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The continuous strength method for the design of aluminium alloy structural elements

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ABSTRACT

Aluminium alloys are nonlinear metallic materials with rounded stress–strain curves that are not well represented by the simplified elastic-perfectly plastic material model used in most existing design specifications. Departing from current practice, the continuous strength method (CSM) is a recently developed design approach for aluminium alloy structures, which gives consideration to strain hardening for non-slender sections. The CSM is a deformation-based method and employs a base curve to define the continuous relationship between cross-section slenderness and deformation capacity. This paper explains the background and the two key components of the CSM: (1) the base curve, which is extended herein such that the method covers both non-slender and slender sections and (2) the strain hardening material model. Three international design specifications from America, Australia/New Zealand and Europe, as well as the CSM are compared with approximately 900 aluminium alloy experimental and numerical results. Reliability analyses have been carried out to assess the reliability level of different design methods according to both the American Institute of Steel Construction (AISC) and European Standard (EN 1990) approaches. Finally, worked examples of the CSM for aluminium alloy stub columns and continuous beams are illustrated in this paper.

1. Introduction

Aluminium alloys are being increasingly used in building facades, roof systems, moving bridges and structures situated in humid environments. For efficient and economical structural design, it is important to recognise the key characteristics of aluminium alloys and to fully utilise them in design. Aluminium alloys exhibit nonlinear material stress–strain curves with significant strain hardening and reasonable ductility. This study focuses on strain hardening of aluminium alloys at the cross-sectional level and moment redistribution in indeterminate structures at the global system level, neither of which are fully exploited in current aluminium alloy specifications.

The continuous strength method (CSM) was originally developed for stainless steel and carbon steel materials, and is a deformation-based design framework that allows for the beneficial influence of strain hardening. A series of studies [1–5] have been conducted to develop and improve the CSM in the past decade. Owing to the general similarity of structural behaviour between stainless steel and aluminium alloys, the authors investigated the feasibility of applying the CSM to aluminium alloy structures. The key components of the CSM for aluminium alloy structures are described in this paper, including the base curve and the bi-linear (elastic, linear hardening) material model. Furthermore, for indeterminate structures, the CSM considers the degree of rotation at each plastic hinge, leading to different cross-section capacities at different hinges. The CSM is then used to predict the capacities of aluminium alloy stub columns, simply supported beams as well as continuous beams of a range of cross-section shapes – I-sections, channels, angles and square and rectangular hollow sections (SHS/RHS) with and without internal cross stiffeners. The data set used for comparisons is made up of a collection of test results and numerical simulations from the literature.

There are a number of established aluminium alloy structural design specifications currently available, such as the Aluminum Design Manual [6], the Australian/New Zealand Standard [7] and Eurocode 9 [8]. These specifications provide design rules for a range of structural components and applications though, in some areas, including the capacity of aluminium alloy compression and flexural members, design provisions are often conservative [9–17]. In the case of Class 1 and Class 2 cross-sections [8], this conservatism is largely attributed to the lack of account for strain

