Experimental analysis of stability of aluminium beams in case of fire, experiments

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Stability of aluminium beams in case of fire, experiments

O. R. (Ronald) van der Meulen^{*,1,2,3}, Frans Soetens², and Johan Maljaars³

¹ Materials innovation institute (M2i), Delft, the Netherlands

² Eindhoven University of Technology, Eindhoven, the Netherlands

³ TNO, Delft, the Netherlands

*Corresponding author, - E-mail: ronald@vandermill.eu

ABSTRACT

Fire is often the dominant design criterion for aluminium structures. Present design rules for aluminium constructions in fire neglect both the decrease in susceptibility to local buckling and the effects of creep, that are intrinsic to aluminium. They may therefore either overestimate or underestimate the temperature of failure, depending on the load and exposure period. As part of a larger research program aimed at remedying this situation, the present paper reports the results of an experimental study on 28 aluminium SHS members of alloy AA6060-T66 loaded in bending, with varied cross-sections, temperature(-gradient)s and rates of heating. The experimental set-up employs an electric heating tube or ‘sock’ on the inside of the specimen as well as heated supports and load application point, delivering a high degree of control of temperature in time.

1 INTRODUCTION

In the design of aluminium structures, such as helicopter platforms, living quarters on offshore platforms, atria, and lightweight architectural speciality structures, the behaviour of the structure during a fire is frequently the dominant factor driving the required strength and hence the thickness, weight and cost of the structure. In aluminium structures, direct contact to the flames is generally prevented by designing structures to be far from potential sources of heat, insulation, or active cooling measures. Relatively modest temperature rises still require careful designing using accurate design rules, as over half the strength of aluminium is lost in the temperature range of approximately 175 °C to 300 °C. Present design rules such as offered by the European standard [1, 2] are inspired by steel standards and neglect aluminium’s decrease in susceptibility to local buckling that is intrinsic to it: the slenderness of a plate and consequently its resistance to local buckling is affected by the ratio $\sqrt{f_{0.2}/E}$. For aluminium at elevated temperatures this ratio increases as the young’s modulus E decreases less with temperature than the 0.2% offset proof stress $f_{0.2}$ [3]. As a result, aluminium cross-sections behave more stocky at elevated temperatures than at ambient temperatures. This positive effect is counteracted by the action of creep, which is the continued straining under a constant load. The rate of creep is a function of both temperature and stress, and is significant in the temperature range considered, even for the relatively short duration of a fire.

1.1 Cross-sectional classes

The ability of a bending member to withstand local buckling, and thus its strength as a function of its full elastic or plastic bending moment is treated in most building codes by means of some cross-sectional classification scheme. In this paper we will explore the suitability of classification system of the European standard for aluminium constructions [1] and aluminium constructions in fire [2]. In both standards (which share a single set of geometrical limits between classes), the class of the cross-sections’s plates is determined by their width-over-thickness-ratio and a material factor. To calculate the ultimate design resistance $M_{u,Rd}$ four classes are discriminated between, from the most slender to the most stocky: class 4, ultimate resistance below elastic moment ($M_{u,Rd} < M_{0.2}$); class 3, able to reach elastic moment ($M_{u,Rd} = M_{el}$); class 2, able to reach the full plastic moment ($M_{u,Rd} = M_{pl}$); Class 1, same strength but are defined as having a stable rotation

Figure 1: 4 cross-sectional classes and rotation capacity

capacity $R_0 \geq 3$ [4], which allows plastic design with redistribution of forces. In figure 1a an illustration is drawn of load displacement diagrams according to the 4 classes. In figure 1b the concept of rotation capacity is demonstrated. Two measures exist, the stable (R_0) and the total (R), which are defined by

$$R_0 = \frac{\phi_u}{\phi_{0.2}} - 1, \quad R = \frac{\phi_m}{\phi_{0.2}} - 1, \quad (1)$$

where ϕ_u is the ultimate rotation between points of zero moment (at supports in this case), and ϕ_m is the rotation between the same points of zero moment after the moment decreases below the elastic value after having reached a higher value first.

