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Tests of aluminium alloy CHS columns with circular openings

Ran Feng [a,b,*], Xinling Mou [a], Anying Chen [a], Yihong Ma [a]

[a] *School of Civil Engineering, Hefei University of Technology, Hefei 230009, China*
[b] *School of Civil and Environmental Engineering, Harbin Institute of Technology, Shenzhen 518055, China*

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ABSTRACT

This paper describes a test program on a wide range of aluminium alloy circular hollow section (CHS) columns with circular openings. A total of 27 specimens including 18 perforated CHS columns and 9 CHS columns were tested with uniform axial compression force applied to the pin-ended columns, which were fabricated by extrusion of CHSs using 6061-T6 and 6063-T5 heat-treated aluminium alloys. The influence of the column slenderness ratio, the plate slenderness ratio, the opening size ratio and the number of openings on the strength and behaviour of aluminium alloy CHS columns were carefully evaluated. The ultimate strengths, failure modes, load versus axial shortening curves and strain distributions along the circular openings of test specimens were all obtained from the experimental investigation. The test strengths of aluminium alloy CHS columns were compared with the design strengths predicted using the design rules given in the current design specifications. Furthermore, the test strengths of aluminium alloy CHS columns with circular openings were also compared with the design strengths calculated using the current design rules for perforated cold-formed steel structural members, which were derived based on the effective diameter method and effective area method. It is shown from the comparison that the design rules given in American Design Manual (AA) and Australian/New Zealand Standard (AS/NZS) for limit state design of aluminium alloy structural members are generally appropriate but with comparatively high scatter of predictions; whereas the design rules given in Chinese Code are generally appropriate for the design of aluminium alloy CHS columns. In addition, the current design rules for perforated cold-formed steel structural members based on the effective area method are generally more accurate than those based on the effective diameter method for the design of aluminium alloy CHS columns with circular openings.

1. Introduction

Aluminium alloy structural members nowadays are being used increasingly in structural engineering, such as space structures, claddings, curtain walls, bridges and many other practical applications owing to their high strength-to-weight ratio, lightness, corrosion resistance, attractive appearance and ease of production. However, the elastic modulus of aluminium alloy is approximately one third of that of carbon steel, which causes the aluminium alloy structural members to be easily failed by instability due to the loss of stiffness with low proportional limit stress. Furthermore, openings are often introduced in structural members to facilitate the building services such as pipeline, electric wire and heating conduits, as well as inspection and maintenance work of buildings. These openings are usually pre-punched perforations, which could lead to the redistribution of membrane stresses in the members and greatly influence the elastic stiffness and ultimate strengths of structural members. The behaviour of perforated structural members significantly depends on the shape, size, location and number of openings.

Many researches were conducted on the behaviour and design of cold-formed steel structural members with openings. Yu and Davis [1] investigated the structural behaviour of cold-formed steel compression members with a single circular or square hole in web or flange. The experimental and numerical investigations were performed by Feng et al. [2,3] on the axial strength of cold-formed thin-walled channel sections at ambient and uniform high temperatures. The design rules were proposed based on the current design methods by verifying with the test and finite element analysis results. Moen and Schafer [4] investigated the relationship between elastic buckling and structural response of cold-formed steel columns with holes by conducting the compression tests on stub and intermediate cold-formed steel columns with and without slotted web holes. Furthermore, Moen and Schafer [5] also extended the direct strength method given in North American Specification (NAS) [6,7] to the design of cold-formed steel

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[*] Corresponding author.
E-mail address: r.feng@hfut.edu.cn (R. Feng).

