Thin-Walled Structures 124 (2018) 546–557

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Design of aluminium alloy stocky hollow sections subjected to concentrated transverse loads

Mei-Ni Su[a,*], Ben Young[b]

[a] School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester, UK
[b] Dept. of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China

ARTICLE INFO

Keywords:
Aluminium alloys
Concentrated loads
Experimental investigation
Finite element
Reliability analyses
Square and rectangular hollow sections
Web bearing

ABSTRACT

Web crippling is a phenomenon where section webs cripple due to a concentrated force. This phenomenon could be caused by web buckling for slender sections or by web bearing/yielding for stocky sections. The aim of this study is to investigate the web bearing design rules for relatively stocky sections. Experimental tests and numerical modelling results on aluminium alloy square and rectangular hollow sections (SHS/RHS) subjected to web bearing are presented. The tests were conducted under four loading conditions: end-two-flange (ETF), interior-two-flange (ITF), end-one-flange (EOF), and interior-one-flange (IOF). Two different bearing lengths, 50 mm and 90 mm, were investigated. The test specimens were fabricated by extrusion using 6063-T5 and 6061-T6 heat-treated aluminium alloys. Web slenderness values (i.e. the width-to-thickness ratio $h\ /\ t$) ranging from 2.8 to 28.0 have been considered. Non-linear finite element (FE) models were developed and validated against the test strengths and specimen failure modes. Upon validation, the FE models were used to perform a parametric study in order to supplement the experimental work. A total of 138 web bearing data consisting of 34 test results and 104 numerical results were generated in this study. In the ETF and ITF loading conditions, all specimens failed by material yielding at the webs. For the EOF and IOF loading conditions, specimens failed by flexural failure, interaction of web bearing and bending effects or material fracture at the tension flanges. The generated data is used to assess the web bearing design equations in the existing design codes as well as to propose new design rules. The new design rules for ETF and ITF loading conditions are proposed with the consideration of strain hardening effects. Further analyses have been carried out to show the newly proposed design rules are not only accurate and consistent, but also safe and reliable.

1. Introduction

Web crippling is a form of localized failure that occurs at points under concentrated transverse loading of thin-walled structural members and is one of the common local failure modes [1]. Web crippling can be classified in a more detailed way as web buckling for relatively slender sections and web bearing for relatively stocky sections. Up to now, the majority of existing studies were focused on web buckling design of relatively slender sections, including experimental investigation [2–6] and numerical simulation [3,7,8]. Moreover, most of the available test results were on stainless steel members [9–13]. Though stainless steel and aluminium alloys are both metallic materials with similar continuous stress-strain curves without a clear yielding point, for efficient and economical structural design, it is important to recognise the key characteristics of aluminium alloys, such as the non-linear material stress–strain curves with significant strain hardening and reasonable ductility [14]. The present study investigates the performance of aluminium alloy sections subjected to web bearing.

Though web buckling and web bearing are two different failure mechanisms, some of the international design specifications such as the Aluminium Design Manual (AA) [15] and the Australian/New Zealand Standards – Aluminium Structures (AS/NZS) [16] provide only one series of equations for the web design. Other specifications such as Eurocode 9 – Design of Aluminium Structures (EC9) [17], the Specification for Structural Steel Buildings (AISC) [18], the Australian Standard – Steel Structures (AS4100) [19] and Eurocode 3 – Design of Steel Structures EN 1993-1-3 (EC3) [20] do provide corresponding design rules for different failure mode. These existing design rules for the web bearing strength were all derived through semi-empirical and theoretical bases, and are based on experimental investigation conducted by researchers from the 1940s onwards, such as Winter and Pian [21], Zetlin [22], Hetrakul and Yu [23], Young and Hancock [1] and so on.

Aluminium alloy tubular sections are becoming increasing popular in structural applications, especially for roofing system, building

---

[*] Corresponding author.
E-mail addresses: meini.su@manchester.ac.uk (M.-N. Su), young@hku.hk (B. Young).

https://doi.org/10.1016/j.tws.2017.12.015
Received 29 June 2017; Received in revised form 15 November 2017; Accepted 13 December 2017