1.2 Experimental program

Three point bending tests were performed on square hollow profiles of aluminium alloy AA6060-T66. A schematic drawing of the set-up, cross-section and summary of the varied quantities is offered in figure 2. All profiles had nominally equal outer dimensions of 100 mm, but three different wall thickness values were used; 3 mm, 4 mm, and 5 mm, in order to have results for a broad range of slenderness values. Bending tests were performed at both room temperature and elevated temperature. Two different types of test were performed: steady state and transient state.

In the steady state tests, the temperature was kept constant at either ambient temperature, 250 °C, or 300 °C and the force was increased until failure. 18 tests steady state tests were performed, of which 12 had a constant temperature across the height of the beam and 6 had an temperature gradient applied, where the tension zone was between 19 °C and 40 °C warmer than the compression zone. Material properties for all bending members tested are given as a function of temperature in section 2.

In the transient state tests, the load was kept at a predetermined fraction (between 40% and 60%) of the ambient temperature design resistance and the temperature was increased linearly from ambient temperature at a rate of either 2.5 °C min⁻¹ or 10 °C min⁻¹, roughly equating to a 120 min or 30 min at an approximate temperature of failure of 280 °C. In order to investigate the influence of the magnitude of the moment gradient across the length of the beam, 3 tests were performed with a short length between supports of 1.0 m, where in the other experiments it was equal to 2.0 m. long.

2 CONSTITUTIVE PROPERTIES

Tensile tests were performed to derive material models for the aluminium alloy used: AA6060-T66, at both room temperature and at the relevant elevated temperatures associated with fire. The material properties for ambient temperatures are given in section 2.1. Elevated temperature properties are given in section 2.2

2.1 Ambient temperature

The outer dimensions for all specimens tested in the present research are nominally identical. All specimens having the same nominal thickness were sourced from the same production batch and have similar

Figure 2: Setup and cross-section, $D = 150$ mm, $t_1 = t_2 = t_3 = t_4 \approx \{3, 4, 5\}$ mm. Tested in steady state at 20°C , 250°C , and 300°C . Tested in transient state with a heating rate of $2.5^\circ\text{C min}^{-1}$ and $10^\circ\text{C min}^{-1}$. Force F maintained at constant value in range $0.4\text{--}0.6 F_{0.2}$.

Table 1: Ambient-temperature tensile test material model

Sample	Thickness mm	$f_{0.2}$ ($\frac{\text{N}}{\text{mm}^2}$)	E ($\frac{\text{N}}{\text{mm}^2}$)	n_1 (—)	f_u ($\frac{\text{N}}{\text{mm}^2}$)	ϵ_u (%)	n_2 (—)	R^2 (—)
13..	3	256.0	66038	28	273.5	7.53	2.1	0.996
14..	4	217.3	64343	50	234.9	6.78	2.1	0.995
15..	5	222.5	64930	50	236.0	6.83	2.1	0.998

Table 2: Material properties of Promatect®-H loaded in the out-of-plane direction

$f_{0.2}$ ($\frac{\text{N}}{\text{mm}^2}$)	$E_{\perp}$ ($\frac{\text{N}}{\text{mm}^2}$)	n_1 (—)	f_u ($\frac{\text{N}}{\text{mm}^2}$)	ϵ_u (%)	n_2 (—)	ν (—)	$E_{\parallel}$ ($\frac{\text{N}}{\text{mm}^2}$)	G_{12} ($\frac{\text{N}}{\text{mm}^2}$)
5.034	330	7	10.18	9.5	3	0.15	4693	541

constitutive properties therefore. Stress-strain curves were fitted to the composite Ramberg-Osgood curve by Rasmussen [5]:

$$\epsilon = \begin{cases} \frac{\sigma}{E} + 0.002 \left(\frac{\sigma}{f_{0.2}} \right)^{n_1}, & \text{for } f_{0.2} > \sigma \\ \frac{\sigma - f_{0.2}}{E_{0.2}} + \left(\epsilon_u - \frac{f_u - f_{0.2}}{E_{0.2}} - \epsilon_{0.2} \right) \left(\frac{\sigma - f_{0.2}}{f_u - f_{0.2}} \right)^{n_2} + \epsilon_{0.2}, & \text{for } \sigma \geq f_{0.2} \end{cases} \quad (2)$$

where $E_{0.2}$ is the tangent modulus of the stress-strain curve at the 0.2% proof stress ($f_{0.2}$) which is equal to [5]:

$$E_{0.2} \equiv \left. \frac{\partial \sigma}{\partial \epsilon} \right|_{\sigma=f_{0.2}} = \frac{E}{1 + 0.002 \frac{n_1 E}{f_{0.2}}}. \quad (3)$$

