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Fire-thermomechanical interface model for performance-based analysis of structures exposed to fire

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ABSTRACT

This paper presents an interface model to perform a one-way coupling between a fire simulation (CFD model) and a structural analysis (FEM model) aimed at performance-based analysis of structures exposed to fire. The Fire-Thermomechanical Interface (FTMI) model is capable of processing the results from a fire simulation to properly account for the heat transfer by convection and radiation, between the fire and the exposed surfaces, based on Adiabatic Surface Temperature concept. The methodology is presented and verified against simple cases, and the improvements required to achieve complex geometries are introduced. An application is also presented evaluating the fire-thermomechanical behavior of an H-profile column under a localized fire. At the end of the analysis, it is possible to obtain the structural behavior under specific fire scenarios. An automated procedure is created to surpass the isolated member analysis, allowing the simulation of the behavior of global structures discretized with shell and/or solid elements under fire conditions. In these examples, both solid and shell elements are used to demonstrate that the procedure can be applied to evaluate the global behavior of structures. The results also suggest that the methodology can provide reliable performance-based analyses.

1. Introduction

Traditionally, the performance of structures under fire conditions has been achieved by prescriptive procedures, available from international codes and standards [1–3]. Those procedures are generally based on furnace test results, and focused on checking if isolated structural members meet a required fire resistance time by means of analytical formulations. These do not account for the system behavior including connections, second order effects (catenary or membrane action) or large displacements. Nowadays, advanced numerical models based on Finite Element Method (FEM) are capable of predicting the global behavior of structures including large displacements and material nonlinearities. However, the application of these models to fire conditions is generally based on simplified temperature-time curves [2]. These temperature-time curves may not accurately represent the fire development, and generally do not account for the three-dimensional fuel distribution or the fire compartment geometry.

On the other hand, numerical models based on the Computational Fluid Dynamics (CFD) are capable of providing a reliable description of fire evolution and have the capability to simulate the actual fire dynamics for different scenarios. Fire Dynamics Simulator (FDS, [4]) is an open source CFD code developed by National Institute of Standards and Technology (NIST) for fire simulations. Over the last decade, this code has been extensively used for fire engineering and has been validated for a wide range of applications [5,6].

Despite CFD and FEM being mature research fields, coupled fire-thermomechanical analysis (CFD-FEM) is a relatively new area of research [7–12]. After the collapse of the World Trade Center towers Prasad and Baum [7] proposed an interface between the FDS [4] and the ANSYS[1] package [13] to investigate the behavior of structural elements during this event. Their method was called Fire Structural Interface (FSI) and assumed that the heat transfer between fire and exposed surfaces was given only by radiation. Following Prasad and Baum, a European research project called FIRESTRUC [8] analyzed a number of ways to perform an interaction between CFD and FEM codes focusing on the behavior of structures under fire. Among the

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CFD codes considered, FDS has the advantage of including a combustion model to address the fire growth.

One of the big concerns stated by FIRESTRUC was related to determining which variables should be transferred from fire simulations to FEM models. The Adiabatic Surface Temperature (AST) was proposed by Wickström [14] as a variable capable of describing complex convective and radiative conditions into one single scalar quantity. In sequence, an interface between FDS and ANSYS was presented by Wickström et al. [15] and Duthinh et al. [16] using the AST concept. At this point, the coupling procedure was only applied to isolated structural members such as trussed beams or columns. The main issues related to this coupling include the handling of different geometries, the time scale, and the amount and format, of data to be transferred between models.

