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Flexural buckling of fire exposed aluminium columns

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ABSTRACT

In order to study buckling of fire exposed aluminium columns, a finite element model is developed. The results of this model are verified with experiments. Based on a parametric study with the finite element model, it is concluded that the simple calculation model for flexural buckling of fire exposed aluminium columns in EN 1999-1-2 does not give an accurate prediction of the buckling resistance in fire. This paper proposes an alternative design model, which takes into account the shape of the stress–strain relationships of aluminium alloys at elevated temperatures. Predictions of this model agree well with that of the finite element model.

(subscript θ means considered property at temperature θ)

1. Introduction

Aluminium alloys are used for load-bearing structures such as parts of drill platforms, ships and roofs with large spans. The choice for aluminium mainly origins from the low self-weight and good corrosion resistance of the material. Fire design is an important part of the entire design of the above structures. The fast reduction of the mechanical material properties with increasing temperature means that these structures often need to be insulated in order to satisfy fire resistance requirements. This requires accurate design models in order to be able to check the fire resistance. The most up-to-date standard in this field is the Eurocode on aluminium structures—part 1-2: structural fire design [1]. However, due to limited research into fire exposed aluminium structures, some of the design models in EN 1999-1-2 [1] are based on conservative approximations. In particular, the design model for flexural buckling of columns is based on the assumption that the reduction as a function of temperature of the modulus of elasticity E_θ/E is equal to the reduction of the 0.2% proof stress $f_{0.2,\theta}/f_{0.2}$ in case of aluminium alloys (symbols are explained below). A direct consequence of this assumption is that the relative slenderness at elevated temperature equals the relative slenderness at room temperature: $\lambda_{rel,\theta} = \lambda_{rel}$. However, tensile test data e.g. by Kaufman [2] show that this is a gross approximation. This questions the accuracy of the design model in EN 1999-1-2 [1].

Langhelle [3] and Langhelle et al. [4] carried out a set of experiments on flexural buckling of aluminium columns of alloys 6082-T4 and 6082-T6. A finite element model is developed and verified using these experimental data in the current paper.

2. Stress–strain curves for fire exposed aluminium alloys

Stress–strain curves of aluminium alloys 5083-O/H111 and 6060-T66 exposed to fire conditions are determined [5]. Fig. 1 explains how these stress–strain curves are derived. The material is heated with a certain heating rate $d\theta/dt$ (Fig. 1a) and subjected to a stress level which is kept constant in time. The mechanical strain that develops in time depends on the stress level (Fig. 1b). The mechanical strains determined in Fig. 1b are plotted as a function of temperature in Fig. 1c. The stress–strain curve is obtained by plotting the stress levels as a function of the strains developed at a certain temperature (Fig. 1d). The so-called transient state stress–strain curve of Fig. 1d is valid for a certain temperature θ_1 and heating rate $d\theta/dt$. By applying this method, the influence of high temperature creep is incorporated in the stress–strain relationship. A similar procedure is followed for deriving the stress–strain relationships of carbon steel in EN 1993-1-2 [6], see Witteveen and Twilt [7].

The transient state stress–strain curves of aluminium alloys 5083-O/H111 and 6060-T66 are given with solid curves in Fig. 2. The curves are valid for a constant stress in time and for heating rates of 6–12 °C/min, resulting in a fire resistance of 30 min. As a

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Nomenclature

A	area of the cross-section (mm^2)
E	modulus of elasticity (N/mm^2)
E_t	tangential modulus of elasticity (N/mm^2)
F_{cr}	(elastic) critical buckling load (N)
$F_{cr,inel}$	inelastic critical buckling load (N)
F_u	ultimate buckling resistance (N)
I	second moment of area (mm^4)
L_{buc}	buckling length (mm)
b	section width (mm)
e	eccentricity (mm)
h	section height (mm)
$f_{0.2}$	0.2% proof stress (N/mm^2)
$k_{0.2}$	strength reduction factor ($f_{0.2,\theta}/f_{0.2,20\,^\circ\mathrm{C}}$)
n	parameter of the Ramberg–Osgood relationship (dimensionless)
t	time (min) (only in Section 1)
t	plate thickness (mm) (in all sections but Section 1)
t_f	flange thickness (mm)
t_w	web thickness (mm)
u	lateral displacement at midspan (mm)
ε	strain (dimensionless)
θ	temperature (°C)
λ_{rel}	relative slenderness (dimensionless)
$\lambda_{rel,inel}$	inelastic relative slenderness (dimensionless)
σ	stress (N/mm^2)
χ	relative buckling resistance (dimensionless)

reference, stress–strain curves determined in tensile tests at room temperature are also given.

