

COUPLED SIMULATION FOR FIRE-EXPOSED STRUCTURE USING CFD AND THERMO-MECHANICAL MODELS

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Abstract: Fire resistance of buildings belong to fire safety assessment for centuries. It is based on fire element tests in horizontal and vertical furnaces, which are exposed to a rapid increase of temperature by gas burners. However, the tests are very expensive and time consuming. This article presents a coupled simulation of an element loaded by force and fire loading. The simulation solves a weakly-coupled problem, consisting of fluid dynamics, heat transfer and mechanical model. The temperature field from the CFD simulation creates Cauchy boundary condition for the thermal model. Then, the temperature field from element is passed to the mechanical model, which induces thermal strain and modifies material parameters. The fluid dynamics is computed with Fire Dynamics Simulator and the thermo-mechanical task is solved in OOFEM. Both softwares are interconnected with MuPIF python library, which allows smooth data transfer across the different meshes, orchestrating simulations in particular codes, exporting results to the VTK formats and distributed computing.

Keywords: Thermo-mechanical model, Virtual furnace, Computational fluid dynamics, Multiphysics, Fire resistance.

1. Introduction

Several single physical models exist for description of particular physical phenomena. Multi-physical coupled problems extend applications to more complicated tasks. In order to alleviate coupling among models, we created a python library which integrates solutions for computing simulations of structures exposed to fire. This paper presents approach how to interconnect single physical models.

1.2. Fire dynamics analysis

The issue of predicting fire process in defined space domain is solved with the Fire Dynamics Simulator software (FDS), developed at NIST (NIST, 2017). We had to modify the structure of the code to be able to call each computational time-step individually and we had to add several interface functions to get the dimensions of the meshes, the temperatures in the nodes, etc.

1.3. Thermo-mechanical analysis

The thermo-mechanical analysis of the element takes place in OOFEM (Patzák, 2000 and Patzák, 2012) software. The thermal analysis uses a temperature field from FDS, which defines Cauchy boundary conditions on the element. Then, the solution of thermal analysis passes temperature to the mechanical analysis, which induces the thermal strain and modifies the material parameters as yield strength and elastic modulus. Temperature will also be used for timber structures where it controls carbonization process and changes the thermal conductivity.

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2. Interfacing FDS and OOFEM using MuPIF

Interfacing FDS and OOFEM using MuPIF (Patzák, 2010 and Patzák et al., 2015) library, which provides several useful tools such as exporting data to VTU format, parallel computations and advanced handling with data fields and meshes. Both the FDS Fortran and OOFEM C++ codes provide API for communication and they are compiled as shared libraries. Top-level steering script controls execution of both codes, data synchronization etc. The flowchart of the codes is given in Fig. 1.

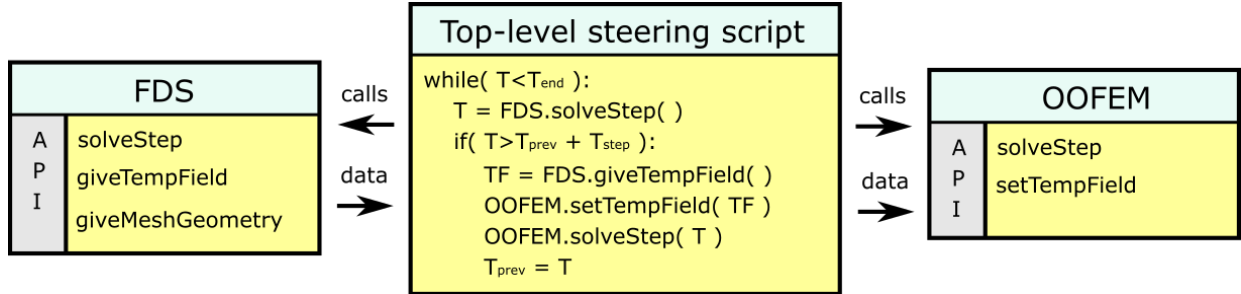


Fig. 1: Flowchart of the codes.

The FDS task consists of one or several uniform hexahedral meshes. In the beginning of the computation the geometries of all meshes are mapped from FDS to MuPIF. The meshes contain discretized temperature field.

Here we describe the loop over one OOFEM time-step, see the data workflow in Fig. 2. First, FDS is called to process several computational steps until we reach the length of our defined time-step of the thermo-mechanical task. The FDS application determines its time-step itself and it is usually much shorter than the OOFEM time-step. Then, we load the temperature fields from FDS and copy them into the MuPIF fields and into the OOFEM boundary-condition field. Then, OOFEM is asked to solve computational step of the thermal task and passes the computed temperatures of the construction to the mechanical task. The material parameters are updated due to the change of the temperature and the temperature strain is added. The mechanical response of the construction is obtained, which is the end of the computational loop.