Values for the different variables are given in table 1. All tests names are formed from 3 digits and one letter, where the 2nd number denotes the nominal thickness, the 3rd the beam from which the specimen was cut and the letter, the part of the beam. Out-of-plane compression tests were also performed to determine the properties of a piece of Promatect®-H calcium silicate insulation plate which, in the bending experiments, was placed between the saddle and the specimen. properties are listed in table 2.

2.2 Elevated temperature

The behaviour of aluminium in a steady state situation, where the temperature is kept constant and the load is increased, is quite different from the transient state situation, where the load is kept constant and the temperature is increased. For the steady state situation, the 0.2% offset proof stress is fitted to the general

Table 3: Coefficients for the 0.2% offset proof stress as a function of temperature according to the Kandare equation (4).

Dataset	$f_{0.2}$ ($\frac{\text{N}}{\text{mm}^2}$)	$f_{0.2}^*$ ($\frac{\text{N}}{\text{mm}^2}$)	$\theta_{50\%}$ ($^{\circ}\text{C}$)	C_1 ($\frac{1}{^{\circ}\text{C}}$)	R^2 (-)
AA6060-T66, 3 mm	256.0	262.2	239.8	$8.461 \cdot 10^{-3}$	0.9937
AA6060-T66, 4 mm	217.3	229.1	217.0	$7.402 \cdot 10^{-3}$	0.9991
AA6060-T66, 5 mm	222.5	224.4	255.0	$1.014 \cdot 10^{-2}$	0.9930

Figure 3: 0.2% offset proof stress $f_{0.2,\theta}$ as function of temperature.

shape of equation as proposed by [6]:

$$f_{0.2,\theta} = \frac{f_{0.2}^*}{2} - \frac{f_{0.2}^*}{2} \tanh[C_1 (\theta - \theta_{50\%})], \quad (4)$$

where C_1 is a material fitting constant and $\theta_{50\%}$ is the temperature where the 0.2% offset proof stress has dropped by 50%. A small correction was applied to equation (4) as compared to the original equation by Kandare [6], as this original equation did not pass exactly through the point $f_{0.2}$ at 20 °C, this was solved by defining

$$f_{0.2}^* = \frac{2 f_{0.2}}{1 - \tanh[C_1 (20 - \theta_{50\%})]}. \quad (5)$$

Tabulated parameters to equation 4 for $f_{0.2,\theta,ss}$ are given in table 3 and a graph of the resulting curves and original tensile test data points is given in figure 3. The young's modulus was found to conform to the tabulated values given in [2, Table 2]. For transient state tests, the creep material model and parameters given in [7] describe the material behaviour well. Graphs of $f_{0.2,\theta,ss}$ as a function of temperature along with measurement data points are given in figure 3. The 0.2% offset proof stress is sensitive to exposure time however, and after completing the bending experiments it became apparent that the 3 mm specimens above 275 °C and the 5 mm samples above 175 °C behave according to the 4 mm model. A verification study with tensile samples tested by an independent lab using the exact temperature history as used in the bending experiments confirmed this, these data points are included in figure 3 as well.

3 EXPERIMENTS

3.1 Set-up

The bending tests were performed using the test set-up schematically drawn in figure 4 and as shown in figure 6a. An upward load was applied at centre span using a steel saddle which was fitted with a 10 mm thick plate of calcium silicate based insulation (Promatect®-H) between the specimen and the saddle. The saddle was used to prevent load initiation induced buckling and is shown in detail in figure 5b. A 2.0 kW