The stress–strain curves in Fig. 2 are described with the Ramberg–Osgood relationship according to Eq. (1) [8]. Applying the values according to Table 1 results in the dashed curves in Fig. 2:

$$\varepsilon = \frac{\sigma}{E_\theta} + 0.002\left(\frac{\sigma}{f_{0.2,\theta}}\right)^n \tag{1}$$

Fig. 2 shows that the Ramberg–Osgood equation with proposed parameters agree well with the actual curves for strains up to 0.01. Larger strains are usually not important for structural applications. Fig. 2 also shows that the transient state stress–strain curves at elevated temperatures are significantly more curved than at room temperature. This corresponds with very low values for parameter n for fire exposure.

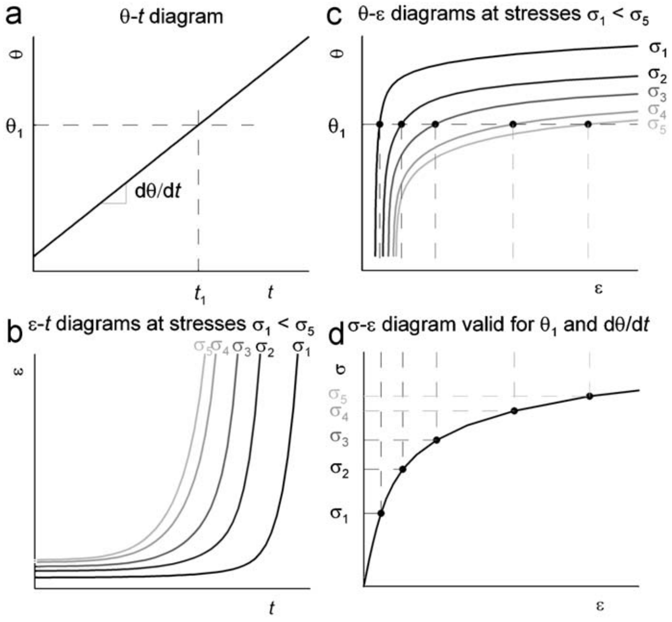

Fig. 1. Derivation of a transient state stress–strain curve.

Table 1
Parameters of the Ramberg–Osgood relationship for aluminium alloys at room temperature and at elevated temperatures.

Alloy	Parameter	θ (°C)				
		20	200	250	300	350
5083-H111	E_θ (N/mm^2)	72 000	60 000	56 000	47 000	40 000
	$f_{0.2,\theta}$ (N/mm^2)	155	95	67	36	19
	n_θ (—)	18	5	4.5	4	3.2
6060-T66	E_θ (N/mm^2)	69 000	60 000	57 000	49 000	42 000
	$f_{0.2,\theta}$ (N/mm^2)	205	112	88	55	34
	n_θ (—)	22	10	8	6	4

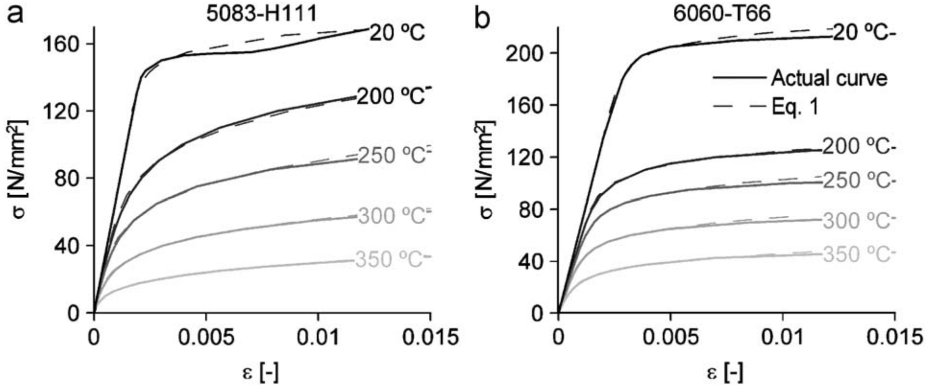

Fig. 2. Transient state stress–strain curves of aluminium alloys exposed to fire conditions for 30 min and stress–strain curves at room temperature ((a) alloy 5083-H111; (b) alloy 6060-T66).

Alloy 6082 is used widely in Europe. Stress–strain relations based on transient state experiments are not available for this alloy. However, steady state experiments results (i.e. results of experiments at a constant temperature and a certain strain rate)