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Modeling creep of steel under transient temperature conditions of fire

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ABSTRACT

This paper presents a methodology for explicit modeling of the time-dependent behavior or creep of structural steel in the Abaqus finite element (FE) models under transient temperature conditions representative of building fires. In this methodology, available creep models based on conventional creep tests under constant or steady-state temperature conditions were used to predict the time-dependent or creep behavior of steel under variable or transient-state temperature conditions. Specifically, user-defined CREEP subroutines were created in Abaqus to define time-dependent or viscoplastic deformation of structural steel under changing temperatures. To demonstrate the robustness of the proposed methodology, the time-dependent behavior of structural steel at elevated temperatures was modeled under three distinct conditions. These were: steady-state temperature conditions, stepwise steady-state temperature conditions, and transient-state temperature conditions. This paper further presents and discusses the application of the methodology in studying the creep behavior of a shear tab connection assembly under the transient temperature conditions of a fire. Through this application, the importance of explicit consideration of creep in predicting the response of connection assemblies at different stages in the evolution of a structural-fire is also emphasized.

1. Introduction and background

1.1. Characterization of thermal creep of structural steel

The stress-strain behavior of structural steel at elevated temperatures is shown to be time-dependent for stresses and temperatures representative of building fires [1,2]. The time-dependent or creep behavior of steel is defined as the time-dependent inelastic strain of structural steel resulting from the application of both stress and temperature. Thermal creep of structural steel is commonly established by conducting steady-state temperature creep material tests in tension. In these tests, the phenomenon of creep is observed through the increase in mechanical strain under the conditions of sustained mechanical stresses and constant temperatures. The resulting inelastic strain-time curves usually exhibit three distinct stages: the primary stage characterized by decreasing creep strain rates, the secondary stage characterized by constant or steady creep strain rate, and the tertiary stage characterized by increasing creep strain rates [2]. Depending on stress and temperature levels, the increasing creep strains in the tertiary stage may result in fracture of the steel coupon specimen [2].

Using the data from creep tests, material creep models have been developed to predict the time-dependent strain behavior of different grades of structural steels for steady-state temperature conditions [2–5]. For example, Harmathy [4,6] and Fields and Fields [5] developed creep models for ASTM A36 steel, Morovat [2] proposed a creep model for ASTM A992 steel, and Wang et al. [3] suggested a creep model for Q460 high-strength steel.

1.2. Creep behavior of steel members and assemblies in fire

The influence of thermal creep of structural steel on the fire response of steel members and assemblies has been recognized in previous studies [2,7–11]. It was shown in these studies that the behavior of structural steel elements can be highly time-dependent depending on the load conditions, duration of exposure to fire, and temperature magnitudes. For instance, in a series of creep buckling tests on ASTM A992 steel columns, Morovat [2] showed how the buckling strength of steel columns became time-dependent as a result of thermal creep of steel. Similar time-dependent buckling phenomenon was observed by Yang and Yu [8] during experiments on columns made of SN490FR fire-resistant steel. In addition, better agreements between experimental and computational predictions were observed when the thermal creep was explicitly modeled in FE simulations [2,7–11]. As an example, studies by Kodur and Dwaikat [9] showed that the explicit

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consideration of thermal creep using ANSYS creep models resulted in more accurate predictions of restraint beams response under fire, and studies were also done to investigate the creep effect under different fire scenarios. Torić et al. [1] showed an example of unrestrained steel beam subjected to fire temperatures up to (600 °C) for about 110 min. The results showed that including creep effect, using implicit creep model, improve the predictions of the beam response compared to experimental results. The National Institute of Standard and Technology (NIST) in its study of WTC building collapse in September 11, 2001 recognized the importance of thermal creep of steel [12,13]. Therefore, creep was considered in all simulations of the WTC building collapse to model both columns and floor trusses. Further, El Ghor and Hantouche [14], and Morovat et al. [11] carried out FE simulations to investigate the effect of creep on isolated flush endplate connections at elevated temperatures, and proposed a methodology to quantify the creep behavior of these connections in the form of isochronous curves.

Recent studies [9,15] showed that explicit consideration of creep is more appropriate and result in more accurate representation of the real case. Kodur et al. [16] made a comparison between different models available in literature including Eurocode 3 [17] temperature-stress-strain relationships. The results show that when effect of creep is explicitly considered, the predicted deflections compared well with the experimental results. Also, when using the Eurocode temperature-stress-strain relationships, which takes into account the effect of creep implicitly, the analysis showed a conservative predictions of beam deflections when compared with the experimental results.

As indicated in previous studies, implementing creep material models in computational tools allows the explicit evaluation of the time- and temperature-dependent response of steel members and assemblies at elevated temperatures. This quantification of structural behavior in terms of both temperature and time is of utmost importance in developing performance-based design frameworks for the fire safety of steel structures. However, since the time-dependent behavior of steel is obtained under constant temperature in a creep test, arguments exist against the applicability of creep test results for structural-fire applications where temperatures are changing throughout the course of a building fire. Therefore, the primary goal of this paper is to show how material creep models developed using creep tests can be utilized in analysis of steel structures exposed to the transient-state temperature conditions of a fire.