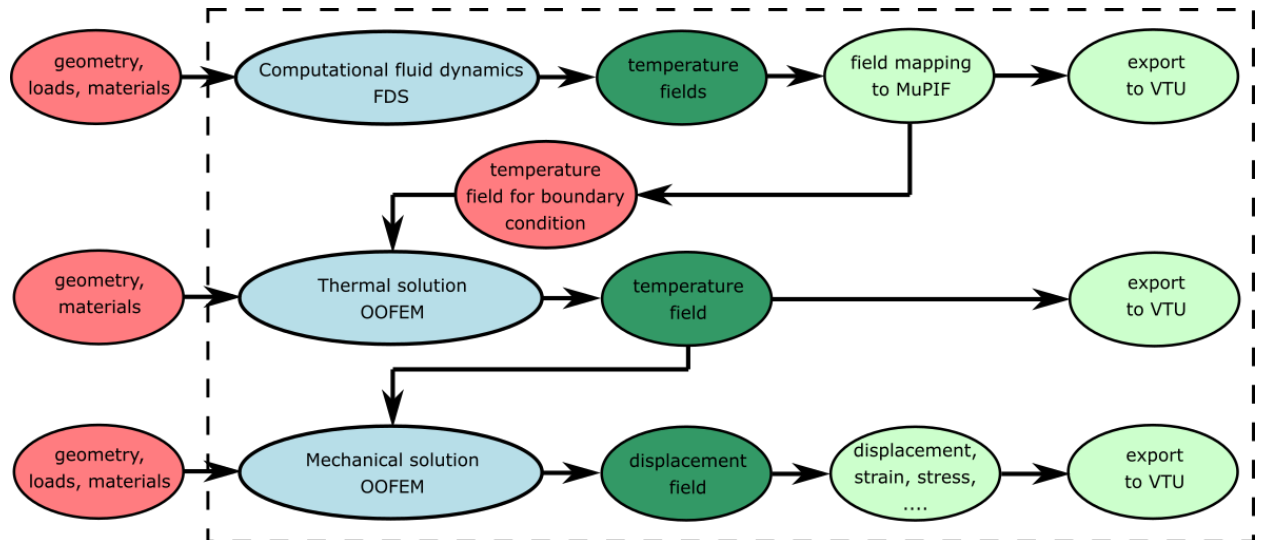


Fig. 2: Data workflow.

As the FDS analysis is very time-consuming process and the computations can last couple of days, we use another MuPIF functionality to store the meshes with all the temperatures in all defined time-steps in files. In this regard, it is possible to precompute FDS simulation and compute multiple thermo-mechanical analyses separately and much faster.

Coarse FDS mesh can be refined in areas where structure elements occur. This improves precision in temperature predictions and gives more realistic results of the thermo-mechanical task.

The MuPIF library has a tool to export the loaded FDS meshes to VTU, so that the FDS temperature fields can be exported into this useful format. OOFEM exports its results to VTU format as well.

3. Example

We demonstrate functionality of coupled CFD-thermo-mechanical task, consisting of a steel beam placed into a furnace with gas burners, see the geometry in Fig. 3. A horizontal furnace of fire laboratory PAVUS a.s. is of dimensions 3.0 m x 4.0 m and 2.2 m height. The furnace is heated by 8 natural gas burners. The simply-supported beam is made from steel I profile, placed just under the furnace ceiling. The steel parameters are $E = 200$ GPa, $\nu = 0.3$, $\rho = 7850$ kg/m³ and $\alpha = 12 \times 10^{-6}$. The length of the beam is 3.8 m. Geometry of the cross-section of the beam is in Fig. 4a. It is loaded only by its weight and the temperature.

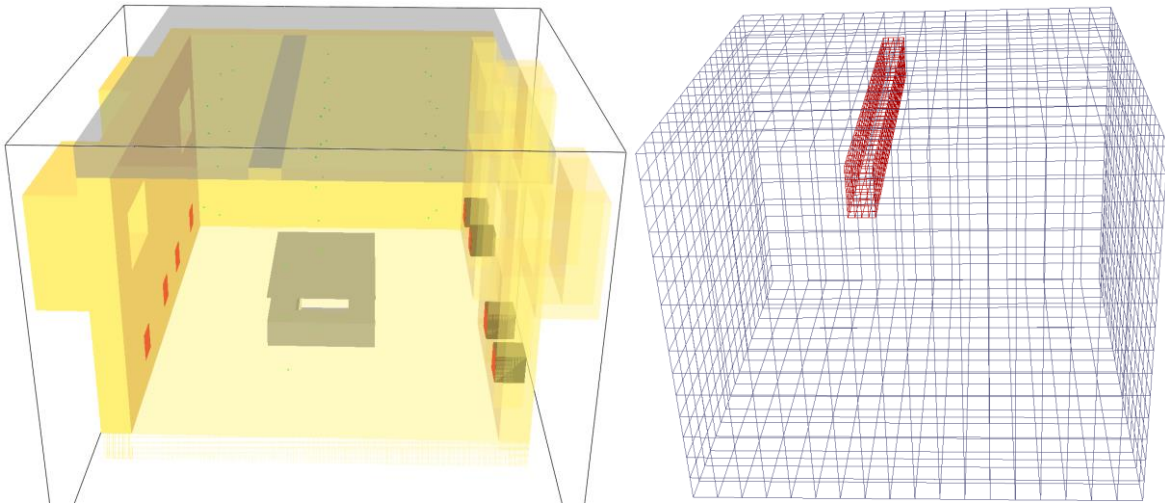


Fig. 3: a) FDS model (Smokeview), b) FDS meshes from MuPIF (Paraview).