Figure 4: Test set-up for bending tests

Figure 5: Roll support, load initiation saddle and rotation sensor

electric heating element was mounted underneath the saddle to match the temperature of the beam. The end supports used were steel rolls, an example is shown in figure 5a. Also visible is the 1.0 kW electric heating plate. Stainless steel threads were used here to limit the flow of heat to the reaction frame and the reaction-force-measuring load-cells. The shorter, transverse, steel beams where the roll supports were connected to, can be seen in figure 6a to have been connected themselves to the main reaction frame through a load cell at both ends. This allows the reaction forces to be measured and checked for symmetry (which was near perfect in all experiments), and allows the cross-beam to behave as a radiator and thus prevent heating of the load-cells and main reaction frame. The solution chosen does induce some undesired flexibility, and the upward movement of the bending specimen at the supports was measured therefore using a laser displacement sensor shown in figure 5c inside a protective casing. Rotation measurements were performed at both ends of the specimen using liquid capacitive inclinometers, which were mounted to the specimen via 400 mm long stainless steel profiles clamped to the specimen at both ends, which allowed natural convection to keep the mounting location of the sensor to below 40 °C. This set-up may also be observed in figure 5c. In the experiments, the specimens were heated from within by means of a purpose made ‘heating sock’ which was

Figure 6: Experimental set-up and cross-section

made from a ceramic welding blanket with 8 electric resistance heater strips attached to the sides and sown together using Teflon coated fibre-glass yarn. The sock was inserted into the specimens and subsequently stuffed with ceramic insulation wool, causing the heating strips to be pressed against the interior of the cross-section. A schematic cross-section of this system is shown in figure 6b. The heating strips were connected together per side of the cross-section to a current controller, which was in turn steered by a software proportional-integral (PI) controller. Temperature sensors connected to the four sides of the cross-section served as feedback for the controller. Predefined temperature profiles in time were followed during the tests. Because, as discussed in the introduction, the range of interest for aluminium fire design has an upper bound of approximately 300 °C, the test temperatures are relatively modest, which allows the use of (ceramic) cloth based heating solutions. Using this kind of heating system instead of the more conventional approach of using furnaces is more cost-effective and gives more control over the temperature. Placing the heating system inside the cross-section simplifies sensor placement and prevents discontinuities at supports and load application point. A 20 mm layer of ceramic fibre insulation was applied to the outside of the specimens to increase the maximum temperature possible and reduce (spatial) temperature variation.

3.1.1 Dimensions

All specimens were measured before testing and their dimensions are listed in table 4. The wall thickness values t_1 — t_4 reflect arithmetic means of six measurements each for the 4 sides of the cross-section as defined in figure 2. H and B are arithmetic means of the outside height and width of the cross-section and D is the length of the supporting insulation at centre span. L is the actual length of the beam between rolls. The elastic and plastic section moduli (W_{el} and W_{pl}) are calculated from the geometric data as given in the preceding columns. Initial geometric imperfections were also measured, detailed surface maps were made for all specimens and constitutive plates[8]. In most instances, the plate was prismatically outward bulging. The absolute value of the maximum initial imperfection per plate was normally distributed with a mean of 72 μm and a standard deviation of 39 μm , with two outliers at 230 μm .

3.2 Temperature measurements

Temperatures were measured at 32 locations in each test with a maximum measurement error of 1.7 °C. An example of the temperatures measured on all four sides, near the centre of the beam, after the heating phase, and as a function of time for a steady state experiment is given in figure 7a. The force-in-time is overlaid in this same figure. The feedback channels for the PI temperature control system were located just left of the saddle and the temperatures for the four faces of the beam, just left of the saddle, were equal to the predefined desired temperatures to within an error of 1 °C, which was the case in all steady state experiments. The temperature

