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Automated two-way coupling of CFD fire simulations to thermomechanical FE analyses at the overall structural level

J.A. Feenstra [a,b], H. Hofmeyer [c,*], R.A.P. Van Herpen [d,e], M. Mahendran [f]

[a] Eindhoven University of Technology, The Netherlands
[b] Holmes Group, New Zealand
[c] Applied Mechanics, Eindhoven University of Technology, The Netherlands
[d] Nieman Consulting Engineers, Zwolle, The Netherlands
[e] Fire Safety Engineering, Eindhoven University of Technology, The Netherlands
[f] Civil Engineering, Queensland University of Technology, Australia

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ABSTRACT

Coupled CFD fire simulations and thermomechanical FE analyses typically consist of fire simulations, heat transfer analyses and structural response analyses, mutually coupled by three coupling steps. There are two coupling approaches, one-way and two-way coupling, where two-way coupling includes the effects of the structural response on fire propagation. In the first part of this paper, one- and two-way coupling approaches including the coupling steps are proposed to include coupling at the structural level. Then a case study comprising an office space with a 12-plate thin-walled steel façade under fire conditions is introduced, as well as the related CFD and FE models. A newly developed automated coupling interface and subprograms are used to perform several one-way and two-way coupled analyses using a coarse and fine CFD mesh for the case study. Slight differences are found in the results of identical simulations due to random effects in the fire simulations. Nevertheless, it can be concluded that two-way coupling is feasible, and that significant differences in the façade failure progression illustrate its effectiveness. Future research includes additional developments of both the fire and structural models, as well as verification and parametric studies to further confirm the findings.

1. Introduction

With an ever-evolving built environment, new challenges arise for fire fighters and researchers. For example, the growing complexity of architectural designs, structural optimization, and the use of innovative building materials and construction techniques introduce new types of fire risks. Therefore an improved understanding of fires, and methods for predicting temperature and smoke development are critical to both structural integrity and human safety.

The common approach used to assess the effects of a fire in structural engineering is to subject a loaded structural element to prescriptive time-temperature curves and subsequently to evaluate its behaviour. The fire safety check involves the structural element meeting a criterion that specifies a certain time for which the element should resist the fire [1]. This approach based on prescriptive time-temperature curves cannot accurately model the real fire conditions and does not take into account the 3D dependency of both the fire compartment and the structural system.

Advancements in the analyses of structures under fire involve the utilization of advanced numerical methods to both simulate the fire and to analyse the structure's thermal and structural behaviour [2]. More specifically Computational Fluid Dynamics (CFD) simulations are used to model the fire driven fluid flow and subsequently coupled to thermal and structural Finite Element (FE) analyses of the structural system under consideration. The combination of CFD simulations and FE analyses is commonly referred to as a coupled fire to thermomechanical analysis or coupled CFD-FEM (Finite Element Method). The interest in the structural response to fire and coupled approaches have been further developed following the collapse of the World Trade Centre (WTC) towers in 2001. This led to the American National Construction Safety Team's (NCST) recommendations to enable software to study realistic fire behaviour, to analyse building response to fire, and to assist in the design of new fire protection systems [3]. However, the development of a coupled CFD-FEM approach is not a trivial task since challenges are found in the underlying differences between the CFD and FE models in relation to the

* Corresponding author.
E-mail address: h.hofmeyer@bwk.tue.nl (H. Hofmeyer).

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discretization, algorithms and time scales. For example, Yu and Jeffers showed successfully that averaging time in the transfer of CFD data to an FE model improves FE convergence and thus computational costs [4], while Beata and Jeffers developed a trapezoid rule algorithm to overcome differences in the mesh size or node locations between CFD and FE models. Compared to other algorithms based on averaging, sampling, and least squares, their method was shown to be increasingly more accurate and efficient [5].

Prasad and Baum [6] have developed an interface model, called Fire Structural Interface (FSI), which can be used to generate realistic thermal boundary conditions for the heating of complex structures. Their interface model, used in the analysis of the collapse of the WTC towers, couples a fire simulation using Fire Dynamics Simulator (FDS) [7] to a structural analysis using ANSYS, based on heat transfer by radiation and conduction. Later research by Baum [8] discusses the potential to predict the effect of fire on building structures by coupled fire to thermo-mechanical analyses. More specifically, it discusses the role of uncertainty in input parameters and the challenges found in the differences in spatial and temporal length scales, numerical techniques, the complexity of the computer codes, and the required computational resources for coupled CFD-FEM analyses. Also Baum [8] underlines the importance of the development of coupled CFD-FEM models for the quantitative assessment of fire effects on structures.

