Engineering Structures 151 (2017) 613–632

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Experimental investigation of aluminum square and rectangular beams with circular perforations

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ARTICLE INFO

Article history:
Received 3 April 2017
Revised 11 August 2017
Accepted 18 August 2017

Keywords:
Aluminum alloy
Circular perforation
Continuous strength method (CSM)
Direct strength method (DSM)
Rectangular hollow section (RHS)
Square hollow section (SHS)

ABSTRACT

Both three-point and four-point bending tests were conducted on aluminum square and rectangular beams with circular perforations. Test specimens consist of 9 perforated and 4 imperforated beams subjected to gradient and constant bending moment. The extrusion of 6061-T6 and 6063-T5 heat-treated aluminum alloys were used to manufacture square and rectangular hollow sections (SHS and RHS), respectively. The evaluation of the strength and behavior of aluminum square and rectangular beams focuses on the effects of the aspect ratio, the ratio of plate width, the ratio of plate slenderness, the ratio of perforation dimension and the number of perforations. Test results including the ultimate strengths, failure modes of local and flexural buckling failure, bending moment versus curvature curves and strain distributions along the circular perforations are all reported, which were employed to assess the suitability of the current design specifications. The comparison of test strengths with design strengths shows that the modified DSM for aluminum structural members is somewhat conservative with the lowest value of COV, whereas other design specifications for cold-formed steel and aluminum structural members are quite conservative with comparatively high value of COV. It is also demonstrated from the comparison that the perforated sections close to the mid-span of the beams are the critical section under gradient and constant bending moment. In addition, the comparison of test strengths with design strengths also reveals that the current design rules for perforated cold-formed steel and aluminum structural members are all conservative, in which North American Specifications (NAS) for perforated cold-formed steel structural members are generally appropriate with the lowest value of COV.

1. Introduction

Aluminum alloy members nowadays have more and more applications in many architectural and structural constructions such as Chongqing International Expo Center and Shanghai Circus City in China, Arvida river-crossing bridge in Canada, Kieuwegein office building in Holland and so on. Many structural members in these buildings were subjected to bending. The increasing use of aluminum alloy members may attribute to the unique characteristics of the aluminum alloy including aesthetic appearance, supreme strength-to-weight ratio and excellent anti-corrosive properties. Furthermore, aluminum alloy members can be easily extruded to almost all sorts of complex profiles that could provide the most economic type of cross sections in the structural design [1].

Many studies were performed on the flexural behavior of aluminum structural members. Moen et al. [2,3] conducted experimental and numerical work on the rotational capacity of aluminum beams under moment gradient. The design codes were evaluated by the research findings. This study improved the understanding of the inelastic behavior of aluminum beams and the cross-section classification in structural design codes. Su et al. [4] studied the deformation-based design of aluminum alloy square and rectangular hollow section (SHS and RHS) beams subjected to gradient and constant bending moment. The experimental and numerical results as well as the test data collected from the previous literatures were used to assess the design codes, which were verified to be conservative from the recognition and systematic exploitation of strain hardening. Su et al. [5] also investigated the flexural behavior of aluminum alloy SHSs and RHSs with internal stiffeners by conducting three-point, four-point and five-point

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http://dx.doi.org/10.1016/j.engstruct.2017.08.053
0141-0296/

