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Finite element modelling of tensile deformation and failure of aluminium plate exposed to fire

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ABSTRACT

This paper presents a coupled thermal–mechanical finite element model for analysing the tensile softening, deformation and failure of aluminium plate exposed to fire. The model consists of two parts: thermal analysis followed by mechanical analysis of aluminium under combined one-sided heating and axial tensile loading. The thermal analysis computes the temperature rise in the aluminium when exposed to one-sided transient radiant heating (e.g. fire simulation) and the mechanical analysis calculates the strength loss, plastic deformation (including necking) and failure of the aluminium under tensile loading. The mechanical model analyses the combined effects of elastic softening, time-independent plastic softening, time-dependent (creep) plastic softening, and thermal expansion on the tensile failure of aluminium plate. The model is validated by comparing theoretical predictions of the tensile deformation and stress rupture times against values measured from fire structural tests performed on aluminium plates. The model predicts the temperature, plastic deformation and failure with good accuracy.

1. Introduction

Aluminium alloy is used extensively in aircraft, ship and civil structures where fire is an ever present risk. While aluminium has many attributes which make it a widely used structural material (e.g. moderate cost, good formability, high specific stiffness and strength), one of the drawbacks is that it softens and melts at temperatures well below those produced by hydrocarbon fuel fires (which have flame core temperatures exceeding 1000 °C). Numerous numerical and experimental studies have assessed the structural response and failure of aluminium structural components in fire [1–15]. However, these studies have focussed almost exclusively on the fire-induced softening and collapse of aluminium structures supporting compression loads. For example, Suzuki et al. [2] measured the failure temperatures of aluminium columns and beams subjected to combined one-sided heating by fire and static compression loading. Maljaars and colleagues [5,7–11] and Feih et al. [14] developed creep-based models for predicting the temperature-time dependent deformation and failure of aluminium structures under compression while heated from one-side by fire. The models were validated using failure time and/or failure temperature data from fire structural tests performed on compression-loaded aluminium alloy plate. Kandare et al. [12] formulated a compression failure model for aluminium exposed to simulated fire attack using a Larson–Miller approach to temperature-time softening, and this model predicted the failure with good accuracy.

Validated models are available for analysing the deformation and collapse of fire exposed aluminium structures subjected to compression [1–5,7–15] or bending forces [6], however similar progress in the analysis of the mechanical response of aluminium structures subjected to tensile loading has not been performed. Many types of aluminium structures at risk of fire attack carry tension loads, and therefore it is important that there is a validated model which considers the deformation and stress rupture caused by tertiary creep in order to assess the fire structural survivability. However, no research work has been reported on the deformation and failure of aluminium structures under combined fire attack and tensile loading.

This paper presents a thermal–mechanical modelling approach solved using finite element analysis to calculate the deformation and failure of aluminium plate subjected to the combined effects of one-sided heating by fire and tensile loading. The paper outlines the model which involves calculating the temperature rise in an aluminium plate with increasing exposure time to one-sided unsteady-state heating by fire. Using the calculated temperatures, a mechanics model is used to determine the elastic and plastic

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deformations, necking and failure of the plate. The mechanics model considers tensile deformations caused by reductions to the elastic modulus and tensile strength as well as by creep. The model also considers thermal tensile strain generated in the plate during fire exposure. Predictions of the deformation, necking and failure of aluminium plate exposed to different tensile stress and stimulated fire conditions are compared with experimental data from artificial fire structural tests in order to validate the modelling approach and assess its numerical accuracy.

2. Thermal–mechanical finite element modelling approach

The finite element (FE) model used to analyse the deformation and failure of aluminium plate consists of a two-stage sequentially coupled analysis: thermal modelling followed by mechanical modelling. A similar two-stage approach was used by Feih et al. [14] in the FE analysis of the compression failure of aluminium exposed to fire, although Feih and colleagues did not consider tertiary creep and stress rupture which must be analysed for tensile loaded structures. A schematic illustration of the modelling condition is presented in Fig. 1, in which aluminium plate is exposed to one-sided heating by fire at a constant radiant heat flux and simultaneously subjected to a constant tensile load in the axial direction. This is a simplified representation of a tensile-loaded plate used in an engineering structure (e.g. building, ship, aircraft) exposed directly to fire.

