Engineering Structures 80 (2014) 339–349

Contents lists available at ScienceDirect

Engineering Structures

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

Deformation-based design of aluminium alloy beams

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ARTICLE INFO

Article history:
Received 30 July 2013
Revised 18 August 2014
Accepted 21 August 2014
Available online 29 September 2014

Keywords:
Aluminium alloys
Bending moment capacities
Continuous strength method
Experimental investigation
Flexure
I-sections
Numerical analysis
Simply supported beams
Square and rectangular hollow sections
Structural design

ABSTRACT

Two series of simply supported bending tests on aluminium alloy square and rectangular hollow sections have been performed. The test program comprised 14 three-point bending tests and 15 four-point bending tests. The test specimens were fabricated by extrusion from grades 6061-T6 and 6063-T5 heat-treated aluminium alloys, with width-to-thickness ratios ranging from 2.8 to 20.5. Measured geometric and material properties, together with the full load–deflection histories from the test specimens, were reported. Observed failure modes included local buckling, material yielding and tensile fracture. Further experimental data were gathered from the literature. Finite element (FE) models were developed and validated against the test results, and then used to perform parametric studies, in which a total of 132 numerical results were generated. The experimental and numerical results were used to evaluate the bending resistance provisions of the American [1], Australian/New Zealand [2] and European [3] Specifications, as well as the continuous strength method (CSM). The moment capacities predicted by the three design specifications were found to be generally conservative, while the CSM provided more accurate and more consistent predictions due to the recognition and systematic exploitation of strain hardening.

1. Introduction

Aluminium alloys are gaining increasing usage in the construction industry, offering high strength-to-weight ratios, good durability and ease of fabrication. A wide variety of cross-section types are available, enabling aluminium alloys to be used efficiently under a broad range of loading conditions. The behaviour of design of aluminium alloy cross-sections in flexure is the subject of the present study.

The earliest documented structural tests on aluminium alloy members subjected to bending were conducted by Dumont and Hill [4]. Since then, both experimental and numerical studies have been carried out by numerous researchers, seeking to improve the design provisions for aluminium alloy beams. For instance, Lai and Nethercot [5] developed finite element (FE) models, which incorporated heat-affected zones to investigate their influence on flexural capacity. Moen et al. [6,7], De Matteis et al. [8,9] and Manganiello et al. [10] conducted a number of experimental and numerical investigations into the strength and rotation capacity of aluminium alloy beams subjected to a moment gradient. Eberwien and Valtinat [11] proposed a method to obtain the moment–curvature response of symmetrical aluminium cross-sections, while recently, the direct strength method (DSM), initially developed by Schafer and Peköz [12] for the design of cold-formed steel structural members, was extended to aluminium alloy thin-walled sections, and verified against a series of beam tests conducted by Zhu and Young [13].

The post-yield material properties of aluminium alloys – strain hardening and ductility – have been found to have a strong influence on the flexural behaviour of aluminium alloy beams [6,7,14]. With an emphasis on these two factors, Kim and Peköz [15] conducted tests and developed numerical models of aluminium alloy stocky section beams to determine the ultimate inelastic bending capacities, where it was found that the ultimate material strength could be achieved. Recently, a deformation-based design approach, the continuous strength method (CSM), was proposed for non-linear metallic structural members [16–20]. The CSM involves determining a limiting strain for the cross-section which is used in conjunction with a strain hardening material model to determine load-carrying capacities.

There are a number of international aluminium alloy design specifications. The most widely used are the Aluminum Design Manual [1], the Australian/New Zealand Standard [2] and Eurocode9 [3]. The width-to-thickness ratio and the yield stress are recognized as the governing design parameters in the design of cross-sections in these specifications. In the case of flexural members, the design strengths predicted by these specifications are generally

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http://dx.doi.org/10.1016/j.engstruct.2014.08.034
0141-0296/