A coupled CFD-FEM analysis can be split into three separate parts: (a) fire simulation; (b) heat transfer analysis; and (c) structural response analysis. They are mutually coupled by coupling steps. Two main approaches to coupling exist. For a one-way coupled approach, data is transferred from the CFD simulation to the FE analysis. For two-way coupling the data from the FE analysis is returned to the CFD simulation. The European research project FIRESTRUC, presented by Welch et al. [9] analysed both coupling approaches in predicting a structure's thermo-mechanical behaviour. It presents a broad examination of approaches to couple CFD and FEM codes first. Then the three parts; fire simulation, heat transfer analysis, and structural response analysis are introduced as well as their mutual coupling steps. Multiple implementation methods are proposed and discussed for both one- and two-way coupled approaches. The variables that should be transferred between CFD simulations and FE analyses are also identified. Luo et al. [10,11] have developed a Fire Interface Simulator Toolkit (AFIST) by integrating FDS with a customized Abaqus structural analyser. A two-way coupling between the fire simulation and heat transfer models was integrated, where heat and mass flow are exchanged at the incremental level. A time-to-failure prediction of a sandwich panel was used for validation and the toolkit was applied to demonstrate the response of a loaded composite panel to a pool fire.

In chronological order, the so-called Adiabatic Surface Temperature (AST) was introduced as a concept by Wickström et al. in 2007 [12]. It is a tool to express the thermal exposure of a surface to fire in a single quantity, thereby reducing the data flow in a coupled analysis. Duthinh et al. [2] utilized the AST to develop their interface between fire simulation software FDS and FEM software ANSYS, and simulated a trussed beam and verified it using a real fire test by NIST. In 2009, Banerjee et al. [13] created an Immersive Visualization Environment (IVE) to visualize and study in real time the structural and thermal behaviour of a chosen structural element in a one-way coupled fire to thermo-mechanical analysis (using FDS and Abaqus). Recently, Silva et al. [14] developed a computational Fire-ThermoMechanical Interface (FTMI) to provide an interface for fire-thermomechanical performance based analysis of structures under fire. The interface allows for one-way coupling of an FDS fire simulation to a thermomechanical ANSYS analysis, taking into account both convective and radiative heat transfer to the exposed surface via the AST concept. In their paper the methodology is described and applied to evaluate the fire-thermomechanical behaviour of an H-section as a column under a localized fire. In addition, the implemented code has been added to the FDS repository under the name FDS2FTMI (using among others FDS2ASCII) to allow for one-way coupling of FDS and the finite element program ANSYS. Most recently, additional validation of FDS2FTMI was completed by Zhang et al. [15].

The overview above presents the various approaches and challenges in the coupling of fire simulations to thermomechanical analyses. Coupling methodologies in literature focus on fire-to-thermal and thermal-to-structural coupling steps, both one-way and two-way. However, the effects of changes at the structural level during fire propagation and further structural failure progression are not addressed so far. For instance, failures of a window or a local structural element result in openings that change the fire behaviour, and consequently influence the fire load on the structural elements.

The contribution of this paper is to introduce this problem and to investigate the feasibility of an automated one-way and two-way coupling of CFD fire simulations to thermomechanical FE analyses at the structural level. Additionally it assesses the effectiveness of two-way coupling by illustrating the difference in failure progression of a thin-walled steel façade in a two-way coupled analysis compared to a sequential one-way coupled analysis. The approach is discussed in Section 2; a case study is presented in Section 3; the program and scripts are introduced in Section 4, which is followed by results in Section 5 and several verification steps in Section 6. Finally, Section 7 gives a discussion, followed by conclusions in Section 8.

2. Approach

As shown in Fig. 1, a coupled fire to thermomechanical analysis consists of three parts: (A1) a fire simulation; (A2) a heat transfer analysis; and (A3) a structural response analysis. Moreover, these parts are mutually coupled by three steps: (C1) coupling of the fire simulation to the heat transfer analysis; (C2) coupling of the heat transfer analysis to the structural response analysis; and (C3) coupling of the structural response analysis to the fire simulation. Now a distinction can be made between one-way and two-way coupling procedures where for two-way coupling the influence of structural changes on the fire propagation is taken into account by coupling (C3), whereas (C3) is not used for one-way coupling. These two approaches differ in their implementation, as one-way coupling is a linear process while two-way coupling needs to be solved iteratively: The one-way coupled analysis consists of a fire simulation for the full duration of the intended analysis and then continues sequentially with the heat transfer and structural response analyses, again for the full duration. Instead, in the two-way coupled analysis it is necessary to verify, during the fire simulation, if some parts of the structural model have changed and, if positive, to undertake appropriate modification in the fire and FE models. Therefore time increments are

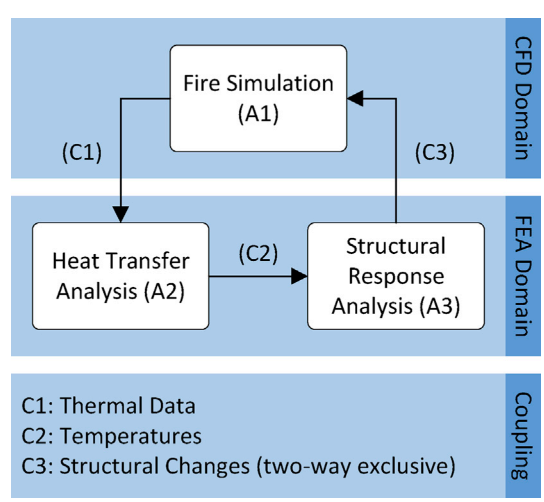

Fig. 1. Approach for one-way and two-way coupled fire to thermomechanical analyses. (Three analysis parts and three coupling steps can be identified).