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Nomenclature

A	cross-sectional area
B	section width
C_1	coefficient to define a ‘cut off’ strain to avoid over-predictions of material strength
C_2	coefficient to define the strain hardening slope
C_3 and C_4	coefficients used in the predictive expression for ultimate strain
C_P	correction factor
E	Young’s modulus
E_{sh}	strain hardening modulus
f_{csm}	CSM limiting stress
f_y	yield strength, taken as the 0.2% proof strength
f_u	ultimate tensile strength
F_{AA}	ultimate load of continuous beams predicted by the AA
$F_{AS/NZS}$	ultimate load of continuous beams predicted by the AS/NZS
F_{coll}	ultimate load level at which a plastic collapse mechanism forms (with cross-sectional capacity at the plastic hinges equal to $W_{pl}f_y$)
F_{csm}	ultimate load of continuous beams predicted by the CSM
F_{design}	design load of continuous beams
F_{EC9}	ultimate load of continuous beams predicted by the plastic hinge method in Annex H of EC9
F_{exp}	experimental ultimate load of continuous beams
F_m	mean value of fabrication factor
F_u	experimental and numerical ultimate load for continuous beams
H	section height for SHS/RHS
L	member length
M_{AA}	ultimate moment of simply supported beams predicted by the AA
$M_{AS/NZS}$	ultimate moment of simply supported beams predicted by the AS/NZS
M_{csm}	ultimate moment of simply supported beams predicted by the CSM
M_{design}	design moment capacity of simply supported beams
M_{EC9}	ultimate moment of simply supported beams predicted by Annex F of EC9
M_{el}	$W_{el}f_y$ is the elastic moment capacity
M_{exp}	experimental ultimate moment of simply supported beams
M_m	material over-strength
M_{pl}	$W_{pl}f_y$ is the plastic moment capacity
M_u	experimental and numerical ultimate moment of simply supported beams
P_{AA}	ultimate load of stub columns predicted by AA
$P_{AS/NZS}$	ultimate load of stub columns predicted by AS/NZS
P_{csm}	ultimate load of stub columns predicted by the CSM
P_{EC9}	ultimate load of stub columns predicted by Annex F of EC9
P_m	mean value of test-to-predicted load ratios
P_y	Af_y is the yield load of stub columns
P_u	experimental and numerical ultimate load of stub columns
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
W_{el}	elastic section modulus
W_{pl}	plastic section modulus
x	proportion of ultimate strain
y	distance to the neutral axis
y_c	distance between extreme compressive fibre and the neutral axis
β	reliability index
δ	displacement at hinge point
δ_u	end shortening at ultimate load
ε	strain
ε_{csm}	CSM limiting strain
ε_{lb}	local buckling strain, equal to stub column end shortening divided by stub column length at ultimate load
ε_u	strain at ultimate tensile stress
ε_y	f_y/E is the yield strain
γ_{M0}	partial safety factor
κ	curvature
κ_{el}	curvature at yield
κ_u	curvature at ultimate load
ϕ	resistance factor
$\bar{\lambda}_p$	cross-section/plate slenderness
θ	rotation at plastic hinge
α	hinge rotation demand
σ	stress
σ_{cr}	elastic buckling stress
Δd	difference in stress

hardening and moment redistribution. This is recognised in Annex F of EC9 [8] for stub columns and simply supported beams as well as in Annex H of EC9 [8] for continuous beams, where alternative design methods are provided to consider strain hardening and global plastic analysis.

2. Continuous strength method (CSM) for aluminium alloys

2.1. General concepts

The continuous strength method (CSM) is a deformation-based design framework that allows for the beneficial influence of strain hardening. The method is focussed primarily on non-slender sections where local buckling occurs after yielding and hence where additional strength from strain hardening can be exploited [9,10,12]. For slender sections, local buckling failure occurs prior to yielding and hence strain hardening is generally not encountered. However, for some non-doubly symmetric slender sections in bending, even if the extreme fibre strain in compression is less than the yield strain, strains significantly beyond the yield strain can be experienced in tension; these strain are accompanied by strain hardening, which can therefore be exploited in design. Examples of such cases include angle sections, channel sections in minor axis bending and T-sections in major axis bending. In light of this, the CSM base curve for non-slender sections [9,10,12] is extended to also cover slender sections in this study, thus enabling the CSM to be applied to the full spectrum of cross-section slenderness.

The two main features of the CSM are (1) a base curve defining the level of strain that a cross-section can tolerate as a function of cross-section slenderness and (2) a strain hardening material model. These two components have been established for structural carbon steel and stainless steel in previous studies [1–5]. Building on recent proposals [9–12,17,18], developments of a base curve, a suitable strain hardening material model and a global plastic analysis approach for aluminium alloy structures are described in the following sections.