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A COMPUTATIONAL FRAMEWORK FOR THERMAL COUPLING IN HYBRID FIRE SIMULATION

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Abstract. In structural fire engineering, it is crucial to estimate the global structural behavior in a realistic scheme. This necessity arises from the reason that the single element testing doesn't represent the global behavior of the structure correctly due to the possible load redistribution into alternative load paths and change of static systems in case of global fire. Therefore, hybrid simulation method can be accounted as a key method, which fulfills the possibility of study of the global structural behavior in structure with coupling the numerical simulation and experimental testing. In this method, the numerical simulation procedure of the whole structure is coupled and controlled with the outcomes of the experiment performed on a single part of the structure, which is critical or difficult to study numerically.

So far, several attempts have been made to study hybrid fire simulation. There, however, exist severe shortcomings in so-far research: - the correct consideration of the stiffness and material properties for the heated element and their degradation during fire exposure, - retaining the compatibility and the equilibrium between the substructures, - the automatic real-time interaction between the substructures and also - realistic consideration of the thermal coupling between substructures with regard to the transfer of the heat from fire exposed component to adjacent elements.

In hybrid fire simulation, the thermo-mechanical coupling can be studied realistically, when the heat exposed to the single compartment, its transfer to the adjacent substructures and the effect of two latter on the mechanical response of the structure is considered. In the current paper, this purpose is studied on a steel structure benchmark with two different approaches: sequentially-coupled thermal-stress analysis and fully-coupled thermal-stress analysis. Here, the mathematical and mechanical aspects of each approach and their difference regarding the response of the structure will be investigated. Also, their application in the hybrid fire simulation and the importance of the real-time issue in these approaches are outlined. In this paper, the numerical model of the intended benchmark which interacts automatically with another numerical model, representing the experimental substructure

exposed to fire is studied. Therefore, the implementation of hybrid fire simulation and different aspects of the thermal coupling including the existence of heat transfer and mechanical and thermal properties will be discussed.

1 INTRODUCTION

Fire is one of the most important hazards in structural engineering, since it is vital to study the resistance of the whole structure in a certain time period of fire exposure. Single element testing cannot represent completely correct the global structural behavior and it is because of possible load redistribution and changes in static system of the structure. Therefore, the performance of structures in fire has to be investigated in the full scale. In one hand, the full-scale fire tests are costly and on the other hand, pure numerical simulations on the large scale structures would be afflicted with uncertainty due to existing complexions in some sub-parts of the structure. Hybrid fire simulation counts as a new method, which overcomes the existing limitations and provides the capability to study the performance of structures globally.

Hybrid fire simulation provides the tool to study the global behavior of structures under fire loadings. It couples the numerical simulation representing the whole structure and an experimental test, performed on the parts which will be exposed to fire in a fire test experiment. In this method, the mechanical equilibrium of the global structure will be solved and controlled incrementally by receiving the measured data from the substructure exposed to fire and simultaneously the numerical simulation updates the commands for proceeding the test procedure in a real time. Therefore, the strength degradation and change of material properties in the physical substructure is considered in the mechanical response of the whole structure.

The first idea of combining numerical simulation and physical testing was proposed by Takanashi et al. [1] in 1970s who did the coupling for estimation of seismic behavior of structures referring as “online testing”. This technique then was followed by many researchers in earthquake engineering, represented as “Hybrid testing” [2-5]. However, due to the existence of thermal effects, procedures in fire engineering are different from seismic engineering and there should be some other adjustments that meet the requirements of structural fire design.

Korzen et al. [6] firstly explained the idea of separating the whole structure to sub-parts in structural fire engineering with suggesting a substructuring method. They applied some fire tests with updating thermo-mechanical boundary conditions of the element exposed to fire in interaction with adjacent substructure. This method still didn’t consider the automatic real-time communication between the numerical part and the experimental part of the hybrid simulation. Also, the equilibrium of displacement and forces was only based on the numerical part without taking into account the stiffness of the experimental part.

