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Deriving temperature-dependent material models for structural steel through artificial intelligence

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HIGHLIGHTS

- Temperature-dependent material models are derived using artificial intelligence.
- Unified and unbiased material models for fire resistance analysis are proposed.
- The proposed material models are validated against tests and finite element analysis.

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ABSTRACT

Structural steel undergoes significant metallurgical and physio-chemical degradation under fire conditions. This degradation is often represented by temperature-dependent material models commonly adopted in fire codes and standards. A closer look into such models reveals few surprising, and to some extent, concerning facts. For instance, presentation of temperature-induced degradation in structural steel properties substantially varies across different fire codes. This not only causes inconsistences among researchers/practitioners with regard to carrying out fire resistance analysis, but also hinders ongoing standardization efforts. Further, and despite recent advancements in material science over the past few decades, code adopted temperature-dependent material models have not been updated nor revised. In order to promote a harmonized fire assessment methodology and to ensure realistic prediction of fire performance of steel structures, this paper utilizes Artificial Intelligence (AI) and machine learning tools to derive temperature-dependent thermal and mechanical material models for structural steel. The validity of the proposed models in predicting thermal and structural response of steel structures is demonstrated through number of case studies carried out using a highly nonlinear finite element model developed in ANSYS simulation environment.

1. Introduction

Structural steel is widely used in civil construction due to its ductility and high strength properties as well as ease of erection and sustainability [1,2]. However, the high thermal conductivity and low specific heat of steel, when combined with the lower sectional mass (slenderness) associated with steel shapes, leads to rapid temperature rise in steel members once exposed to fire conditions. As the yield strength and stiffness properties of structural steel are highly sensitive to elevated temperatures, this rapid rise in temperature induces significant metallurgical changes to steel micro-structure which causes degradation in load carrying capacity under fire conditions [3]. As a result, steel structures exhibit lower fire resistance than structures made of other construction materials such as concrete [4,5]. Concrete has better fire resistance properties due to its inert nature and slower loss of strength under elevated temperatures [5].

The adverse effects of fire on constituent materials, such as structural steel, can be represented by temperature-dependent material models. These models often comprise of simplified relations, expressions, charts, and/or material-based reduction factors which can be compiled from results of small scale material tests in which steel coupons are tested either under thermal (temperature) conditions or under simultaneous thermal and mechanical loading [6,7]. Hence, two sets of material models are usually developed, "thermal" and "mechanical" models. The thermal models, which trace temperature rise and distribution within a steel section, include density, thermal conductivity, and specific heat properties. On the other hand, the mechanical properties, which

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contains yield strength, Young's modulus, and stress-strain curves, determine structural behavior of a fire exposed steel member. It should be noted that other material properties such as creep and thermal expansion are grouped under "deformational" models [6]. Deformational models determine the extent of deformations steel structures undergo once exposed to fire conditions.

Thu number of studies have presented temperature-dependent material models for structural steel, these models seem to vary significantly [7–11]. This variation can be mainly attributed to the lack of testing standards and guidance in 1960-1990′s which led discrepancies in testing methods, loading/heating regimes, use of test facilities and equipment, sensitivity of sensors, data collection and processing techniques etc. Another factor that also seems to contribute to this diversification in material models, but is often neglected, is the fact that there exists distinct differences in metallurgical composition of structural steel in different regions of the world. Such differences arise due to variations in amount/type of supplementary minerals/additives, and also due to differences in fabrication/milling process.

In lieu of above discussion, a review of recent studies indicates that bulk of the fire engineering community seems to adopt temperature-dependent material models recommended by ASCE [12] and Eurocode 3 [13]. Although these models have been extensively used in number of research studies, such models continue to have few shortcomings [7,14]. For a start, ASCE and Eurocode material relations implies that micro-structure and behavior of steel is independent of its origin, material composition, and fabrication process which is some scenarios may not be realistic. Further, these codal-promoted material models were arrived at and collected using vintage apparatus, which unlike modern testing equipment, provided researchers with limited set-ups, and relatively inferior measurements [15,16]. Moreover, both ASCE and Eurocode 3 models have never been revised since their establishment which dates back to a few decades ago.