Table 4: Geometric properties of test specimens

Name	t_1 (mm)	t_2 (mm)	t_3 (mm)	t_4 (mm)	H (mm)	B (mm)	D (mm)	L (m)	W_{el} (mm ³)	W_{pl} (mm ³)
<i>Steady state</i>										
135A	2.90	3.04	2.99	2.90	99.94	99.93	151.0	2.0	35963	41693
131B	3.05	3.00	3.00	2.89	99.91	99.96	150.0	2.0	36525	42245
134A	2.90	3.03	3.01	2.89	99.92	99.94	152.0	2.0	35968	41682
133A	2.90	3.00	2.98	2.91	99.85	99.86	149.0	2.0	35791	41477
144B	3.95	3.93	4.10	4.12	99.94	99.90	145.0	2.0	47417	55519
141B	4.08	4.12	3.96	3.90	99.99	99.91	146.0	2.0	47379	55457
145A	4.12	3.96	3.90	4.09	99.99	99.91	146.0	1.0	47331	55423
141A	4.08	4.12	3.96	3.90	99.99	99.91	146.0	2.0	47379	55457
151B	4.81	4.75	4.82	4.88	100.03	100.01	151.5	2.0	55535	65522
154B	4.74	4.83	4.86	4.79	100.01	100.02	157.5	2.0	55398	65364
154A	4.74	4.82	4.85	4.79	100.00	100.03	150.0	1.0	55349	65308
151A	4.79	4.75	4.83	4.86	100.03	100.01	152.0	2.0	55461	65430
<i>Steady state, with temperature gradient</i>										
134B	2.91	3.06	2.98	2.89	99.94	99.95	150.0	2.0	35974	41709
135B	2.90	3.04	2.98	2.89	99.92	99.94	150.0	2.0	35846	41559
145B	4.12	3.98	3.92	4.25	99.90	99.96	150.0	2.0	47625	55865
143A	4.11	3.95	3.90	4.09	99.90	99.95	150.5	2.0	47243	55324
153A	4.73	4.82	4.86	4.79	100.01	100.03	151.0	2.0	55336	65289
152A	4.82	4.85	4.80	4.73	99.99	99.95	152.0	2.0	55377	65311
<i>Transient state</i>										
132A	2.90	3.01	3.00	2.90	99.92	99.92	148.0	2.0	35898	41597
131A	2.91	3.04	2.98	2.89	99.92	99.93	149.5	2.0	35888	41601
132B	2.90	3.01	2.99	2.89	99.92	99.90	148.0	2.0	35878	41570
142A	3.96	3.92	4.08	4.09	99.94	99.90	149.0	2.0	47348	55418
143B	4.11	3.95	3.90	4.09	99.90	99.95	150.0	2.0	47234	55308
142B	3.96	3.92	4.08	4.09	99.94	99.90	149.0	2.0	47348	55418
144A	3.96	3.91	4.10	4.12	99.95	99.90	150.0	1.0	47438	55528
152B	4.83	4.86	4.79	4.72	100.00	99.96	147.0	2.0	55377	65318
153B	4.74	4.82	4.86	4.80	100.00	100.03	150.0	2.0	55402	65372
155A	4.79	4.73	4.83	4.86	100.02	99.99	150.0	2.0	55426	65376

just to the right of the saddle was constant to within 2 °C, in the relevant portion of the force curve, where the force is above 90% of the ultimate or elastic resistance. The temperature measurements at midspan show a decline in the post buckling (declining force) part. This is caused by the external insulation tearing as a consequence of the high curvature. As this only occurs in the post buckling regime and when the force is decreased below the elastic level, this is of no concern as it cannot influence any of the test result parameters.

The temperatures measured by sensors along the, bottom, compression flange are plotted in figure 7b as a function of longitudinal coordinate, where 0 is centre span. Confidence markers indicate the range of measured temperatures for the time where $F \geq F_{0.2,\theta,ss}$. As can be seen in figure 7b, the temperature is close to the desired temperature of 250 °C in the centre 1.0m of the specimen. Near the ends of the specimen, the temperature is lower as a consequence of heat losses due to insulation interruptions and the rotation-sensor mounts. As the experiments were three point bending tests with a maximum moment at centre span and zero moment near the supports, the exact temperatures near the supports are less important. It is noted that the temperature along the cross-section is constant for each length coordinate, except for the experiments with an intentional temperature gradient applied over the height of the specimen, for these the temperate gradient was

Figure 7: Example of temperature as a function of time and location. 4 sensor readings are shown in (a) per cross-section.

linear over the height.