The thermal component of the FE model is used to calculate the temperature rise in the aluminium with increasing exposure time to a constant radiant heat flux. Based on the thermal analysis, the mechanical component of the FE model calculates the elastic softening (caused by the reduction in Young's modulus), time-independent plastic flow (caused by the reduction in yield stress) and time-dependent creep flow (incorporating the primary, secondary and tertiary stages of creep) which causes the aluminium to deform, neck, and then fail within the necked region under the applied tensile stress, as illustrated sequentially in Fig. 1.

The analysis was performed using the FE code ABAQUS (Version 6.10), and the plate was modelled with eight-node continuum shell elements with temperature degrees of freedom (Type SC8RT). A mesh sensitivity analysis revealed that having one element in the thickness of the plate with five integration points together with the global element area of $5 \times 5\ \text{mm}^2$ provided an optimum balance between convergence in the numerical calculations and minimizing the computation time. Fig. 2 shows the necking initiation and final failure time calculated using the FE model for mesh sizes ranging from $3 \times 3\ \text{mm}^2$ to $10 \times 10\ \text{mm}^2$, and the results become grid independent for mesh sizes equal to or smaller than $5 \times 5\ \text{mm}^2$.

2.1. Thermal modelling

Thermal analysis involves calculating the nodal temperatures of the aluminium plate when exposed to one-sided unsteady-state heating for increasing periods of time. The analysis is described in detail by Feih et al. [14], and is summarised here. To represent the experimental results more accurately, the thermal boundary conditions in the FE model are defined directly by the temperature-time profile of the fire at discrete points along the specimen length. Such a profile can be a known temperature-time condition resulted from a fire modelling simulation or measured in a fire experiment. The outcome of thermal analysis, in either case, is a temperature-time profile at any location in an aluminium structure exposed to the heating conditions of fire.

Heat transfer from the heated surface into the aluminium plate is analysed using 3D heat conduction theory:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[k_x(T)\frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial y}\left[k_y(T)\frac{\partial T}{\partial y}\right] + \frac{\partial}{\partial z}\left[k_z(T)\frac{\partial T}{\partial z}\right] \tag{1}$$

where T is the temperature, t is the heating time, and ρ is the density of aluminium. The subscripts x and y refer to the transverse and longitudinal directions of the plate and z is the through-thickness direction where $z = 0$ is the heated surface (refer to Fig. 1). The thermal conductivity $k(T)$ and specific heat $C_p(T)$ of the aluminium are analysed as functions of temperature. For the aluminium alloy used

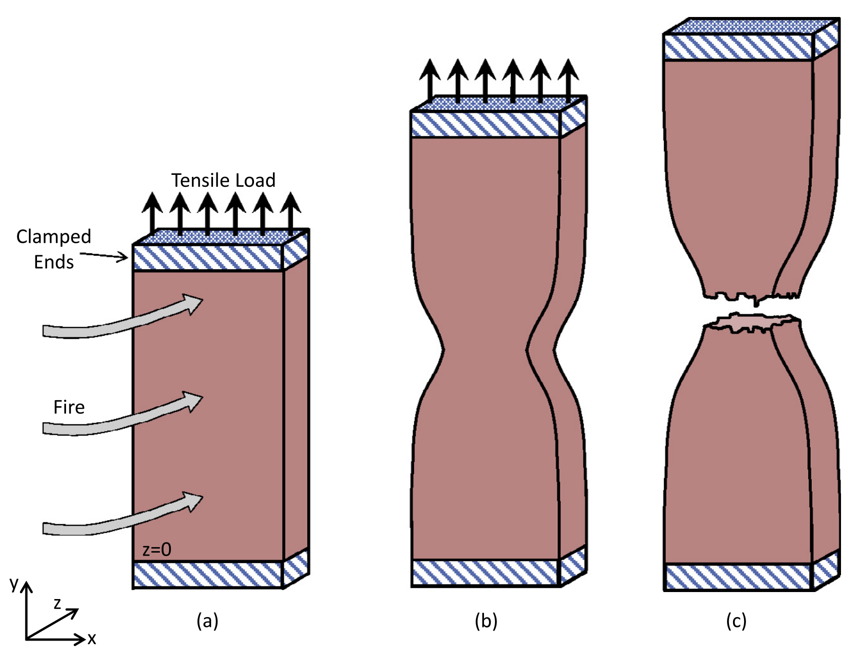

Fig. 1. Representation of the thermal–mechanical modelling condition of an aluminium plate being heated from one-side by fire while loaded in tension. The figure shows the plate (a) before the plastic necking phase, (b) during necking and (c) after final failure.