Mostafaei [7, 8] then aimed at developing a hybrid modeling approach to be used for the analysis of the global structural behavior of a six-storey reinforced concrete building with a compartment fire scenario located on the ground floor. The experimental part of his hybrid model consists of a reinforced concrete column that was tested at full scale inside a furnace and the mechanical and thermal load application was performed in two consecutive steps. Mostafaei’s approach lacked also an automated controlling interface between the two substructures, which is error-prone and excludes reproducibility in any other fire test facility.

Also, the solution evolution neglected an iterative loop to achieve displacement compatibility with the thermal expansion and accumulated an error.

Sauca et al. [9, 10] discussed the drawbacks of previous approach with implementing a new method, which assures displacement compatibility and fulfilling of stability with independency from the stiffness ratio between the substructures.[9]. Major shortcomings of their study is lack of consideration of continuous degradation of the stiffness with continuous increase of temperature due to fire in calculation of stiffness ratio of the substructures. They assumed the stiffness of the physical substructure as an initial elastic tangent stiffness and to remain constant, which is far from the reality of the structural behavior in fire. The stiffness calculation in numerical simulation was also considered as a predetermined elastic matrix.

The alternative phrase “Consolidated Testing” was proposed by Fontana et al. [11] for thermo-mechanical modeling of global structural behavior. In this method, the idea was to test a single element as a part of a whole structure and to apply the results of the global numerical simulation to control the test in real-time. Schulthess et al. [12, 13, 14] developed for the first time the basic requirements for the hybrid fire simulation method in the real time for a benchmark in laboratory scale, which considered an automatic communication for study of mechanical coupling between the fire-exposed substructure and the adjacent sub-parts, but it still lacks a precise study of the thermal coupling in interaction of the two substructures. A precise view to thermal coupling in hybrid fire simulation is required. Therefore, the focus of this paper is on the study of thermal coupling and the effect of heat transfer from the fire-exposed substructure to the adjacent substructures as well as their influence on the mechanical and thermal equilibrium of the global structure at elevated temperatures.

2 THERMAL COUPLING MECHANISM IN HYBRID FIRE SIMULATION

In hybrid fire simulation the global structure is divided into two substructures, which one part is easier to be studied numerically and one other part is complicated or not straightforward for numerical simulation and therefore it is implemented in experimental testing facilities. In the interface between two substructures, the numerical simulation part gives the displacement and temperature to the physical substructure in order to control experimental procedure and on the other hand with obtaining the measured data from the compartment exposed to fire, the procedure and equilibrium equation of the numerical simulation can be controlled in every increment of FE simulation. It is of importance to consider both mechanical coupling and thermal coupling rigorously according to the global structural behavior in fire. For considering the thermal coupling in a realistic way, not only the single element tested in experiment is going to be exposed to direct temperature due to fire test facility, but also the temperature distribution and heat transfer from the physical component to the adjacent substructures have to be considered. Therefore, in the physical substructure the temperature can be increased with a constant rate and then the induced heat and the temperature distribution in the adjacent components may be studied also in each simulation-time increment. So, the heat flux vector at the point of the interface has to be determined and controlled in each increment of simulation to control also temperature compatibility at the interface besides displacement compatibility to be able to control the equilibrium of forces in the global structure. With considering the produced heat flux and temperature distribution in the adjacent substructures, not only the fire-exposed component changes in material property and stiffness, but also the stiffness would reduce in the adjacent components and due to temperature- and time-dependent material properties, expansion, thermal creep and strength degradation occur also in the non-exposed-to-fire components. This phenomenon would affect the stress analysis of the global structure and therefore it has to be controlled in every time increment with the displacement compatibility at the interface to fulfill the stiffness relationship for the whole structure.

In hybrid fire simulation in every increment of the simulation time the transfer of the heat from the physical substructure to the numerical substructure is influencing the stress analysis of the whole structure with affecting the time- and temperature-dependent material properties and stiffness degradation due to temperature. The temperature increase in the component exposed to fire test, can be defined according to a specific protocol, which deduce the temperature distribution in the physical substructure as well as in the interface of sub-parts independently from the mechanical response. Therefore, heat transfer analysis can be considered with two different approaches at the interface of two substructures. These approaches are presented in the following sub-sections.

