



Thermal creep mechanical-based modeling for flush endplate connections in fire



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ABSTRACT

A mechanical-based model is developed to predict the time-dependent effect (thermal creep) and the fast loading-rate behavior of flush endplate connections at elevated temperatures during a fire. The fast loading-rate behavior model consists of multi-linear springs that predict each component stiffness, strength, and rotation. The multi-linear springs temperature expressions are based on the ambient temperature formulations proposed in *Eurocode3 Part 1.8* where material properties are considered temperature-dependent. To include the effect of thermal creep in the proposed model, a modified *Burgers* creep model is developed to predict the time-dependent connection rotation and temperature of flush endplate connections. The modified *Burgers* creep model consists of linear springs and viscous dashpots that predict the time-dependent connection rotation. The proposed model is validated against experimental results available in the literature and finite element (FE) simulations developed as a part of this study. Through explicit consideration of thermal creep effect, the proposed model helps providing important insights into fire-induced thermal stresses and deformations and their implications on designing of flush endplate connections in fire.

1. Introduction

Flush endplate connections experience loss of strength and stiffness when subjected to fire temperatures. During a fire, the beam would undergo sagging and large connection rotation can be developed leading to connection failure. This failure results in structure instability and causes the whole structure to collapse. Connection failure due to fire does not only depend on loading capacity and temperature but also on the time duration of the applied load. Furthermore, one of the critical factors affecting the connection behavior at elevated temperature is the influence of the thermal creep material effect.

Many studies were conducted to investigate experimentally and numerically (using FE) the combined effects of shear and tension forces on the strength and rotational capacity of flush endplate connections subjected to fire [1,2,3,4]. In these studies, both isolated connections under steady-state temperature conditions and connection sub-assemblies under transient temperature conditions were studied. Results showed that flush endplate connections can undergo significant loss of strength and stiffness and large axial forces can be developed in these connections as a result of restraints to thermal displacements [2]. Further, the results of previous studies showed that strength, rotational capacity, and failure modes of the flush endplate connections were significantly affected by temperature-dependent behavior of their

components (endplate and bolts).

Previous mechanical models were developed for flush endplate connections to predict their fast loading-rate behavior (excluding creep effect) at elevated temperatures specifically the moment-connection rotation characteristics [5,6,7,8]. Also, the effect of the applied and induced axial forces were studied in the literature to examine their influence on the response of flush and shear endplate connections, respectively [8,9]. The stress-strain behavior of structural steel at elevated temperatures is highly time-dependent for some ranges of stresses and temperatures expected during a building fire [10,11]. That is, due to the time-dependent behavior of steel at high temperatures, the strength, rotational capacity, and failure modes of the isolated bare steel connections does not only depend on the applied loads and temperatures but also on the time duration of exposure to fire temperatures. Limited research work has been conducted so far for modeling the effect of creep on steel columns and restrained beams [10,12]. Morovat et al. [10] showed that under fire conditions, steel columns can exhibit creep buckling. A phenomenon in which the critical buckling load for a column depends not only on slenderness and temperature, but also on the duration of the applied load. Further, Kodur and Dwaikat [12] studied the effect of high-temperature creep on the flexural behavior of restrained steel beams subjected to fire. The results indicated that the effect of creep can change the beam behavior

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from flexural to catenary action. This phenomenon is due the fact that creep tends to relax the stressed member by increasing vertical deflection. And the increase in vertical beam deflection leads to increase the axial tensile stress, known as catenary action.

Based on aforementioned literature, very limited research on steel connections in general and on flush endplate connections in particular focused on the importance of thermal creep of structural steel on the behavior of connections exposed to fire temperatures [12] specifically developing a methodology to account for time-effects on the fire response of steel connections [13]. Also, a very recent research developed a rheological (mechanical) model to predict the behavior of A36 steel at high temperature under stress and strain rate controlled test [14]. The model consisted of two *Kelvin-Voight* models and was able to model creep strain development under steady-state and transient heating conditions. All these studies did not include a mechanical model to predict the time-dependent response of flush endplate connections subjected to elevated temperatures due to fire.

In an effort to address this shortcoming, the new contribution is to develop a mechanical model capable of predicting the thermal creep behavior of flush endplate connections in fire. To achieve this, FE simulations of flush endplate connections are conducted in ABAQUS under steady-state temperature analysis to reproduce the experimental work available in the literature [15]. Then, a mechanical model that is based on Eurocode3 part 1.8 [16] is used to predict the fast loading-rate force-connection rotation characteristics of flush endplate connection in fire. Further, FE simulations are conducted in ABAQUS on the same connection to study the effect of creep explicitly on the behavior of flush endplate connection under steady-state creep analysis. Different load to peak load ratios are applied on the connection at different elevated temperatures to study the time-dependent behavior of flush endplate connection when both temperature and load are kept constant. Note that, the effect of creep is considered explicitly in this analysis to investigate the time effect on the connection behavior under different applied constant loads and temperatures. This is performed to simplify the analysis and make it possible to study the effect of each parameter separately. Then, a modified *Burgers* model is developed and incorporated in the proposed mechanical model to predict the time-dependent connection rotation under both steady-state and transient creep analyses. The proposed mechanical model is validated against the experimental results available in the literature [15] and FE simulations including thermal creep effect.

