Engineering Structures 141 (2017) 29–40

Contents lists available at ScienceDirect

Engineering Structures

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

Classification of aluminium alloy cross-sections

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

[a] Dept. of Civil Engineering, Shenzhen University, Nanshan, Shenzhen, China
[b] Dept. of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong
[c] Dept. of Civil and Environmental Engineering, Imperial College London, London SW7 2AZ, UK

ARTICLE INFO

Article history:
Received 23 August 2016
Revised 13 February 2017
Accepted 4 March 2017

Keywords:
Aluminium alloys
Continuous beams
Continuous strength method (CSM)
Cross-section classification
Effective thickness formula
Reliability analysis
Simply supported beams
Slenderness limits
Stub columns

ABSTRACT

Cross-section classification is one of the key concepts in the design of metallic structures. Current design specifications for aluminium alloys, such as Eurocode 9 (EC9), provide clear definitions and discrete design capacities for four different classes of cross-section. On the basis of substantial, recently generated experimental and numerical data on aluminium alloy cross-sections collected from the literature, the purpose of the present study is to re-evaluate the slenderness limits that define these classes. A total of approximately 900 relevant data points have been gathered, covering stub columns, simply supported beams and continuous beams; the cross-section types include square and rectangular hollow sections (SHS/RHS) with and without internal stiffeners, I-sections, channels and angles. The members were extruded from a variety of aluminium alloy tempers with a wide range of yield and ultimate strengths. Following analysis of the available data, the slenderness limits in EC9 have been re-assessed, and new slenderness limits in the EC9 framework are proposed. In addition, the full cross-section slenderness allowing for element interaction, which is utilised in the direct strength method (DSM) and the continuous strength method (CSM) has been considered as the slenderness parameter in a new classification framework. Corresponding slenderness limits, together with a compatible effective thickness formula for Class 4 sections, are proposed. The suitability of the proposed limits has been demonstrated for the conventional design methods in EC9, as well as the alternative methods in Annexes F and H of EC9.

1. Introduction

Section classification addresses the susceptibility of a cross-section to local buckling and defines its appropriate design resistance [1]. This concept, which is adopted in Eurocode 9 (EC9) [2], treats cross-sections on an element by element basis, ignoring the benefit of element interaction, and utilises an elastic-perfectly plastic material model, excluding the beneficial influence of strain hardening. Ignoring these two effects is generally conservative, as illustrated later, when the classification criteria in EC9 are re-assessed against approximately 900 experimental and numerical results.

As an alternative to the EC9 classification framework, utilisation of the full cross-section slenderness as the slenderness parameter, as adopted in the continuous strength method (CSM) [3] and the direct strength method (DSM) [4], is considered. Note that this classification framework is therefore called 'classification based on full cross-section slenderness' to distinguish it from the traditional EC9 classification framework. Departing from the existing EC9 slenderness definition, the full cross-section slenderness parameter, $\bar{\lambda}_p$, as defined in Eq. (1), where f_y is the material yield stress (or 0.2% proof stress) and σ_{cr} is the elastic buckling stress of the full cross-section under the applied stress distribution, considering both the interaction between the constituent elements of the cross-section and the loading to which the cross-section is subjected.

$$\bar{\lambda}_p = \sqrt{f_y/\sigma_{cr}} \quad (1)$$

The two section classification frameworks provide discrete design capacities for four different classes of cross-section [5]. On the basis of a large collected pool of experimental and numerical results described in Section 2 of this paper, revised slenderness limits for the existing EC9 classification framework (Section 3) and the full cross-section slenderness framework (Section 4) are proposed. Slender (Class 4) cross-sections are considered in Section 5, while comparisons and reliability analyses are presented in Section 6.

* Corresponding author.
E-mail address: young@hku.hk (B. Young).

