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An integrated framework for nonlinear analysis of plane frames exposed to fire using the direct stiffness method

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ABSTRACT

A novel coupled framework for analysis of reinforced concrete (RC) and steel planar frames subjected to fire is developed with three-way coupling between heat transfer, mechanical deformations and pore pressure build-up. Structural members are discretized in space using a two-level scheme where the mechanical solver utilizes 1D line elements, and the thermal and the pore pressure solvers work on 2D finite element (FE) meshes for each sub-span used by the mechanical solver. Such a strategy enables consideration of effects of large deformations, temperature-dependent material properties (thermal, moisture transport and mechanical), and spalling. None of the earlier developed frameworks considered a three-way coupling between mechanical, thermal and pore pressure solvers without employing a full-fledged 3D FE scheme. A matrix method type approach, developed herein, enables modeling of the three main physical processes taking place in RC members during fire without the need to consider full-fidelity 3D FEM. Several numerical examples are presented to demonstrate the accuracy and applicability of the developed framework in fire analysis of normal and high strength RC and steel structures.

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1. Introduction

Modern construction practice predominantly utilizes reinforced concrete (RC) and/or steel frames as main load-bearing mechanisms. Given that all structures carry the risk of being exposed to fire during their service lives, it is essential for them to be analyzed and designed for fire in addition to the regular service loads. The performance of structures under fire is usually described using fire resistance, which is the time required by structural member(s) to reach a pre-defined failure state. Fire resistance of structural members is typically prescribed by building codes and can also be evaluated using detailed engineering analysis of the system. Building codes [1–3], in general, specify fire ratings as a function of cross-sectional dimensions and clear cover/insulation thickness. Apart from the codified procedures, several empirical relations have been proposed (e.g. [4]) to estimate temperature profile and subsequently the structural performance of the members. Almost all of these methods (either empirical or code-based) consider exposure of individual structural members (isolated beams or columns) to a standard fire (e.g. ISO 834 or ASTM E119) and are hence, unsuitable for assessing the performance of a structural system as a whole. Moreover, all such relations are scenario specific, i.e., there are separate relations for steel and RC.

In performance-based design procedures, where response of an entire structural system is to be computed, factors such as fire scenarios, geometric effects and consideration of appropriate support conditions become important. In this context, the importance of having an integrated computational framework that can perform such analyses for various scenarios in a unified manner is well acknowledged. Physical phenomena that must be considered by such models include (a) effects of material and geometric nonlinearity, (b) temperature-dependence of material properties, (c) effects of reversible and permanent thermal deformations, (d) consideration of permanent damage in material, and (e) effects of pore pressure in case of concrete with high moisture content or low permeability.

One way to perform such analyses is through detailed finite element (FE) models that work at micro/meso scales. Several researchers have developed such models. For instance, Khennane and Baker [5] developed thermo-plasticity based 3D FE framework for analysis of isolated concrete members exposed to fire, Rigobello et al. [6] developed thermo-plasticity based 3D FE framework for coupled thermo-mechanical analysis of isolated steel members, Yu et al. [7] developed a 3D FE framework for analysis of steel/composite structures exposed to fire and implemented it in the software VULCAN [8], Majorana et al. [9] develped a finite strain

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3D FE framework for coupled hydro-thermo-mechanical analysis of concrete structures subjcted to fire, Kumar and Srivastava [10] and Kumar [11] developed FE models for RC frames with and without infills. Such detailed FE models can be applied in a variety of situations but are computationally very intensive and hence, are applicable only to individual members or very small structural assemblies. Moreover, such models usually require a large number of parameters to be estimated/calibrated for proper functioning and face difficulties related to numerical convergence even after moderate fire exposures [11–13].

An alternative to detailed FE models is the macro-modeling approach that aims to reduce computational complexity through relevant physical idealizations. Kassimali and Garcilazo [14] developed a matrix analysis based framework for thermo-mechanical analysis of plane frame members considering linear elastic homogeneous material models and a linear temperature gradient across member cross-sections. Wang and Moore [15] developed a FE based macro model for thermo-mechanical analysis of steel frames. Kodur and Dwaikat [16] developed a moment-curvature based macro model for individual RC beams/columns incorporating the effects of spalling. Bionidi and Nero [17] developed a cellular FE based macro model for nonlinear analysis of RC structures subjected to elevated temperatures. Cai et al. [18] developed FE based 3D macro model for coupled thermo-mechanical analysis of steel/concrete structures and successfully implemented it in the software VULCAN [8]. Franssen [19] developed FE based 3D macro model for coupled thermo-mechanical analysis of composite steel-concrete structures and implemented it in the SAFIR program [20]. All of the aforementioned frameworks require discretization of the structural members into several sub-elements for reasonable level of accuracy. This results in higher computational intensiveness while modeling large scale structural systems subjected to fire. Furthermore, none of the available frameworks consider mutual coupling between heat transfer, moisture transport and mechanical deformations. No coupling implies that heat transfer analysis is performed first and mechanical deformation analysis is performed based on the pre-computed temperature field, thus, effects of cross-sectional changes due to spalling cannot be considered in thermal analysis. Prakash and Srivastava [21] recently developed a two-way coupled framework capable of performing coupled thermo-mechanical analysis. However, the effects of axial deformations were not considered and same constitutive behavior was considered for compression and tension.