2.1 Sequentially coupled thermal-stress analysis

In this simplified approach, the distribution of the temperature and heat at the interface of two substructures can be studied primarily for a pure transient heat transfer analysis on the global structure. The heat equation as finite element discretization is as follows:

$$[C]\left\{\dot{T}\right\}+\left[K_{c}\right]\{T\}=\{R_{T}\} \tag{1}$$

Where $[C]$ is the heat capacity matrix, $[K_C]$ is the conductivity matrix, T represents the temperature field and $\{R_T\}$ is the residual thermal vector.

Physical substructure is exposed to a temperature increase with a constant temperature rate for each time increment of the simulation. The constant temperature increase rate for the physical substructure may provide though a nonlinear temperature distribution in the adjacent substructure which can be specified in each time increment of the global numerical simulation. The temperature-time increment history for the numerical substructure can be as an input for the stress analysis of the global structure in hybrid fire simulation to study the mechanical coupling of two substructures consecutively after their thermal coupling. Considering temperature distribution in both substructures will necessarily affect the stiffness relationship and displacement equilibrium of the structure. The important point in a sequentially analysis, is the finite element compatibility in FE simulation of both pure heat transfer analysis and following static analysis.

This simplified approach would avoid the simultaneous study of heat equation and stress analysis, with performing the thermal coupling and mechanical coupling sequentially at the interface of the two substructures. Therefore, this method can be accounted as an intermediate or preliminary step for the next approach, which will be explained.

The advantage of this simplified method is saving calculation time in the transient heat analysis of the numerical simulation of hybrid fire simulation, since the temperature history would be primarily defined in the adjacent substructures and then hybrid fire simulation studies consecutively the global structural behavior according to the predefined thermal coupling from previous analysis. Though in pure heat transfer analysis of the sequentially approach, the target temperature is applied on the physical element itself and not to the gas around it in fire test facility. Therefore, in hybrid fire simulation in sequential stage, the deviations in the temperature increase rate in the furnace of fire test facility for physical element in each increment and the difference of target temperature in the gas in the furnace with the existing temperature of the specimen, may cause an incompatibility for the temperature distribution history in the adjacent substructure regarded to the existing temperature in specimen.

This approach can be applied primarily in a pure numerical hybrid simulation which avoids the existent errors in experiment environment in order to study the effect of thermal coupling in equilibrium of the structure. A schematic overview of the algorithm of the hybrid fire simulation using sequentially coupled analysis is shown is Figure 1.