Perhaps one of the major concerns that continue to arise is the fact that there exists a large discrepancy in temperature-dependent material models between ASCE and Eurocode 3. This presents a major challenge to designers wishing to carryout fire resistance analysis on steel structures and also is a key issue that hiders standardization efforts. For example, if flexural capacity, M, of a W-shape section is to be evaluated at 450 °C, this capacity can be calculated by multiplying plastic section modulus, Z, by the yield strength of steel at 450 °C, $f_{y450^\circ C}$, such that; $M_{450^\circ C} = Z \times f_{y450^\circ C}$. The plastic section modulus of a steel section is a geometric feature that is not influenced by elevated temperature. On the contrary, the yield strength of structural steel is material-sensitive property. The yield strength at 450 °C can be estimated through a temperature-dependent reduction factor, $k_{450^\circ C}$, multiplied by the yield strength of steel at ambient condition (i.e. $f_{y450^\circ C} = k_{450^\circ C} \times f_{y20^\circ C}$).

According to ASCE and EC3 material models, the value of this temperature-dependent reduction factor at 450 °C ($k_{450^\circ C}$) equals to 0.63 and 0.88, respectively. Thus, the evaluated flexural capacity of a typical W-shaped steel section can, in theory, vary by 25%. Such large variation could lead to overestimating (or underestimating) flexural capacity and subsequently fire resistance (i.e. failure) of a fire exposed steel structural member. This variation in material models could potentially complicate fire resistance analysis and design especially when an engineer is required to check for complex load effects (ex: shear, buckling, moment-shear interaction) under fire conditions, select appropriate fire insulation type/thickness/rating, or carry out consulting services [17–19].

In order to overcome some of the above discussed concerns, and in support of current effort to promote a more standardized procedure for fire resistance analysis and design, this paper presents a novel approach to derive temperature-dependent material properties of structural steel at elevated temperature utilizing machine learning and artificial intelligence (AI) techniques. More specifically, this study presents a brief review on high temperature properties of structural steel and development of an artificial AI model that can be used to develop simplified expressions for temperature-dependent thermal and mechanical material properties of structural steel. To ensure high model predictability, the developed AI model integrates data collected from number of fire codes and standards, as well as reports collected from various elevated temperature material tests published in the open literature. In essence, this paper hypothesizes that using AI and machine learning tools could potentially lead to developing a modern and unbiased temperature-dependent material models for structural steel that could pave the way towards developing universal constituent models for other construction materials. The validity of the proposed material models in predicting thermal and structural response of steel structures is demonstrated through number of case studies carried out in ANSYS [20].

2. Temperature-dependent material properties of structural steel

The response of steel structures exposed to fire is generally governed by thermal and mechanical properties of structural steel material[1]. While thermal properties determine temperature rise, and propagation within a steel section, the mechanical properties govern degree of temperature-induced loss in strength and stiffness and eventually the degrading load carrying capacity under fire conditions. Both thermal and mechanical properties vary with temperature and are highly influenced by material phase changes associated with temperature rise. This section provides a brief review of the thermal and mechanical properties of steel, together with available high-temperature constitutive models for structural steel.

2.1. Thermal properties

Thermal material properties are those that influence temperature rise and distribution in a steel member. These properties are density, thermal conductivity, specific heat, thermal expansion, and thermal diffusivity, and their behavior depends on the composition and characteristics of the constituent materials. From structural fire analysis point of view, density, thermal conductivity, and specific heat are of utmost importance [6,7]. The density of structural steel, ρ (kg/m^3), is defined as the mass of a unit volume and often equals to 7850 kg/m^3. The thermal conductivity, K, determines temperature rise, as a result of heat flow, in a steel member. Carbon steels usually have thermal conductivity between 46 and 65 W/m.K [6]. On the other hand, the specific heat, C_ρ, is the characteristic that describes the amount of heat required to raise a unit mass of steel a unit temperature. The specific heat of structural steel may vary in the range of 420–435 J/kg.K at ambient conditions [6].

Since density of steel is assumed to be constant under fire conditions, then the two main thermal properties that influence temperature rise in structural steel are those referred to as thermal conductivity and specific heat [6]. Thu, there is limited test data on these properties, specifically under fire conditions, ASCE and Eurocode 3 recommend few relations to evaluate thermal properties of structural steel. These relations are presented in Eqs. (1)–(4).

Thermal conductivity (W/m.K.)

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[1] It should be noted that there exist a third type of material properties, referred to as deformation properties, which determine the extent of deformations under fire conditions such as thermal expansion and creep. For brevity, deformational properties will not be discussed herein but the reader is encouraged to review following studies for additional information [6].