Structures 6 (2016) 134–145

Contents lists available at ScienceDirect

Structures

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

Finite element modeling of structural steel component failure at elevated temperatures

Mina Seif *, Joseph Main, Jonathan Weigand, Therese P. McAllister, William Luecke

National Institute of Standards and Technology (NIST), 100 Bureau Drive, Stop 8611, Gaithersburg, MD 20899, USA

ARTICLE INFO

Article history:
Received 22 October 2015
Received in revised form 9 March 2016
Accepted 11 March 2016
Available online 12 March 2016

Keywords:
Stress–strain relationship
Fire loading
Uniform strain
Elevated temperatures
Finite element
Fracture

ABSTRACT

A key issue in evaluating the response of structural systems to fire effects is the representation of material behavior at elevated temperatures. In addition to stress–strain behavior, modeling of fracture is required to capture failure modes such as tear out in connection plates and bolt shear. Fracture can be simulated in explicit finite element analysis using element erosion, in which elements are removed from the analysis when specified failure criteria are satisfied. However, the basis for determining and implementing material failure criteria at elevated temperatures is not well-established in the literature. A finite element material modeling methodology is presented for structural steels and structural bolts at elevated temperatures that incorporates erosion-based modeling of fracture. Temperature-dependent stress–strain relationships for structural steel and structural bolts were combined with a plastic strain-based failure criterion for element erosion to enable modeling of fracture in analysis of structural connections and assemblies. The failure criterion was calibrated against high-temperature experimental data on elongation of tensile coupons at fracture, and its dependence on temperature and mesh size was investigated.

1. Introduction

Fire effects on steel structures can produce failures of connections, including fracture of connection plates, shear rupture of bolts, and bolt tear-out failure of beam webs or connection plates. Fig. 1 illustrates such failure modes for a typical shear tab connection at elevated temperatures, based on explicit finite element analyses described by Seif et al. [1]. Whether such failures occur depends not only on the loads that can be sustained by the various components of a connection, but also on the deformations that can be accommodated prior to fracture, since fire-induced forces result from the restraint of thermal expansion or contraction. The ductility of steel components thus plays an important role in the performance of connections at elevated temperatures. In addition, ductility can potentially allow redistribution of loads after failure of one or more connection components.

While implicit finite element methods are prone to convergence problems when local failures occur, explicit finite element methods are well suited for simulating successive failures and the subsequent redistribution of loads. Fracture for both tensile and shear failure modes can be simulated in explicit analyses (in an approximate sense) using element erosion, in which elements are automatically removed from the analysis when specified failure criteria are met. The erosion process may continue until a component has lost elements across its entire section, representing complete fracture, as illustrated in Fig. 1(c). The basis for determining and implementing material failure criteria at elevated temperatures, however, is not well-established in the literature. The objective of this paper is to demonstrate a practical material modeling approach for structural steel and structural bolts at elevated temperatures that incorporates erosion-based modeling of fracture and that can be implemented in FE analysis using currently available tensile coupon data at elevated temperatures. Such an approach is needed in the context of performance-based design, to enable evaluation of the performance structural components, assemblies, and systems under fire effects.

Failure modes such as tear-out and bolt shear rupture are ductile fractures with significant plastic deformation before fracture, particularly at elevated temperatures. Key factors influencing the initiation of ductile fracture in steel are the equivalent plastic strain and the stress triaxiality, defined as the ratio of the mean or hydrostatic stress to the effective or von Mises stress. Micromechanics-based models for predicting ductile fracture generally require calibration against experimental fracture data at different levels of triaxiality (e.g., Kanvinde and Deierlein [2]). However, experimental data on fracture of steel at elevated temperatures are currently insufficient to enable calibration of such micromechanics-based models. Accordingly, researchers tend to model strain hardening and softening, but do not address fracture at elevated temperatures (e.g. Garlock and Selamet [3], Sarraj et al. [4], and Pakala et al. [5]). The material model for structural steel at elevated temperatures in the Eurocode [6] also does not address material

* Corresponding author.
E-mail addresses: mina.seif@nist.gov (M. Seif), joseph.main@nist.gov (J. Main), jonathan.weigand@nist.gov (J. Weigand), therese.mcallister@nist.gov (T.P. McAllister), william.luecke@nist.gov (W. Luecke).