The present study develops a large deformation Euler-Bernoulli beam-column element comprising of several fibers along its length that can consider effects of material degradation at elevated temperatures and temperature-induced spalling. The developed element considers an updated Lagrangian co-rotational formulation and temperature-dependent stability and bowing functions. A two-level discretization strategy enables the typical 1D idealization in mechanical analysis while maintaining the cross-sectional details for heat transfer and pore pressure analysis through a 2D FE mesh. Integration of thermal effects into member stability and bowing functions yields higher accuracy with fewer number of sub-elements compared to previously discussed macro models. Use of the direct stiffness method approach enables much faster computation times when compared to full fidelity 3D FE models.

Section 2 presents the detailed theoretical development of the model including discretization strategy, thermal, pore pressure and mechanical solvers, and the staggered solution strategy implemented to enable mutual coupling of the three solvers. Three-way coupling between the solvers is a unique feature of the developed framework. Section 3 discusses the relevant material models for concrete and steel. Section 5 presents several numerical examples for validating the developed framework against available experimental data for RC and steel structural members and illustrates the use of the developed framework for fire analysis of a two-storey two-bay portal frame.

2. Theoretical development

Mechanical analysis of systems of beams and columns can be performed in a computationally efficient manner by considering the so-called structural elements (e.g. Euler-Bernoulli beam element) as opposed to the usual continuum finite elements (e.g. the hexahederal element). Such an approach typically considers the behavior of the neutral axis of the member with certain assumptions with respect to its cross-section, hence, converting an otherwise 3D problem to an equivalent 1D idealization. While this allows computation of deformations under mechanical loads relatively accurately, considering the effects of additional physical phenomena (e.g. heat transfer and moisture transport) that demonstrate rich behavior across the cross-section of structural members becomes challenging.

To facilitate consideration of heat and moisture transport along with mechanical deformations, necessary for appropriately modeling structures under fire, the present study considers a two-level discretization of the physical domain, as shown in Fig. 1. For mechanical analysis, the member is discretized along its length (shown by slices or nodes i) similar to a typical matrix analysis procedure. It is assumed that along the length of a sub-span (i.e. length between i and $i+1$, etc.), temperature and moisture conditions do not change with x. Variations of these conditions along the overall length of the member can be considered by increasing the total number of sub-spans.

The variation in temperature and moisture across the cross-section is considered through a 2D finite element solution procedure using a separate yz mesh in each sub-span, as shown in Fig. 1. Thus, an exclusive 2D heat transfer and moisture transport analysis is performed for each sub-span of the member. In order to consider effects of variation of mechanical properties with changes in temperature and/or moisture, fibers are considered along the length of the member in accordance with the 2D mesh, as shown in Fig. 1, and an equivalent 1D fiber is constructed for mechanical analysis, as discussed later.

2.1. Heat transfer analysis

Let a typical cross-section of the structural member be denoted by an area Ω enclosed by a boundary Γ having a unit normal $\mathbf{n}$. Heat transfer analysis is performed by solving the transient heat equation in Ω given by

$$\nabla \cdot (\kappa \nabla T) + Q = \rho c \frac{\mathrm{d}T}{\mathrm{d}t}, \tag{1}$$

where κ, ρ and c are the temperature-dependent thermal conductivity, mass density and specific heat of the material, and Q represents the heat source; t represents time and T is the temperature. Convective and radiative boundary conditions can be enforced on Γ as

$$\kappa \nabla T \cdot \mathbf{n} = h(T - T_\infty), \tag{2}$$

where, T_∞ is the ambient or fire temperature, and h is the combined convective and radiative heat transfer coefficient. Four node bilinear quadrilateral elements are used along with Galerkin approximation for spatial discretization of (1) which yields a first order nonlinear system of ODEs in time domain as

$$\mathbf{M}_\mathrm{T}\dot{\mathbf{T}} + \boldsymbol{\kappa}_\mathrm{T}\mathbf{T} = \Psi, \tag{3}$$

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