2. FE modeling

2.1. Flush endplate connection

The connection prototype selected for analysis follows the flush endplate connection details and design incorporated in the experiment conducted at University of Sheffield [15]. More specifically, as shown in Fig. 1(a), the flush endplate connection specimen used in the analysis consisted of a PL13 × 8 × 0.4 in. (PL323.4 × 200 × 10 mm) endplate, a W12 × 26 (UB305 × 165 × 40) beam, and a W10 × 60 (UC 254 × 254 × 89) column. Further, six grade 8.8 M20 bolts are used to connect the endplate to the column. Details of the connection configuration can be found in [1,2,15].

2.2. Boundary conditions

Boundary conditions are applied on the connection elements throughout the analysis. During the pretension step, all bolts are restrained against any translation to ensure contact between the bolt head and nut with the base material. During the loading step, the previous boundary condition is deactivated. The column is restrained against any translation and rotation throughout the analysis as shown in Fig. 2.

2.3. Material properties and modeling considerations

An idealized bilinear stress-strain relationship with isotropic hardening is used to model the mechanical behavior of both structural bolts and structural steel. The ambient temperature properties incorporated in connection simulations are based on the reported values in the experimental data at University of Sheffield [1,2,15]. Retention factors proposed by [17,18] are used to model the creep free stress-strain characteristics of structural steel and structural bolts at elevated temperatures, respectively. To account for the time-dependent behavior of structural steel at elevated temperatures, a power law creep model proposed by Fields and Fields [19] is included in mechanical properties of structural steel to model both the beam and the endplate. Fields and Fields [19] represents creep strain, ϵ_c , in the form of a Norton-Bailey equation [20] as follows:

$$\epsilon_c = At^B\sigma^C \quad (1)$$

In this equation, t is time and σ is stress. The parameters A , B and C are temperature-dependent material properties. Fields and Fields [19] derived equations for these temperature-dependent material properties for ASTM A36 steel. The model developed by Fields and Fields [19] is capable of predicting creep in the temperature range of 350 °C to 600 °C and for creep strains up to 6%. The creep model by Fields and Fields [19] is used in this study on the time-dependent response of steel flush endplate connections to fire. Note that thermal creep of structural bolts is ignored in connection simulations and the algorithm for creep strain rate is incorporated in ABAQUS via a user define subroutine.

2.4. Model discretization

All the connection components are meshed with eight-node brick elements with reduced integration (C3D8-R) as shown in Fig. 2. To improve the accuracy of predictions, a finer mesh is used around the connection region, where failure is likely to occur. Moreover, to account for stress concentration around the bolt-holes, a mapped meshing technique is used to discretize bolts and their surrounding areas. The surface interactions between the bolt shank, flush endplate, and the column flange are modeled using finite sliding, with a friction coefficient changes with temperature.

2.5. Time-dependent behavior (thermal creep)

Two series of FE analyses are performed in ABAQUS to investigate the effect of thermal creep on the behavior of flush endplate connection in fire. In the first series, steady-state temperature analysis are conducted to characterize the strength of flush endplate connections under combined shear and tension forces at elevated temperatures. At each specific temperature (450 °C, 550 °C, and 650 °C), an inclined concentrated force (with the initial angle of 35°) is monotonically applied to the beam end with an angle varying throughout the loading step in accordance with the experimental protocol at University of Sheffield [15]. Note that these tests were performed under fast loading rate where the effect of time is not significant. Fig. 3 shows sample results of such analysis where experimental and FE predictions of the strength of flush endplate connections are compared at various temperatures. As seen in Fig. 3 and as shown in previous studies [1,2], FE simulations are capable of predicting the experimental observations with reasonable accuracy.

In the second series, steady-state temperature creep tests are performed to investigate the thermal creep response of flush endplate connections under combined shear and tension forces at elevated temperatures. More specifically, at each specific temperature (450 °C, 550 °C, and 650 °C), an inclined force, equal to a fraction of the ultimate load predicted in the first series of analysis, is applied and kept constant throughout the test. Simulations are conducted for 240 min or until connection failure. Note that Fields and Fields

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