Nomenclature

B_{br}, B_{bt}, B_c, B_p, B_r, C_c, D_c, D_p	buckling constant
b	outer width of SHS and RHS
COV	coefficient of variation
d	diameter of circular perforation
E	Young's modulus
E_{sh}	strain hardening modulus
F_C	critical buckling stress
F_{cy}	compressive yield stress
f	design value of flexural strength
f_b	ultimate compressive stress in the beam
f_f	ultimate compressive stress in the flange
f_o	characteristic value of 0.2% tensile proof stress
f_u	ultimate tensile stress
f_w	ultimate compressive stress in the web
f_y	tensile yield stress (0.2% tensile proof stress)
h	outer depth of SHS and RHS
I_y	moment of inertia of a beam about axis parallel to web
J	torsion constant
L	overall length of SHS and RHS
L_b	length of a beam between bracing points
L_0	effective length of SHS and RHS
M_{AA}	design bending moment resistance obtained from American Design Manual
$M_{A/N1}$	design bending moment resistance obtained from LSD given in Australian/New Zealand Standard
$M_{A/N2}$	design bending moment resistance obtained from ASD given in Australian/New Zealand Standard
M_{CC}	design bending moment resistance obtained from Chinese Code (GB 50429-2007)
$M_{CSM\text{-}M}$	design bending moment resistance of imperforated section at the mid-span obtained from modified CSM
$M_{CSM\text{-}M}{}'$	design bending moment resistance of perforated sections close to the mid-span obtained from modified CSM
M_{cre}	critical elastic bending moment for lateral-torsional buckling
M_{crl}	critical elastic bending moment for local buckling
M_{DSM}	design bending moment resistance obtained from DSM
$M_{DSM\text{-}M}$	design bending moment resistance of imperforated section at the mid-span obtained from modified DSM
$M_{DSM\text{-}M}{}'$	design bending moment resistance of perforated sections close to the mid-span obtained from modified DSM
M_{EC}	design bending moment resistance obtained from European Code
M_{Exp}	test bending moment resistance at the mid-span
$M_{Exp}{}'$	test bending moment resistance at the perforated sections close to the mid-span
M_{NAS}	design bending moment resistance of imperforated section at the mid-span obtained from North American Specification
$M_{NAS}{}'$	design bending moment resistance of perforated sections close to the mid-span obtained from North American Specification
M_{ne}	nominal flexural strength for lateral-torsional buckling
M_{nl}	nominal flexural strength for local buckling
n_y	safety factor of yield strength
S_C	elastic modulus of effective section calculated relative to the extreme compression fiber
S_g	section modulus relative to the extreme fiber in the first yield
S_y	elastic modulus of gross section bending about the minor axis
s	interval between center of adjacent circular perforations
t	wall thickness of SHS and RHS
W_{eff}	elastic modulus of effective section
W_{el}	elastic section modulus
W_{enx}	elastic modulus of net section bending about the minor axis
W_{ey}	effective section modulus of compression edge bending about the major axis
W_{net}	elastic modulus of net section allowing for perforations and HAZ softening
W_{pl}	plastic section modulus
Z_c	section modulus of a beam on compression side
α	shape factor
γ_{M1}, γ_{M2}	partial factor
γ_x	plastic adaption coefficient of cross section bending about the minor axis
ε_{csm}	limiting strain in CSM
ε_f	elongation at fracture from a gauge length of 50 mm
ε_u	strain at the ultimate tensile stress
ε_y	yield strain
$\bar{\lambda}_p$	cross-section slenderness
σ_{cr}	elastic critical buckling stress
σ_u	static ultimate tensile stress
$\sigma_{0.2}$	static 0.2% tensile proof stress
φ_b	overall stability coefficient
ϕ_b, ϕ_y	strength reduction factor

bending tests and numerical analyses. The Continuous Strength Method (CSM) was recommended to be used for aluminum alloy SHS and RHS stiffened flexural members. Wang et al. [6] conducted experimental study and finite element analysis on I-section beams made of 6061-T6 and 6063-T5 aluminum alloys. Eurocode 9 was found to underestimate the load-carrying capacity of the specimens since the post-buckling strength was significant increased. Bardel et al. [7] also performed the macrographic and microcosmic analysis on the residual stresses of the electron beam welding in a 6061 aluminum alloy. An isokinetic approach was used to provide relatively good results for the residual elastic deformations of beams exposed to a single-pass process of welding through a coupling between a simple metallurgical model and a thermal analysis.

It is worth noting that structural members are commonly prepunched to facilitate layout of electric wires and heating pipes. In addition, holes are also introduced in structural members for the purpose of aesthetic appearance. These perforations significantly deteriorated the integrity and continuity of the structural members and greatly influenced their elastic stiffness and ultimate strength, which depends on the shape, dimension, location and number of perforations. Little research was carried out on the behavior of aluminum structural members with perforations. Irene et al. [8] performed finite element analysis on perforated aluminum alloy square plates with various slenderness ratios subjected to local buckling. It was summarized that the resistance decreased with the increase of the ratio of plate slenderness and ratio of perforation dimension. It was also implied that the design equations describing the reduction of the resistance due to the holes for steel could also be used for aluminum alloy, even though the resistances of plates of these materials are significantly different. Feng and Young [9] conducted experimental work on