The results were computed and exported to VTU files. Fig. 4b shows a cross-section through the middle of the furnace. We can see the two FDS meshes, one coarse on the whole furnace and one finer around the beam, which is necessary for the interpolation close to the ceiling. Detailed temperatures of the beam are displayed in Fig. 5a, the normal stress σ_x is in Fig. 5b.

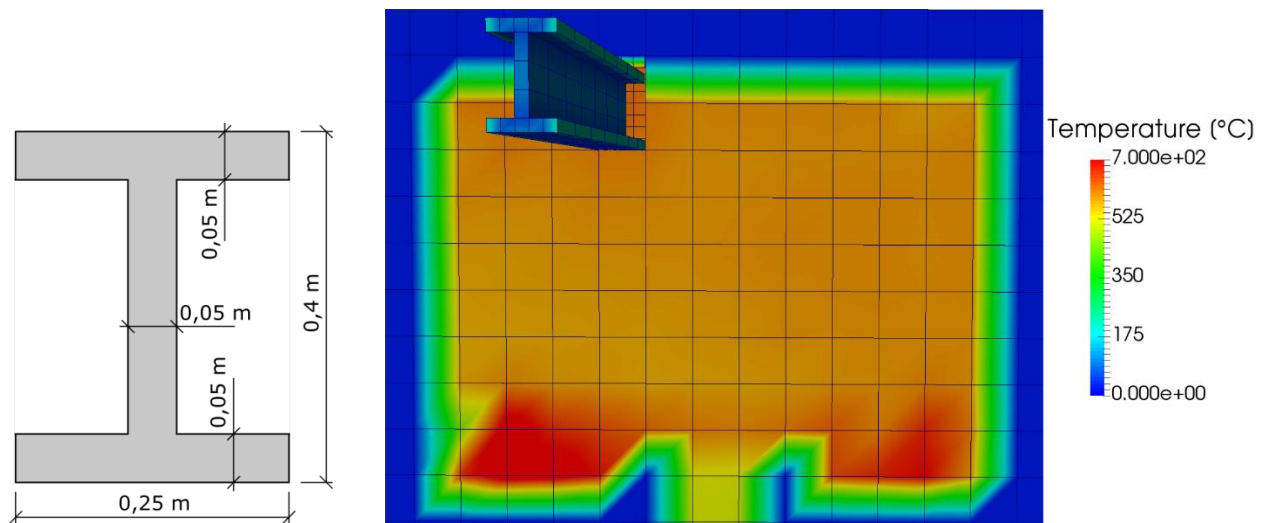


Fig. 4: a) Cross-section of the beam, b) Results at $t = 576$ s, section in the middle of the furnace.

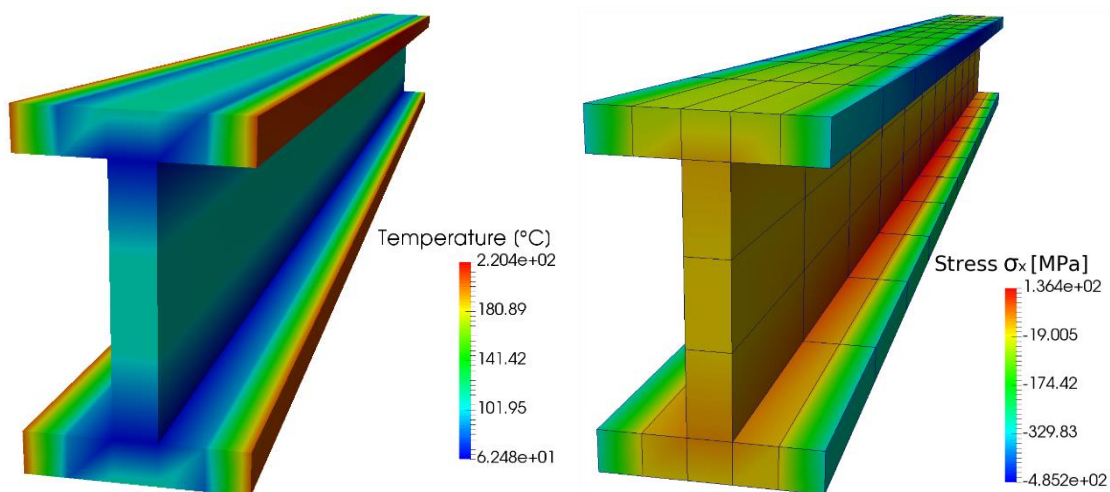


Fig. 5: Results at $t = 576$ s, a) temperature, b) stress σ_x .

4. Conclusions

This paper presents an approach for computing weakly-coupled problems, focusing on computational fluid dynamics coupled with thermo-mechanical analysis. Temperature field from FDS was validated previously (Cábová et al., 2017), Performance of structure elements presents a consecutive step. Validation of this multi-physical approach happens during 2017 on steel and timber structural elements.

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