Fire Safety Journal 83 (2016) 15–24

Contents lists available at ScienceDirect

Fire Safety Journal

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

Probability analysis of the fire structural resistance of aluminium plate

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ARTICLE INFO

Article history:
Received 29 March 2015
Received in revised form
27 March 2016
Accepted 23 April 2016
Available online 4 May 2016

Keywords:
Fire
Structures
Aluminium
Failure
Model

ABSTRACT

An experimental and numerical study into the intrinsic scatter in the fire structural resistance of aluminium plate supporting tension loads is presented. Small-scale simulated fire structural tests performed on two aluminium alloys (AA5083 and AA6061) show for the first time a large amount of scatter in the tensile deformation rate and rupture stress. Multiple simulated fire tests conducted under identical heat flux exposure and tensile load conditions reveal scatter in the softening behaviour of the two aluminium alloys; there is large variability in the deformation rate, rupture stress and time-to-rupture, particularly at low stresses when creep dominates the softening process. Finite element analysis (incorporating elastic, plastic and creep softening effects) and elevated temperature material testing reveals that the scatter is caused mainly by variability in creep properties such as creep activation energy. A probability density function is used to quantify the scatter in the creep activation energy, and the finite element model using Monte Carlo simulations computes the scatter in the fire structural resistance of aluminium, which is not possible with existing deterministic models.

1. Introduction

Aluminium alloys are used extensively in engineering structures due to their moderate cost, light-weight, high specific modulus and tensile strength, and good corrosion resistance in most environments. However, a concern with aluminium structures is softening and failure in the event of fire. The softening temperature (defined by 50% reduction in tensile properties) of structural-grade aluminium alloys is ~250 °C, which is much lower than for steel (~650 °C). For this reason, it is often essential to insulate aluminium structures with fire protective material (e.g. ceramic fibre mat and intumescent coating) when used in high fire-risk applications.

The fire resistance of aluminium materials and structures has been evaluated using analytical models [1–5], numerical models [6–9] and experimental tests [1,2,4,6,9–12]. In this paper, fire resistance is defined as the capacity of a structural material to retain its load-bearing strength in fire. A large amount of experimental information is available on the softening and failure of simple aluminium structures, such as beams [1,2,4,6,9,11], wide plates [12], and hollow columns [10], exposed to actual or simulated fire. Virtually all the experimental studies have been performed on aluminium structures supporting a static compression load [1,4,10,12] or bending force [2]. The fire resistance of aluminium structures subjected to tensile loading has not been investigated until recently [9]. The fire resistance under tensile loading is complex because the aluminium undergoes high strain localised plastic flow via necking ultimately leading to failure, unlike the buckling failure that usually occurs for compression or bending.

Existing FE and analytical models do not consider the scatter in the fire resistance of aluminium structures that can occur for nominally identical loading and fire conditions. Similarly, most models for analysing the fire resistance of steel and other metal structures are deterministic [13–20], and lack the statistical framework to determine the scatter in the softening rate, failure stress and failure temperature. Deterministic models cannot compute the influence of material variability on the scatter in the fire resistance of metal structures. Several probabilistic models have recently been developed to analyse the scatter in the fire resistance of steel structures under compression loads using uncertainty parameter analysis [21], probability analysis of the thermal and mechanical properties of steel and insulation coatings (if present) [22] and Monte Carlo analysis of the plastic strain limit [23].

This paper investigates the variability in the fire resistance of aluminium plates used in engineering structures. A simple statistical (probability density function) model using Monte Carlo simulations is integrated into an FE model to analyse the scatter in the distortion and failure stress of aluminium alloys under combined tension loading and exposure to a radiant heat flux from

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http://dx.doi.org/10.1016/j.firesaf.2016.04.004
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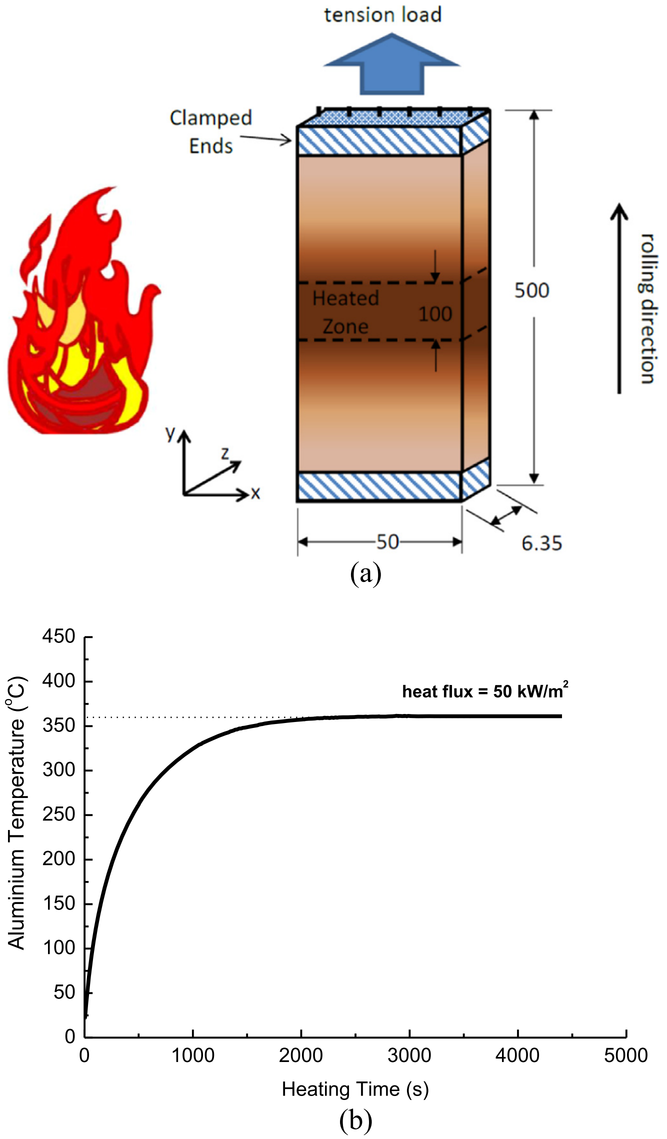