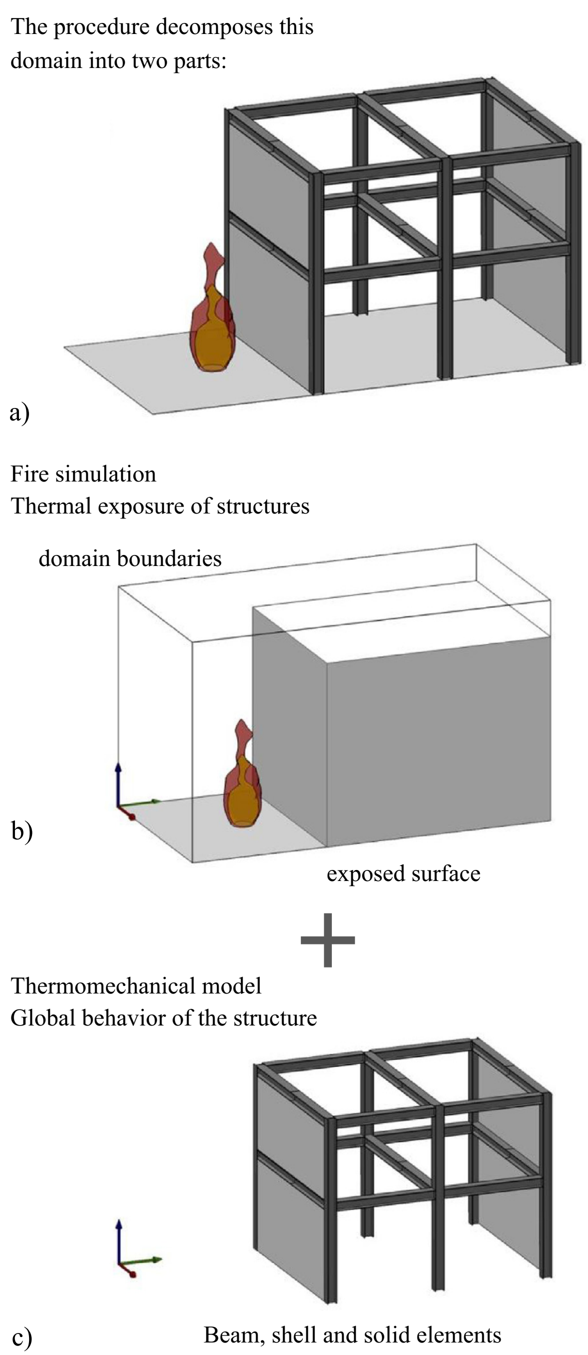

Fig. 1. Illustration of the coupled field domain decomposition: (a) problem description; (b) fire simulation domain; (c) thermomechanical analysis discretization.

The main purpose of this paper is to provide an interface model to performance-based analysis of structures under fire conditions. The Fire-Thermomechanical Interface (FTMI) improves the reach of fire engineering by providing an automated code to extract the data from fire simulations, transform the information, and prescribe the correct boundary conditions to the thermomechanical analysis. This automated procedure surpasses the isolated member analysis allowing the simulation of the behavior of global structures discretized with shell and/or solid elements under fire conditions. In the next sections the FTMI methodology is presented. In this paper, FDS [4] is used for the fire simulation and the commercial package ANSYS [13] is used for the thermomechanical analysis. The interface method, however, can be easily applied to other computer models. Verification examples and an application case are provided to show FTMI applicability for solids and shell elements.

2. Fire-Thermomechanical Interface: FTMI

The description of structural behavior under fire conditions by a fire-thermomechanical model is related to a domain that includes the structure and its components. The boundary conditions include the thermal loads (fire model) and mechanical loads (structural model). The thermomechanical problem needs to address the differences in the physical phenomena involved between the two types of analysis.

The procedure described in this paper decomposes fire-thermomechanical model domain, illustrated in Fig. 1, into two parts: the first part is devoted to fire simulation and the second is focused on the thermomechanical behavior. In the fire simulation, the structure geometry is simplified and the overall domain size extends beyond the structure to properly capture the fire propagation and the smoke and hot gas flow (cf. Fig. 1b). For the thermomechanical analysis, only the structure is modeled and the fire simulation is represented by heat fluxes, applied as boundary conditions at the exposed surfaces, as shown in Fig. 1c. In order to exchange data, both models have the same coordinate system and a consistent geometry (Fig. 1).

This approach is commonly referred to as one-way coupling. In a two-way coupling strategy, the thermomechanical results are transposed back to the fire simulation (i.e. displacements, collapses, etc). The two-way approach can lead to a more complex simulation, increasing the amount of data to be transferred between the models. Its advantages are related to cases where displacements and/or collapses can change the ventilation and thereby the fire source or the fluid flow pattern, creating a different fire scenario. With one-way coupling it is possible to develop each model separately, by different model users/developers, each one with their own expertise. In addition, the one-way procedure can be achieved for different discretization levels (FEM mesh) and small modifications or dimensioning does not imply the entire calculation to be restarted, as the structures geometry is simplified for the fire simulation.

2.1. Heat transfer from fires

Heat can be transferred from flames and hot gases to a structure's surfaces by radiation and convection, as illustrated in Fig. 2. The total heat flux (q''_{tot}) is defined by the sum of these two parcels:

$$q''_{tot} = q''_{rad} + q''_{conv} \quad (1)$$

The radiative heat flux (q''_{rad}) is obtained through the balance between the radiative energy absorbed ($e''_{r,abs}$) and emitted ($e''_{r,emi}$) by the surface and can be represented by the following equation:

$$q''_{rad} = e''_{r,abs} - e''_{r,emi} \quad (2)$$