http://dx.doi.org/10.1016/j.istruc.2016.03.002
2352-0124/

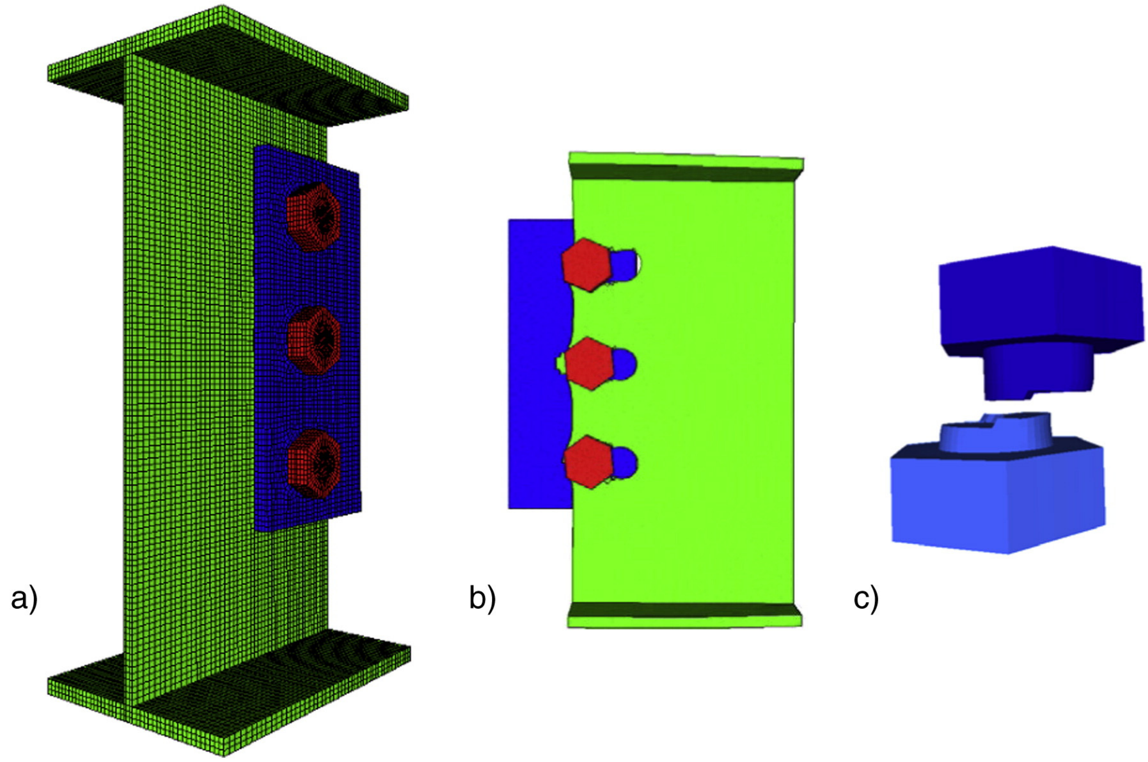

Fig. 1. (a) Detailed model of a shear tab connection, (b) tear-out failure in beam web, and (c) shear fracture of a bolt.

fracture. Instead, the yield strength is reduced to zero with a linear material softening between 15% and 20% strain.

The proposed material modeling approach for structural steel uses an empirical power–law form of stress–strain relationship recently developed by Luecke (Seif et al. [7]), which was fit to a large set of experimental data at elevated temperatures. A tri-linear stress–strain relationship is proposed to model the temperature-dependent behavior of structural bolts, for which experimental data at elevated temperatures are more limited. Rather than using a micromechanics-based model, a relatively simple plastic strain-based failure criterion is proposed for modeling fracture of both structural steel and structural bolts in structural system analyses. Similar approaches have been successfully implemented in detailed finite element analyses of moment connections (Sadek et al. [8]) and simple shear connections (Main and Sadek [9]) under column removal scenarios at ambient temperature. In this study, the erosion strain (the local plastic strain at which element erosion is activated) was calibrated against available high-temperature experimental data on elongation of tensile coupons at fracture, and it was found that a temperature-dependent value of the erosion strain was required to capture the experimental data. The dependence of the failure criterion on temperature and mesh size was also investigated, and for structural bolts, analyses of double-shear tests were performed to assess the performance of the material modeling approach under shear loading.

2. Temperature-dependent material model for structural steel

The material model developed by Luecke (Seif et al. [7]) is a temperature-dependent empirical model for any structural steel with a nominal yield strength less than 450 MPa (65 ksi). The model is based on experiments conducted at the National Institute of Standards and Technology (NIST) and experimental data gathered from multiple sources reported in the literature. The model accounts for temperature-dependent changes in yield strength and post-yield strain hardening but does not include creep effects. The model, presented in Section 2.1, is formulated in terms of true stress as a function of true strain, as is typical in material models for continuum finite element analysis. Relationships between true stress–strain and engineering stress–strain for uniaxial tension are presented subsequently in Section 2.2, which discusses the onset of necking at the ultimate tensile strength. Section 2.3 discusses the modeling of post-ultimate necking behavior and erosion-based modeling of fracture. Finally, Section 2.4 addresses some of the assumptions and limitations associated with this modeling approach.

2.1. True stress–strain relationship

The temperature-dependent relationship between true stress and true strain incorporates temperature-dependent expressions for the elastic modulus and the yield strength. The elastic modulus E is expressed as follows:

$$E(T) = E_0\left[\exp\left(-\frac{1}{2}\left(\frac{\Delta T}{e_3}\right)^{e_1} - \frac{1}{2}\left(\frac{\Delta T}{e_4}\right)^{e_2}\right)\right] \tag{1}$$

where $E_0 = 29\,900$ ksi (206 GPa) is the value at ambient temperature, ΔT (in °C) is the increase in temperature above the ambient temperature, and e_1 through e_4 are coefficients depending on the type of steel. For rolled structural steel, $e_1 = 3.768$, $e_2 = 1.000$, $e_3 = 639$ °C, and $e_4 = 1650$ °C. Fig. 2 shows the degradation of the normalized elastic modulus with increasing temperature using Eq. (1) with the listed coefficients. The temperature-dependence of the yield strength F_y is expressed as:

$$F_y(T) = F_{y0}\left[r_5 + (1-r_5)\cdot\exp\left(-\frac{1}{2}\left(\frac{\Delta T}{r_3}\right)^{r_1} - \frac{1}{2}\left(\frac{\Delta T}{r_4}\right)^{r_2}\right)\right] \tag{2}$$

where F_{y0} is the yield strength at ambient temperature and r_1 through r_5 are coefficients depending on the type of steel. For rolled structural steel, $r_1 = 7.514$, $r_2 = 1.000$, $r_3 = 588$ °C, $r_4 = 676$ °C, and $r_5 = 0.090$. The degradation of the normalized yield strength with increasing temperature is also shown in Fig. 2 using Eq. (2) with the listed coefficients.