3.3 Results

The primary results for the bending tests are the force–rotation graphs for the steady state experiments and the temperature–rotation graphs for the transient state experiments. In order compare the data, all results are normalized to their respective values upon reaching 0.2% offset proof stress at the relevant temperature. These are calculated according to:

$$M_{0.2} = f_{0.2} W_{el}, \quad (6)$$

$$F_{0.2} = \frac{4M_{0.2}}{L - D}, \quad (7)$$

$$\kappa_{0.2} = \frac{2 \epsilon_{0.2}}{H - t} = \frac{2 f_{0.2}}{E} \frac{1}{H - t}, \quad (8)$$

$$\phi_{0.2} = \frac{f_{0.2}}{E} \left(\frac{L + D}{H - t} \right), \quad (9)$$

$$U_{0.2} = \frac{1}{4} \kappa_{0.2} \left[\frac{1}{3} (L - D)^2 + D (L - D) \right], \quad (10)$$

where $M_{0.2}$, $F_{0.2}$, $\kappa_{0.2}$, and $U_{0.2}$ are the moment, force, curvature, and displacement, at centre span, upon reaching the 0.2% offset yield stress. $\phi_{0.2}$ is the rotation between the two ends of the beam. A suffix $_{\theta, SS}$ is applied to constants, when based on the elevated temperature, steady state 0.2% offset proof stress $f_{0.2, \theta, SS}$. A suffix $_{\theta, TT}$ is used for values based on the transient state $f_{0.2, \theta, TT}$.

In figure 8 the force–rotation curves for the steady state experiments are given. On the right-hand-side figures, tests results from tests with a temperature gradient along the height of the beam are given. They are distinguishable from the equal-temperature experiments given in the same graphs for comparison, by the temperature range in their label, where the lower temperature denotes the temperature in the compression flange and the higher value the temperature in the tension flange. From figure 8 it may be observed that at elevated temperatures the resistance against local buckling is indeed higher. Relevant parameters are obtained from the figure and placed in table 5.

The transient state experiment results are given in figure 9. From these graphs it can be seen that a higher initial usage factor $F/F_{0.2}$ leads to a lower run-away temperature, which is an expected result. A lower heating rate, $2.5 \text{ } ^\circ\text{C min}^{-1}$ instead of $10 \text{ } ^\circ\text{C min}^{-1}$ also leads to a lower temperature at run-away failure. Signifying that, all other things being equal, a 30 min fire has a higher failure temperature than a 120 min fire.

From the curves in figures 8 and 9 the ultimate strength, stable- and total rotation capacity, and the temperature at run-away failure may be determined. These are collected in tables 5 and 6 and are subsequently collected in graphs in section 3.3.1 and used to draw conclusions. Additional test data and details of the set-up may be found in [8].

Figure 8: Normalized moment-rotation graphs for steady state experiments. Normalization to lower flange, compression flange temperature for gradient tests.

3.3.1 Discussion

The ultimate force F_U , as obtained from the steady state experiments, and the constant force F in the transient state experiments, are shown together in figure 10. All values are normalized to their respective values at the 0.2% offset proof stress according to equations (7) and (4). The temperatures used in equation (4) are indicated in the figure and are equal to the nominal test temperature in the case of a steady state experiment, and the temperature at run-away failure [9] for a transient state case. Values are plotted as a function of the slenderness of the compression flange, where the definition of the Eurocode [1, table 6.2] is followed as well

Figure 9: Normalized moment-rotation graphs for transient state experiments

as the temperature dependent material factor e_θ [10].

$$e_\theta = \sqrt{\frac{250E_\theta}{E f_{0.2,\theta}}}. \quad (11)$$

The strength of the beam according to the Eurocode [1] is shown in the figure as well. Two material classes, A and B, are distinguished by the standard, where class A is reserved for heat treated alloys having a Ramberg-Osgood exponent $n \geq 10$ [11]. The horizontal portion of the lines given in figure 10 signify cross-sectional slenderness class 1 or 2 of Eurocode [1], the curved piece at the right hand side is class 4 and the high gradient, straight, connecting, line-piece is class 3. At ambient temperatures, the alloy used, AA6060-T66, is of material class A, but at elevated temperatures its exponent n decreases for transient state (fire) situations suggesting that it should be considered of class B in those instances. For steady state situations, the material behaviour is almost bilinear ($n = \infty$) and class A might be more appropriate.

