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Efficient Three Dimensional Nonlinear Thermo-Mechanical Analysis of Structures Subjected to Fire

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Abstract

In this paper, a computationally efficient integrated frame-work is developed for coupled thermo-mechanical analysis of 3D frames. It can account for physical phenomena like large deformations, temperature dependent material degradation, permanent plastic deformations and fire induced spalling which are prevalent at elevated temperatures. The developed frame-work utilizes three way sequential coupling between thermal, mass transport and structural analysis. A two level discretization scheme is incorporated where 1D beam column elements are utilized for structural analysis, the cross-section of these beam-column elements are further discretized into matrix of segments. Aforementioned strategy entails sequential coupling of effects of non-uniform temperature and pore pressure across the cross-section into structural analysis. Subsequently structural analysis is performed with an updated Lagrangean based formulation with force deformation relationships deduced form classical Euler-Bernoulli beam column theory. Critical physical phenomena like cracking, crushing, spalling and transient states of strain in case of concrete and yielding in case of steel are duly accounted. Cross-sectional reduction due to spalling are accounted for by replacing the spalled segments with void segments in the subsequent time steps. Numerical examples of steel and concrete structures subjected to various fire scenarios are presented to demonstrate the accuracy of developed framework. Furthermore, progressive collapse analysis is carried out for concrete and steel 3D subjected to fire.

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1. Introduction

In recent years, structural design for fire has received increasing attention and a number of design procedures have been developed over past few decades. These design procedures are classified into two categories, prescriptive and performance-based procedures. Prescriptive methods yield fire rating as a function of clear cover/insulation thickness and cross-sectional dimensions whereas performance based procedures yield fire ratings based on scenario based engineered fire analysis of structural member/system subjected to fire [1]. Critical physical phenomena that must be incorporated for scenario based analysis for accurate prediction of thermo-mechanical response include a) geometric and material nonlinearities, b) temperature-dependent material properties, c) natural fire scenarios, and d) fire induced spalling. Incorporating these phenomena, several structural fire analysis tools have been developed over the past few decades. They are broadly classified into two types: empirical methods and advanced calculation methods. Empirical methods, for instance [2,3], predict the response of structures under fire with the aid of simplified design equations. They are usually scenario specific and cannot be utilized in all cases. Advanced calculations are the numerical finite element (FE) models which work at micro and macro levels and perform time variant structural analysis under fire.

FE Micro models essentially utilize 3-D FE for structural fire analysis of steel/concrete composite structures. For instance, Khennane and Backer [4] developed 3-D FE model for structural fire analysis of concrete structures. Yu et al. [5] developed 3-D FE based micro model and successfully implemented in the VULCAN solutions [6]. Franssen developed a 3-D FE micro model and successfully implemented in the SAFIR program [7]. Commercial software like ANSYS and ABAQUS have also been utilized for structural fire analysis of steel/concrete composite structures. For instance, Kumar [8] demonstrated structural fire analysis of steel/concrete structures utilizing 3-D FE micro models in ANSYS. Even though, FE micro models account for complex geometries and boundary conditions they are computationally intensive and face lot of convergence issues even for moderate fire exposures and demand numerous parameters to be calibrated [9]. Also, very few FE micro models incorporate actual elevated temperature strain decomposition as observed in laboratory experiments. Due to higher computational efforts, these are better suited for isolated and small scale structural assemblies subjected to fire.

FE macro models are computationally efficient compared to FE micro models and are ideal for structural fire analysis of full structural systems. Structural fire analysis of isolated member vs. complete structural system is an interesting subject for fire engineering community and is gaining significant attention in recent years. For instance, full-scale fire test conducted at BRE fire research laboratory at Cardington [10] indicated augmented fire resistance of structural system as whole compared to isolated members. The main reason for this phenomenon was interaction between heated and non-heated structural members. For a performance based design, such interactions need to be incorporated and fire rating needs to be quantified considering entire structural system considering various fire scenarios. Currently, two of the most used FE macro models for structural fire analysis of steel/concrete composite structural systems are VULCAN and SAFIR. VULCAN solutions [6] has been developed at the University of Sheffield while SAFIR program [7], at the University of Liege. Apart from these, there are some other notable formulations. For instance, Rigobello et al. [11] developed solid like finite elements for thermo-mechanical analysis of steel frames. Bionidi and Nero [12] developed cellular finite element based FE macro model for coupled thermo-mechanical analysis of RC frames. Caldas et al. [13] developed a 3-D FE macro model for coupled thermo-mechanical analysis of steel/concrete composite structures. However, these macro models too require FE discretization for reasonable levels of accuracy and structural fire analysis will become computationally intensive if large scale structural systems are considered. Moreover, these macro models are one-way coupled i.e. thermal analysis is performed first followed by structural analysis. This will be inaccurate when cross-sections of structural may change during fire (e.g. due to fire induced spalling). Also, in situations like moving fires, both by natural movement and movement induced by structural collapse, mutual coupling of physical phenomena is required.

There are two approaches which address above mentioned limitations. First, the moment curvature based macro model developed by Kodur et al.[14] and second, is the direct stiffness method (DSM) based formulation developed by Srivastava and Prakash [15]. The moment curvature based macro model developed by Kodur et al. [14]