1.3. *Contribution of this study*

This paper describes a methodology to consider the creep effects on the behavior of steel structures exposed to changing temperatures of fire. To consider the thermal creep of structural steel under transient-state temperature conditions, user-defined subroutines were developed and implemented in computational analyses using the general-purpose FE software Abaqus. The constitutive model proposed by Fields and Fields [5] for the creep of ASTM A36 steel under steady-state temperature conditions were chosen in the development of the methodology. To show the capability of the proposed methodology in predicting time-dependent behavior of steel structures under varied temperatures, three distinctive temperature environments were considered: steady-state, stepwise steady-state, and transient-state temperature environments. The application of the developed methodology in considering thermal creep of steel under the transient-state temperature conditions of fire is further shown through the study of creep response of a steel shear tab connection assembly. Finally, the importance of explicit consideration of creep in predicting the response of connection assemblies at different stages in the evolution of a structural-fire is further indicated and discussed.

2. Development of the methodology

This section describes the proposed methodology for explicit modeling of the thermal creep of steel under transient-state temperature environment of structural fires. Specifically, a procedure is developed and implemented as user-defined subroutines in Abaqus to modify and extend a steady-state temperature creep model for structural-fire applications.

2.1. *Formulation of thermal creep of steel*

In order to develop a procedure to explicitly account for the creep of structural steel under changing temperature environment of a building fire, a computational material creep model was formulated. The constitutive material law in the form of power-law creep by Fields and Fields [5] was utilized in the formulation of the computational creep model and its implementation as a user-defined subroutine CREEP in Abaqus. The creep material model by Fields and Fields [5] was originally developed for the ASTM A36 steel in the temperature range of 350 °C–600 °C, and for creep strains up to 6%. To develop the procedure, it was further assumed that the total strain under constant temperature could be divided into three independent components:

$$\varepsilon_T = \varepsilon_e + \varepsilon_p + \varepsilon_c \tag{1}$$

In Eq. (1) ε_T is the total strain, ε_e is the time-independent elastic strain, ε_p is time-independent plastic strain, and ε_c is the time-dependent plastic or creep strain. Therefore, the two components ε_e and ε_p are temperature- and stress-dependent, whereas the creep strain component is time-, temperature-, and stress-dependent.

The empirical equation proposed by Fields and Fields [5] in the form of power-law creep (Norton-Bailey power-law creep) is shown in Eq. (2).

$$\varepsilon_c = \ a t^b \sigma^c \tag{2}$$

In Eq. (2), t is time, σ is stress, and coefficients a, b, and c are temperature-dependent material constants. Formulas for the calculation of these material constants are presented in Eqs. (3)–(5).

$$b(T) = \ b_0 + b_1 T \tag{3}$$

where $b_0 = -1.1$ and $b_1 = 0.0035$

$$c(T) = \ c_0 + c_1 T \tag{4}$$

where $c_0 = 2.1$ and $\mathrm{c}_1 = 0.0064$

$$a(T) = \ (0.145^c)10^{-(a_0 + a_1 T)} \tag{5}$$

where for $T < 500°C$, $a_0 = 8.1$ and $\mathrm{a}_1 = 0.00573$, and for $T > 500°C$, $a_0 = 15.25$ and $\mathrm{a}_1 = -0.00851$.

In Eqs. (3)–(5), T is in °C, t is in minute, σ is in MPa, and ε_c is in mm/mm (unitless).

To formulate the computational material creep model and calculate creep strains, an equation for the creep strain rate is necessary. Creep strain rate can be represented in two different formats: strain- and time-hardening formats. In the strain hardening formulation, the creep strain rate is defined as a function of the creep strain (as shown in Eq. (6)), whereas in the time hardening formulation, the creep strain rate is defined as a function of time (as shown in Eq. (7)). Fig. 1 further depicts these two representations of the creep strain rate. It has been shown in previous studies [2,6] and confirmed in this study that the strain hardening formulation yields better and more accurate results when computing the time-dependent strains for variable stress history. Therefore, in this study, the Fields and Fields [5] equation is described in a strain-hardening formulation.

$$\dot{\varepsilon}_c = F(\varepsilon_c;\, \sigma;\, T) = a^{\frac{1}{b}} b \varepsilon_c^{\frac{b-1}{b}} \sigma^{\frac{c}{b}} \tag{6}$$

$$\dot{\varepsilon}_c = F(t;\, \sigma;\, T) = abt^{b-1}\sigma^c \tag{7}$$

In Eqs. (6) and (7), $\dot{\varepsilon}_c$ is in per minute. Eq. (6) can be further simplified, through the change of the constants (a, b, and c), as shown in Eq. (8):