Nomenclature

B	section width	M_{pl}	$W_{pl}f_y$ is the plastic moment capacity
b	flat width of flange	n	exponent in Ramberg–Osgood expression
COV	coefficient of variation	R	rotation capacity
E	Young's modulus	t	wall thickness
E_{sh}	strain hardening modulus	W_{eff}	elastic modulus of effective section
f_y	yield strength, taken as the 0.2% proof strength	W_{el}	elastic section modulus
f_u	ultimate tensile strength	W_{pl}	plastic section modulus
H	section depth	ε_{csm}	CSM limiting strain
h	flat depth of web	ε_u	strain at ultimate tensile stress
L	member length	ε_y	f_y/E is the yield strain
M_{AA}	ultimate moment capacity predicted by the AA (2010)	κ_{pl}	elastic curvature corresponding to the plastic moment M_{pl}
$M_{AS/NZS}$	ultimate moment capacity predicted by the AS/NZS (1997)	κ_{rot}	curvature at the point where the moment resistance drops back below M_{pl}
M_{csm}	ultimate moment capacity predicted by the CSM	$\bar{\lambda}_p$	cross-section/plate slenderness
M_{EC9}	ultimate moment capacity predicted by Annex F of EC9 (2007)	θ_{pl}	elastic rotation corresponding to the plastic moment M_{pl}
M_{el}	$W_{el}f_y$ is the elastic moment capacity	θ_{rot}	rotation at the point where the moment resistance drops back below M_{pl}
M_{exp}	experimental ultimate moment	σ_{cr}	elastic buckling stress
M_{FE}	ultimate moment capacities of simulated models		

overly conservative [6,13,15,21], especially for stocky (non-slender) sections. This is recognised in Annex F of EC9 [3], where an alternative design method accounting for strain hardening is provided, and this more favourable approach is employed herein for all comparisons made with EC9.

The majority of available beam test results from the literature relate to experiments conducted on specimens of relatively slender proportions. Hence, the assessment of design specifications for stocky cross-sections is relatively limited. This paper firstly presents three-point and four-point bending tests on aluminium alloy tubular sections, the results of which are subsequently compared. Secondly, numerical models of both configurations are developed and validated against the experimental data, after which a parametric study is conducted to generate 132 additional numerical results. Finally, the test and numerical results generated in the present study, together with those gathered from previous tests conducted by other researchers, are compared with the design strengths predicted by the American [1], Australian/New Zealand [2] and European [3] specifications as well as the CSM.

2. Experimental investigation

An experimental program comprising three-point and four-point bending tests was conducted on aluminium alloy square and rectangular hollow sections (SHS/RHS). The test specimens were manufactured by extrusion from grades 6061-T6 and 6063-T5 heat-treated aluminium alloys. There were 29 flexural specimens, defined using the symbols illustrated in Fig. 1. The cross-sectional dimensions and tensile material properties shown in Tables 1 and 2 are the average measured values for each test specimen. The symbols presented in Tables 1 and 2 are defined as follows: L is the beam length, E is the Young's modulus, f_y is the 0.2% proof stress, which is conventionally used as the yield stress, f_u is the ultimate tensile stress and n is the exponent of the Ramberg–Osgood expression. The measured material properties of each specimen were determined by means of longitudinal tensile coupon tests and Webster hardness measurements. Coupon tests conformed to the Australian standard AS 1391 [22] and the ASTM standard [23]. Webster hardness measurements were conducted according to the Standard Test Method for Indentation Hardness of Aluminium Alloys by Means of a Webster Hardness Gage [24]. The average measured local imperfection amplitude of the test specimens was 0.2 mm.

The specimens were labelled according to the type of material, cross-sectional dimensions and test configuration. For example, the label "H70 × 55 × 4.2B3-R" defines an RHS specimen of high "H" strength aluminium alloy 6061-T6, with nominal cross-sectional dimensions of width (70 mm) × height (55 mm) × thickness (4.2 mm). If the label starts with "N", it means the specimen is of normal strength aluminium alloy 6063-T5. The symbol "B3" following the dimensions refers to the three-point loading configuration, whereas "B4" signifies the four-point loading configuration. If a test is repeated, a letter "R" is included in the label. The arrangement of the cross-sectional dimensions also refers to the bending axis. In this case, the specimen H70 × 55 × 4.2B3-R was bent about the minor axis, while the specimen H55 × 70 × 4.2B3 was bent about the major axis.

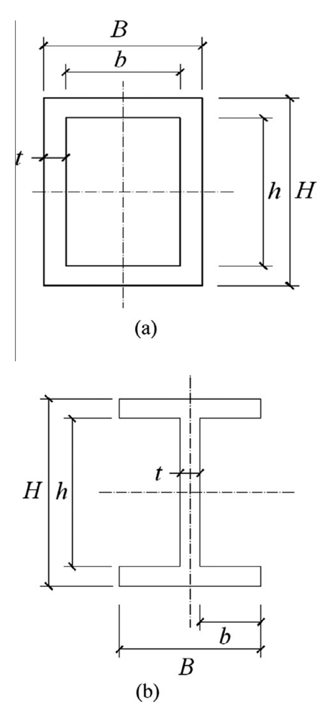

Fig. 1. Definition of symbols for (a) SHS/RHS and (b) I-section.