http://dx.doi.org/10.1016/j.engstruct.2017.03.007
0141-0296/

Notation

A	cross-sectional area
A_{eff}	effective cross-sectional area
b	flat width of flange
E	Young's modulus
f_{csm}	CSM limiting stress
f_y	yield strength, taken as the 0.2% proof stress
$f_{y,\ mean}$	measured yield strength from tensile coupon tests
$f_{y,nom}$	nominal yield strength
F_{EC9}	ultimate load predicted by EC9
$F_{EC9\text{-}Annex\ H}$	ultimate load predicted by the plastic hinge method in Annex H of EC9
F_u	experimental or numerical ultimate load of continuous beams
F_m	mean value of fabrication factor
h	flat depth of web
M_{EC9}	ultimate moment capacity predicted by EC9
$M_{EC9\text{-}Annex\ F}$	ultimate moment capacity predicted by Annex F of EC9
M_{el}	$W_{el}f_y$ is the elastic moment capacity
M_u	experimental or numerical ultimate moment of simply supported beams
M_m	material over-strength
M_{pl}	$W_{pl}f_y$ is the plastic moment capacity
N_{EC9}	ultimate load of stub columns predicted by EC9 [2]
$N_{EC9\text{-}Annex\ F}$	ultimate load of stub columns predicted by Annex F of EC9 [2]
N_u	experimental or numerical ultimate load of stub columns
t	thickness
t_{eff}	effective thickness
R	rotation capacity
V_F	coefficient of variation of fabrication factor
V_M	coefficient of variation of material factor
W_{el}	elastic section modulus
W_{pl}	plastic section modulus
β/ε	slenderness parameter employed in EC9
γ_{M0}	required partial safety factor at slenderness limit under consideration
$\overline{\lambda}_p$	cross-section/plate slenderness
ρ_c	local buckling reduction factor
κ_{pl}	elastic curvature corresponding to the plastic moment M_{pl}
κ_{rot}	curvature at the point where the moment resistance drops back below M_{pl}
θ_{pl}	elastic rotation corresponding to the plastic moment M_{pl}
θ_{rot}	rotation at the point where the moment resistance drops back below M_{pl}
σ_{cr}	elastic buckling stress
ν	Poisson's ratio
k	buckling coefficient allowing for different loading and boundary conditions

2. Review of existing experimental and numerical data

Previous test data on aluminium alloy stub columns, simply supported beams and continuous beams, together with numerical results from parametric studies, have been collected and analysed herein. The assembled results are summarised below.

2.1. Stub columns

Stub column test results on different aluminium alloy tempers and a wide range of cross-section types of various proportions have been collected. The stub column data pool includes a total of 346 results, with both closed and open sections: 110 square and rectangular hollow sections (SHS/RHS) [6–14], 203 plain channel sections [12,15] and 33 angle sections [16]. The average measured cross-sectional dimensions and material properties can be found in the cited papers. The specimens cover all four classes of cross-sections, as defined by EC9 [2].

2.2. Simply supported beams

For cross-sections in bending, 53 experimental data points obtained from three-point bending tests on SHS/RHS and I sections [18–20], as well as 38 data points from four-point bending tests on SHS/RHS [17–19,21,22] have been assembled. In addition, a total of 192 numerical results from validated finite element models of aluminium alloy beams (half in three-point bending and half in four-point bending) have been collected [18,19]. A wide spectrum of b/h (width-to-height) ratios (0.3–3.6) and b/t (width-to-thickness) ratios (4.3–55.1) are covered by the numerical results.

2.3. Continuous beams

For continuous beams, data from an experimental program featuring 46 SHS/RHS test specimens with and without internal cross stiffeners [19,23], have been collected. The beams were tested in three symmetrical five-point bending configurations. Both normal strength (i.e. 6063-T5) and high strength (i.e. 6061-T6) aluminium alloys were considered. In addition to the experiments, a numerical parametric study was also conducted, and the 210 generated results [19,24] are utilised in the present study.

3. EC9 classification framework

EC9 [2] defines four classes of cross-sections, while the American [25] and Australian/New Zealand [26] specifications classify cross-sections into three categories according to their failure modes: yielding (equivalent to Classes 1 and 2 in EC9), inelastic buckling (equivalent to Class 3 in EC9) and elastic buckling (equivalent to Class 4 in EC9). There is also some variation between the slenderness limits adopted in the different design standards – this is attributed to the pool of available structural performance data utilised in their development and to the different regional practice in terms of structural reliability [27].

The classification of cross-sections in EC9 [2] depends on their most slender constituent element. The adopted slenderness measure is β/ε, which takes account of the flat width-to-thickness ratio of the element b/t and the yield stress f_y, as given by Eq. (2). A reduction factor is used to allow for the applied stress distribution. For example, for elements in pure bending, the element width is multiplied by a reduction factor of 0.4, as given by Eq. (3).

$$\frac{\beta}{\varepsilon} = \frac{b/t}{\sqrt{250/f_y}} \tag{2}$$

$$\frac{\beta}{\varepsilon} = \frac{0.4b/t}{\sqrt{250/f_y}} \tag{3}$$

Note that the unit of f_y must be in MPa.