Fig. 1. (a) Schematic representation of the fire structural test. All dimensions in millimetres. (b) Measured temperature-time curve at the heated aluminium plate surface used in the fire structural test.

one-side. In addition, mechanical property tests at elevated temperature and small-scale simulated fire structural tests are performed on two structural grade aluminium alloys (AA5083 and AA6061) to determine the variability in the fire resistance, and compared to the statistical FE model simulations. The AA5083 and AA6061 were selected because of their wide-spread uses as structural aluminium alloys in ships, railway carriers, pressure vessels and many other applications.

2. Materials and experimental methodology

2.1. Aluminium alloy plates

Scatter in the fire resistance of aluminium was investigated using AA5083-H116 and AA6061-T6. These materials were supplied by Alcoa as rolled plate with a thickness of 6.35 mm.

2.2. Fire structural testing

Small-scale simulated fire structural tests were performed on rolled AA5083 and AA6061 plates under combined tensile loading and one-sided exposure to a constant heat flux, as illustrated in Fig. 1. Rectangular samples were cut from the same plate along the rolling direction. Taking samples from the same plate ensured that variability between plates was not the cause for any scatter in the fire structural resistance. The samples had an unrestrained length of 500 mm, width of 50 mm and thickness of 6.35 mm. The surfaces of the aluminium specimens were smooth and free from machining marks, scratches and other imperfections that can affect the test results.

The sample was loaded axially to a constant tensile stress using a 250 kN MTS machine while heated from one side. Samples were loaded in tension at constant stress between 20% and 90% of the yield stress at 20 °C, which was 265 MPa and 310 MPa for the AA5083 and AA6061, respectively. While under load, the plate was exposed to an incident heat flux of 50 kW/m^2 radiated by a conical-shaped electric heater located 25 mm away. A heat flux gauge was used to measure the incident flux at the front surface of the aluminium test specimen. Before testing, the aluminium samples were coated with a high temperature resistant black paint which maintained the thermal emissivity at about 0.95, and this limited the amount of heat radiated back to the heat source. Thermocouples were attached to the front and back surfaces of the sample during testing. The thermocouples were attached using high temperature steel wire to ensure they did not move or detach during testing. The sample was heated uniformly at the constant incident heat flux over a length of 100 mm, while outside of this region the material was thermally insulated. While only the heated region is exposed to the heat flux, heat is conducted from this region along the unheated regions. The increase in temperature at the aluminium surface within the heated region is shown in Fig. 1b. The temperature increased at a non-uniform rate over the initial ~2000 s and then reached the steady-state value of 360 °C. The heating profile was highly repeatable and consistent between tests.

The in-plane deformation of the plate was recorded continuously during fire structural testing from movement of the cross-head of the MTS testing machine. Constant load was applied to the aluminium sample for the duration of the test until failure. Multiple tests were performed on the AA5083 and AA6061 plates under identical stress and one-sided heating conditions to measure the scatter in the deformation rate and failure time.

2.3. Tensile testing

The tensile modulus and yield stress of the aluminium plates were determined at temperatures between 20 °C and 500 °C, above which the materials were nearly fully-softened. Tensile tests were performed using a dog-boned shaped specimen with a gauge length of 110 mm, width of 5.0 mm and thickness of 6.35 mm. Specimens of the AA5083 and AA6061 were machined with the gauge section aligned in the rolling direction. The samples were tested to failure at a loading rate of 100 N/s, which was slow enough to minimise strain rate effects. Strain was recorded over an initial length of 25 mm within the centre of the specimen gauge region. The samples were machined from the same plate to ensure any scatter was not caused by batch variability. Multiple tensile tests were performed at room and elevated temperatures to determine the magnitude of the scatter in the elastic modulus and yield stress of the aluminium alloys.

2.4. Creep testing

Creep tests on the AA5083 and AA6061 were performed with the same specimen type used for elevated temperature tensile testing. Creep tests were conducted at temperatures between