In figure 10, the ambient temperature results demonstrate a reasonable agreement with the class A line of [1], which should itself be considered a lower bound rather than a best fit. The regular steady state experiments at 250°C conform to the standard as well, but the high moment gradient, 1 m long specimen's results, as indicated by an asterisk behind their name, are below it. This might be due to limitations of the

Table 5: Condensed results of steady state bending experiments.

Name	Temp. (°C)	Strain rate (s ⁻¹)	$F_{0.2,\theta}$ (kN)	$\phi_{0.2,\theta}$ (rad)	$U_{0.2,\theta}$ (mm)	$\frac{F_u}{F_{0.2,\theta}}$ (-)	$\frac{\phi_u}{\phi_{0.2,\theta}}$ (-)	$\frac{\phi_m}{\phi_{0.2,\theta}}$ (-)
<i>Steady state</i>								
135A	Amb.	$1.94 \cdot 10^{-5}$	19.92	$8.11 \cdot 10^{-2}$	26.75	0.955	1.088	-
131B	Amb.	$1.99 \cdot 10^{-5}$	20.22	$8.12 \cdot 10^{-2}$	26.77	0.946	1.122	-
134A	250	$1.58 \cdot 10^{-5}$	9.32	$4.87 \cdot 10^{-2}$	16.05	0.980	1.301	-
133A	300	$2.73 \cdot 10^{-5}$	4.035	$2.43 \cdot 10^{-2}$	8.02	1.024	1.761	2.122
144B	Amb.	$1.83 \cdot 10^{-5}$	22.22	$6.94 \cdot 10^{-2}$	22.91	1.077	1.285	1.59
141B	250	$1.55 \cdot 10^{-5}$	8.88	$3.56 \cdot 10^{-2}$	11.74	1.208	1.789	3.30
145A	250	$3.26 \cdot 10^{-6}$	19.30	$1.90 \cdot 10^{-2}$	3.05	1.027	1.937	2.350
141A	300	$1.28 \cdot 10^{-5}$	5.33	$2.45 \cdot 10^{-2}$	8.088	1.050	1.992	3.25
151B	Amb.	$1.94 \cdot 10^{-5}$	26.74	$7.18 \cdot 10^{-2}$	23.69	1.121	1.504	2.222
154B	250	$1.62 \cdot 10^{-5}$	10.44	$3.60 \cdot 10^{-2}$	11.88	1.192	1.892	4.548
154A	250	$3.55 \cdot 10^{-6}$	22.62	$1.92 \cdot 10^{-2}$	3.08	1.120	2.000	4.205
151A	300	$3.03 \cdot 10^{-5}$	6.26	$2.48 \cdot 10^{-2}$	8.17	1.128	2.651	5.486
<i>Steady state, with temperature gradient</i>								
134B	228.6-250	$1.76 \cdot 10^{-5}$	11.15	$5.58 \cdot 10^{-2}$	18.39	0.854	1.246	-
135B	262.3-300	$1.84 \cdot 10^{-5}$	8.24	$4.46 \cdot 10^{-2}$	14.71	0.736	1.294	-
145B	229.4-250	$1.83 \cdot 10^{-5}$	10.66	$4.08 \cdot 10^{-2}$	13.45	1.126	1.865	3.101
143A	272.8-300	$1.12 \cdot 10^{-5}$	7.13	$3.04 \cdot 10^{-2}$	10.04	0.939	1.773	-
153A	231.1-250	$1.80 \cdot 10^{-5}$	12.22	$4.07 \cdot 10^{-2}$	13.41	1.219	2.052	4.200
152A	256.3-300	$1.09 \cdot 10^{-5}$	9.28	$3.45 \cdot 10^{-2}$	11.38	0.845	1.692	-