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Nomenclature

A	Gross cross-section area
A_e	Effective area
A_s	Total surface area of member
A_0	Total surface area of opening
B_c, C_c, D_c	Buckling constant
b_e	Effective width
D	Outer diameter of circular hollow section
D_e	Effective diameter
D_i	Inner diameter of CHS cross section
d	Diameter of circular opening
E	Young's modulus
F_c	Allowable compressive stress
F_{cy}	Compressive yield stress
F_L	Limit state stress
F_n	Nominal buckling stress
f	Design value of compressive strength
f_o	Characteristic value of 0.2% tensile proof stress
f_y	Yield stress (0.2% tensile proof stress)
k_c	Coefficient for compression member
k_1, k_2, k_3	Set of coefficient
L	Overall length of aluminium alloy column
L_e	Effective length of aluminium alloy column
n	Number of hole
n_u	Safety factor for ultimate strength
n_y	Safety factor for yield strength
P_{AA}	Design strength obtained from design formulae of American Design Manual
P_{ASD}	Design strength obtained from design formulae of AS/NZS 1664.2:1997
P_{CC}	Design strength obtained from design formulae of GB 50429-2007
P_{cre}	Overall buckling load
P_{crl}	Local buckling load
P_{DS}	Design strength proposed by Dhanalakshmi and Shanmugam
$P_{DS\text{-}A}$	Design strength proposed by Dhanalakshmi and Shanmugam based on effective area method
$P_{DS\text{-}D}$	Design strength proposed by Dhanalakshmi and Shanmugam based on effective diameter method
P_{DSM}	Design strength obtained from design formulae based on direct strength method
P_{EC}	Design strength obtained from design formulae of EN 1999-1-1:2007
P_{LSD}	Design strength obtained from design formulae of AS/NZS 1664.1:1997
P_{MS1}	Design strength proposed by Moen and Schafer based on the first scenario
P_{MS2}	Design strength proposed by Moen and Schafer based on the second scenario
P_{MS3}	Design strength proposed by Moen and Schafer based on the third scenario
P_{MS4}	Design strength proposed by Moen and Schafer based on the fourth scenario
P_{MS5}	Design strength proposed by Moen and Schafer based on the fifth scenario
P_{NAS}	Design strength obtained from design formulae of North American Specification
$P_{NAS\text{-}A}$	Design strength obtained from design formulae of North American Specification based on effective area method
$P_{NAS\text{-}D}$	Design strength obtained from design formulae of North American Specification based on effective diameter method
P_{ne}	Nominal axial strength for overall buckling
P_{nl}	Nominal axial strength for local buckling
P_{SD}	Design strength proposed by Shanmugam and Dhanalakshmi
$P_{SD\text{-}A}$	Design strength proposed by Shanmugam and Dhanalakshmi based on effective area method
$P_{SD\text{-}D}$	Design strength proposed by Shanmugam and Dhanalakshmi based on effective diameter method
P_{sq}	Squash load
P_{STT}	Design strength proposed by Shanmugam et al.
$P_{STT\text{-}A}$	Design strength proposed by Shanmugam et al. based on effective area method
$P_{STT\text{-}D}$	Design strength proposed by Shanmugam et al. based on effective diameter method
P_u	Ultimate strength
P_y	Yield strength
P_{ynet}	Yield strength considering influence of holes
r	Radius of gyration of circular hollow section
s	Distance between center of adjacent openings
t	Thickness of circular hollow section
w	Flat width of cross section
γ_{M1}	Partial factor
γ_R	Resistance factor
δ	Overall geometric imperfection
ε_f	Elongation after fracture based on a gauge length of 50 mm
η	Strength ratio
κ	Reduction factor to allow for the weakening effects of welding
σ_u	Static ultimate tensile stress
$\sigma_{0.2}$	Static 0.2% tensile proof stress
φ	Stability coefficient
χ	Reduction factor for relevant buckling mode
ϕ	Strength reduction factor

columns with holes. The effect of perforation positions on the load carrying capacity of cold-formed steel structural members with lipped channel cross section subjected to axial compression was investigated by Kulatunga and Macdonald [8] using finite element analysis, which was verified by the corresponding experimental and theoretical results. In addition, the influence of perforation shapes on the buckling behaviour of cold-formed steel structural members with lipped channel cross section subjected to axial compression was also evaluated by Kulatunga and Macdonald [9] using both finite element analysis and experimental investigation. It should be noted that the aforementioned studies were all performed on perforated cold-formed steel structural members. Up to the authors' knowledge, there is little research being carried out on the behaviour of aluminium alloy structural members with openings. The behaviour of aluminium alloy square hollow section (SHS) tubes with a circular hole in the webs subjected to web crippling was studied by Zhou and Young [10] using both experimental and numerical investigations. Feng and Young [11] conducted an experimental investigation on a wide range of aluminium alloy SHS stub columns with central circular openings. The appropriateness of the current design rules for perforated carbon steel structural members was evaluated for the design of aluminium alloy SHS stub columns with circular openings.

Design rules for aluminium alloy structural members are