/L)^{-0.12})$
β	reliability index
ε_f	elongation (tensile strain) at fracture
λ_c	non-dimensional slenderness for flexural buckling $(\sqrt{P_y/P_{cre}})$
λ_l	non-dimensional slenderness for interaction of local and flexural buckling $(\sqrt{P_{ne}/P_{crl}})$
ρ_c	local buckling coefficient specified in the Eurocode 9
ρ_{haz}	heat-affected zone (HAZ) softening factor specified in the Eurocode 9
ϕ	resistance factor
$\sigma_{0.2}$	static 0.2% proof stress
σ_u	static ultimate tensile strength

carried out. A non-linear FEM for aluminum columns of SHS and RHS with and without transverse welds has been developed by Zhu and Young [9]. In this study, a non-linear FEM for aluminum columns of CHS was developed and verified against experimental results.

The purpose of this paper is firstly to investigate the behavior and design of aluminum CHS columns using non-linear FEA. The verified FEM is used for a parametric study of cross-section geometries. Secondly, the current DSM is used for the design of aluminum non-welded and welded columns of CHS. Thirdly, design rules for aluminum welded columns of CHS are proposed based on the current DSM. The column strengths predicted by the FEA were compared with the design strengths calculated using the American Aluminum Design Manual (AA), Australian/New Zealand Standard (AS/NZS) and European Code (EC9) for aluminum structures, as well as the DSM and proposed design rules. Lastly, reliability analysis was performed to assess the reliability of these design rules.

2. Summary of test program

2.1. Column tests and material properties

Experimental results of aluminum alloy circular hollow sections compressed between fixed ends have been reported by Zhu and Young [13]. The test specimens were fabricated by extrusion using 6063-T5 and 6061-T6 heat-treated aluminum alloys. The test program included 21 fixed-ended CHS columns with both ends welded to aluminum end plates, and eight fixed-ended CHS columns without the welding of end plates. In this paper, the term "welded column" refers to a specimen with transverse welds at the ends of the column, whereas the term "non-welded column" refers to a specimen without transverse welds. The testing conditions of the non-welded and welded columns are identical, other than the absence of welding in the non-welded columns. The experimental program included four test series with different cross-section geometry and type of aluminum alloy, as shown in Table 1 using the symbols illustrated in Fig. 1. The measured cross-section dimensions of each specimen are detailed in Zhu and Young [13]. The specimens were tested between fixed ends at various column lengths ranged from 300–3000 mm. The test rig and operation are also detailed in Zhu and Young [13]. The experimental ultimate loads (P_{Exp}) and failure modes observed at ultimate loads obtained from the non-welded and welded column tests are shown in Tables 2–6. The test specimens were labeled such that the type of aluminum alloy, test series, welding condition and specimen length could be easily identified, as shown in Tables 2–6. For example, the label

Table 1
Nominal specimen dimension of test series

Test series	Type of material	Dimension, $D \times t$ (mm)
N-C1	6063-T5	50×1.6
N-C2	6063-T5	50×3.0
H-C1	6061-T6	50×1.6
H-C2	6061-T6	50×3.0

Note: 1 in. = 25.4 mm.