Nomenclature

B	section width
b	flat width of flange
b_y	length that bearing stresses spread out
E	Young's modulus
E_{sh}	strain hardening modulus
f_{cr}	elastic buckling stress
f_{csm}	CSM limiting stress
f_u	ultimate tensile strength
f_y	yield strength, taken as the 0.2% proof strength
F_m	mean value of fabrication variables
H	section depth
h	flat depth of web
L	member length
l_e	parameters in formulae for effective loaded length
M_m	mean value of material factor
m_1, m_2	parameters in formulae for effective loaded length
N	length of bearing plate
P_{AA}	design strengths from AA
P_{AISC}	design strengths from AISC
P_{AS4100}	design strengths from AS4100
$P_{AS/NZS}$	design strengths from AS/NZS
P_{EC3}	design strengths from EC3
P_{EC9}	design strengths from EC9
P_{exp}	experimental web bearing strength
P_{FE}	numerical web bearing strength from finite element analysis
P_m	mean value of test-to-predicted load ratios
P_{pl}	applied loads calculated from the plastic bending moment
P_{prop}	design strengths from the proposed design method
P_u	experimental and numerical web bearing strength
t	wall thickness
V_F	coefficient of variation of fabrication factor
V_M	coefficient of variation of material factor
V_P	coefficient of variation of test-to-predicted load ratios
α_p	coefficient used to calculate the nominal bearing yield capacity for square and rectangular hollow sections
α	web crippling coefficient
β	reliability index
ε	engineering strain
ε_{csm}	CSM limiting strain
ε_{true}	plastic true strain
ε_f	strain at fracture
ε_u	strain at the ultimate tensile stress
ε_y	yield strain (f_y/E)
k_F	buckling factor for transverse force
λ_F	slenderness parameter for local buckling due to transverse force
$\bar{\lambda}_p$	cross-section/plate slenderness
σ	engineering stress
σ_{true}	true stress
χ_F	reduction factor due to local buckling

facade, moving bridges and structures in corrosive environment. The webs of tubular members may be subjected to concentrated forces when used in a floor system [5]. Two loading conditions are considered in the specifications: interior loading and end loading. The AISI Specification [24] specifies that when the distance from the edge of the bearing to the end of the member is less than or equal to 1.5 times the clear depth of the web, it is classified as end loading, otherwise it is classified as interior loading. When considering the concentrated load acting on one flange or two flanges, four loading conditions of prime interest are classified: end-one-flange (EOF), interior-one-flange (IOF), end-two-flange (ETF), and interior-two-flange (ITF). Some design codes treat the one-flange and two-flange loading conditions as being the same.

In this paper, aluminium alloy square and rectangular hollow sections (SHS/RHS) were tested under the four loading conditions of EOF, ETF, IOF, and ITF. The concentrated loads were applied by means of bearing plates of two bearing lengths, 50 mm and 90 mm. The test specimens were extruded by normal strength (6063-T5) and high-strength (6061-T6) aluminium alloys. Finite element (FE) models were developed using ABAQUS version 6.12 [25] and validated against the test results generated in this study. The validated models were then used to conduct a parametric study and 104 additional numerical results were generated. Since this research focuses on web bearing design, only the specimens failed by web bearing are included. The combined experimental and numerical data, with slenderness values (h / t) of 2.8–28.0, were used to assess the web bearing design rules in the aforementioned international specifications. Using the results, a series of more accurate design equations for two-flange loading configurations were proposed, and assessed by reliability analyses.

2. Experimental investigation

A series of tests on aluminium alloy square and rectangular hollow sections (SHS/RHS) subjected to web bearing were performed at the structural laboratory at The University of Hong Kong.

2.1. Test specimens

The test specimens consisted of different cross-section dimensions with nominal heights of the webs ranging from 50 mm to 120 mm. Tables 1–4 show the measured test specimen dimensions and material properties. Fig. 1 illustrates the section dimensions, where B is the flange width, H is the web width, h is the flat width of web, t is the

Table 1
Measured specimen dimensions and material properties for the ETF loading condition.

Specimen	B (mm)	H (mm)	t (mm)	L (mm)	h / t	E (GPa)	$f_{0.2}$ (MPa)	f_u (MPa)	ε_u (%)	ε_f (%)
H95 × 50 × 10.5-ETF-N50	94.7	49.6	10.36	125	2.79	70	179.2	220.5	8.1	14.1
H50 × 95 × 10.5-ETF-N50	49.7	94.7	10.35	196	7.14	69	192.0	232.2	7.7	10.9
H50 × 95 × 10.5-ETF-N50-R	49.7	94.7	10.38	193	7.13	69	192.0	232.3	7.7	10.9
N120 × 70 × 10.5-ETF-N50	119.7	69.8	10.40	155	4.72	71	139.1	194.0	6.6	14.1
N70 × 120 × 10.5-ETF-N50	69.9	119.9	10.41	230	9.51	71	139.1	194.0	6.6	14.1
N120 × 120 × 9.0-ETF-N50	119.8	119.8	8.88	231	11.50	71	182.9	224.8	9.7	14.3
H95 × 50 × 10.5-ETF-N90	94.7	49.7	10.34	166	2.80	70	179.2	220.5	8.1	14.1
H50 × 95 × 10.5-ETF-N90	49.7	94.8	10.35	234	7.15	70	232.0	244.5	4.3	7.9
H120 × 70 × 10.5-ETF-N90	119.8	69.8	10.38	194	4.73	69	225.7	238.3	7.9	10.1
H70 × 120 × 10.5-ETF-N90	69.9	119.9	10.43	272	9.50	69	225.7	238.3	7.9	10.1
N120 × 120 × 9.0-ETF-N90	119.8	119.9	8.90	270	11.47	71	182.9	224.8	9.7	14.3