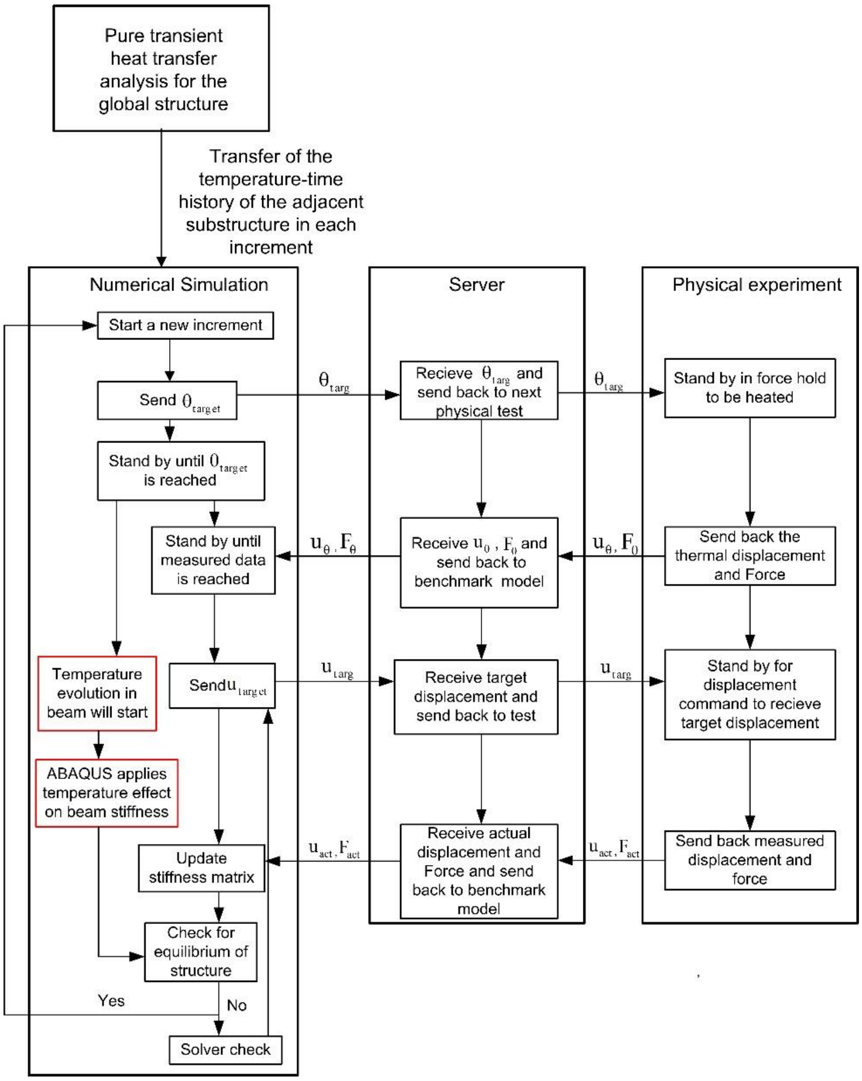

Figure 1: Sequentially coupled algorithm of thermal coupling in hybrid fire simulation

2.2 Fully-coupled thermal stress analysis

In this approach the thermal analysis and stress analysis are studied simultaneously at each time increment, so the temperature distribution at the physical substructure, the numerical substructure and their interface will be studied with the stress analysis simultaneously, which is affected by the change of temperature and time dependent material properties, degradation of stiffness both in physical component and numerical component and also the thermal expansion. The equation of the fully coupled analysis will be as below:

$$\begin{bmatrix} K_{uu} & K_{u\theta} \\ K_{\theta u} & K_{\theta\theta} \end{bmatrix} \cdot \begin{bmatrix} \Delta u \\ \Delta\theta \end{bmatrix} = \begin{bmatrix} R_u \\ R_\theta \end{bmatrix} \quad (2)$$

in which K_{uu} and $K_{\theta\theta}$ are the submatrices regarding displacement and temperature in the coupled Jacobian matrix. $K_{u\theta}$ represents the coupling effect of temperature on the equation of displacements as thermal expansion and $K_{\theta u}$ is submatrix regarding the influence of displacement on thermal response which may be assumed zero. R_u and R_θ are mechanical and thermal residual vectors and Δu and $\Delta\theta$ are displacement and temperature change in each increment time. The algorithm of the fully-coupled thermal stress analysis applied in hybrid fire simulation is shown in Figure 2.