Table 6: Condensed results of transient experiments with a constant load

Name	$\frac{F}{F_{0.2}}$ (-)	Heating rate ($\frac{^{\circ}\text{C}}{\text{min}}$)	Failure (°C)	$F_{0.2}$ (kN)	$\phi_{0.2}$ (rad)	$U_{0.2}$ (mm)	$\frac{F}{F_{0.2,\theta}}$ (-)
132A	0.416	10	269.5	19.85	$0.810 \cdot 10^{-2}$	26.73	1.079
131A	0.567	10	230.4	19.86	$0.811 \cdot 10^{-2}$	26.74	1.026
132B	0.420	2.5	254.3	19.84	$0.810 \cdot 10^{-2}$	26.73	0.934
142A	0.461	10	271.9	22.23	$0.695 \cdot 10^{-2}$	22.94	1.412
143B	0.638	10	240.8	22.14	$0.696 \cdot 10^{-2}$	22.96	1.473
142B	0.465	2.5	256.6	22.23	$0.695 \cdot 10^{-2}$	22.94	1.236
144A	0.416	10	276.3	48.51	$0.372 \cdot 10^{-2}$	5.96	1.341
152B	0.503	10	268.5	26.60	$0.717 \cdot 10^{-2}$	23.66	1.537
153B	0.664	10	234.2	26.65	$0.718 \cdot 10^{-2}$	23.68	1.486
155A	0.479	2.5	249.9	26.66	$0.718 \cdot 10^{-2}$	23.68	1.226

experiments (load initiation induced buckling) rather than a moment gradient related effect and this needs to be investigated further in finite element simulations. All steady state experiments at 300 °C fail to reach the relative strength predicted according to [1], where it is noted that the experimentally derived strength $f_{0.2,\theta,ss}$ used in the normalization term is higher than the minimum value given by [2, Table 1a], and a structure designed using this value would have been safe. But as values for $f_{0.2,\theta,ss}$ are based on tensile tests following the precise temperature and strain history of the flanges at centre span in the bending experiments, it is surprising to see that the predicted plastic strength of $\pm 1.2M_{0.2,\theta,ss}$ is not reached. It is unclear why this happens, it is possible that regions closer to the neutral axis, and those further away from centre span, which

Figure 10: Normalized, ultimate, force F_u as a function of slenderness

have a lower strain rate, have a lower yield stress and reduce the ultimate strength and moment. Significant strain-rate dependence was not observed in the tensile tests, however.

The transient state results for a two hour fire (linearly heating from 20 °C to 320 °C) as indicated by downward pointing triangles in figure 10, show a close agreement with the class B line as expected. The results for the 30 minute fire cases are much higher, and this demonstrates the potential for new, less conservative design rules.

The stable and total rotation capacity found in the experiments is plotted as a function of temperature in figure 11. The results of the steady state experiments with a temperature gradient along their height, which were excluded from figure 10, are present as well. The (lower) temperature of their compression zones was used to calculate the temperature dependent properties. Clear trends for the stable and total rotation capacity as a function of slenderness may be observed in figure 11 with relatively little scatter. It is also noted that ambient temperature results are consistent with elevated temperature results. In Eurocode 9 [1, Table 6.2] flanges with slenderness values below 11 and 13 for material classes A and B, respectively, are defined as being of class 1. These limits were determined based on the requirement to have a stable rotation capacity $R_0 \geq 3$ [4]. From figure 11a, it is evident that this requirement is not met in the entire range of slenderness values investigated, though at slenderness values below 11 it should.

4 CONCLUSIONS

Three-point bending experiments have been performed on square hollow aluminium bending members of alloy AA6060-T66 with varied slenderness ratio values at both ambient- and elevated temperatures. Steady state tests at temperatures up to and including 250 °C confirm the applicability of the cross-sectional classification system of Eurocode 9 [1, 2] and its slenderness limits, though the case of shorter beams ($L/H \approx 10$), and low slenderness values ($\frac{\beta}{e_\theta}$) require further investigation. Steady state tests at 300 °C reveal that for ductile (class 1) and compact (class 2) cross-sections the expected plastic strength is not reached, and taking the elastic strength seems more appropriate, though it cannot be guaranteed that this is safe in all circumstances as the causes for the lower-than-expected strength require further investigation.

For transient state tests, which are representative of a real fire where the load is constant and the temperature increases, the results confirm that [1, 2] give safe values for the strength of a cross-section at all temperatures tested and across the entire slenderness range. For a fire of 120 minutes, the experimental results are close the predictions of the Eurocode[2] . For a fire of 30 minutes (or less), the actual strength observed in class 1 and 2

Figure 11: Rotation capacity as a function of slenderness

cross-sections is much greater than expected and the code is overly conservative.

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