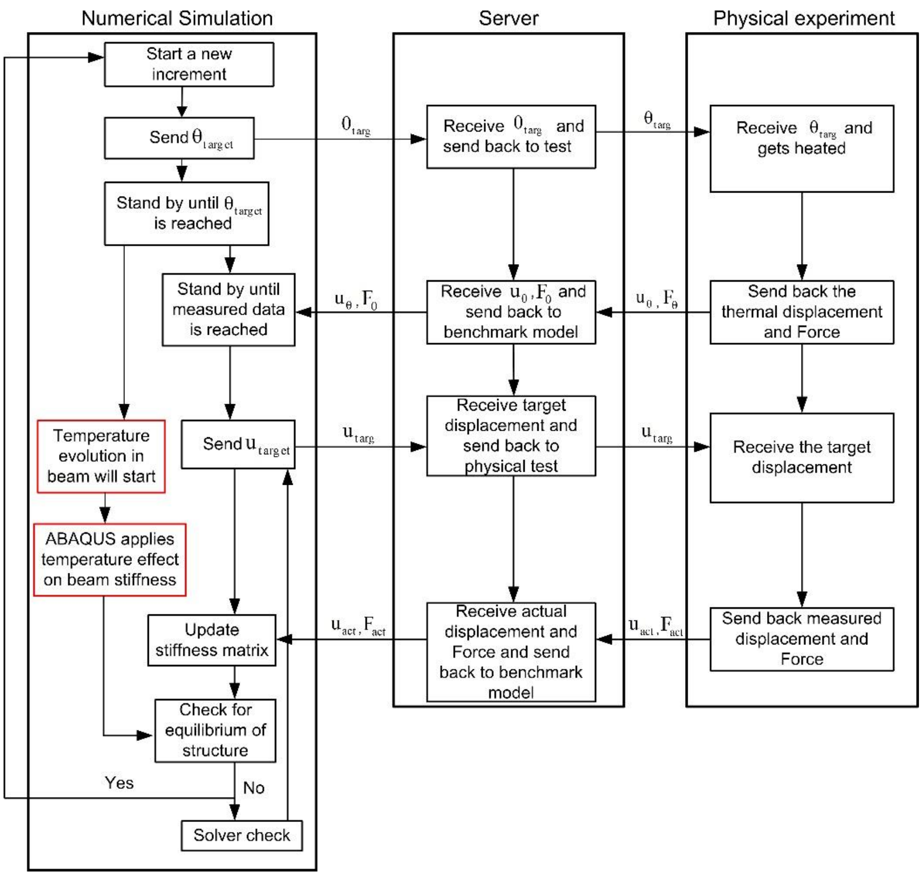

Figure 2: Fully-coupled algorithm of thermal coupling in hybrid fire simulation

In the second approach, in comparison to the simplified approach, the temperature distribution in the whole structure will be applied in the adjacent substructures in the same time of performing the hybrid simulation which is a more rigorous view to thermo-mechanical coupling, so displacement compatibility and the temperature distribution compatibility would be studied in the same time in a fully coupled manner. This would although bring of course more calculation time in the numerical simulation to control the transient fully coupled thermal stress analysis by checking the temperature distribution, the convergence of iterations and fulfilling the equilibrium of forces in each increment. This parameter can affect the real-time issue of the hybrid fire simulation which is a necessity in fire analysis. Calculation time of the numerical simulation in this procedure has to be checked and synchronized with the time which will be needed in experimental set up for reaching to temperature and displacement target in the machine. Therefore, as an intermediate step to hybrid fire simulation the first approach can be utilized to save the calculation time and to simplify the numerical simulation procedure which has to be performed in hybrid analysis.

3. NUMERICAL FRAMEWORK OF HYBRID FIRE SIMULATION

Since the heat transfer study in hybrid fire simulation is a novel topic, different parameters in the numerical simulation and their importance have to be investigated primarily. Therefore, in this paper, both substructures are modeled purely numerical, which they are explained further.

3.1 Thermo-mechanical benchmark problem

To study the method of hybrid fire simulation, it is of great importance to choose an appropriate benchmark problem which can be implemented in laboratory scale and will be provable with pure physical testing.

The benchmark used in this study is referred to the benchmark problem in [12], since a precise study of pure mechanical coupling in the implementation of hybrid fire simulation between numerical simulation and experimental testing were successfully concluded for this benchmark. It consists of a static system for a simply supported beam connected at its mid span through a hinge to a rod (Figure 3a). The rod is the structural element which is supposed to be in a fire test furnace and the temperature increases through it with a predefined specific temperature-time protocol. The beam acts as the adjacent component, which is exposed to the heat transferred from the rod and a nonlinear temperature increase occurs in beam. The whole benchmark is applied to a constant external load P(t) in the mid-span of the beam. Therefore, the internal forces in the rod and supports of the beam are stiffness proportionate. As a first step from time t0 to t1, the load reaches to P(t) and it remains constant for the rest of the procedure (Figure 3b). On the other hand, in the first step temperature is constant at ambient and then a constantly increasing predefined temperature protocol will be applied to the gas in the furnace around the rod. By increasing the temperature at the rod, the internal force in the rod decreases and due to its elongation, there will be a deflection in the mid-span of the beam, which it causes an increase in the reaction forces of the supports of the beam and therefore the equilibrium of the forces with external load will be fulfilled. But later on, with increasing the temperature in the beam, both the stiffness of the beam and rod degrades and the equilibrium of forces have to still be fulfilled and checked. The figure below represents the benchmark problem and loading and temperature protocols.

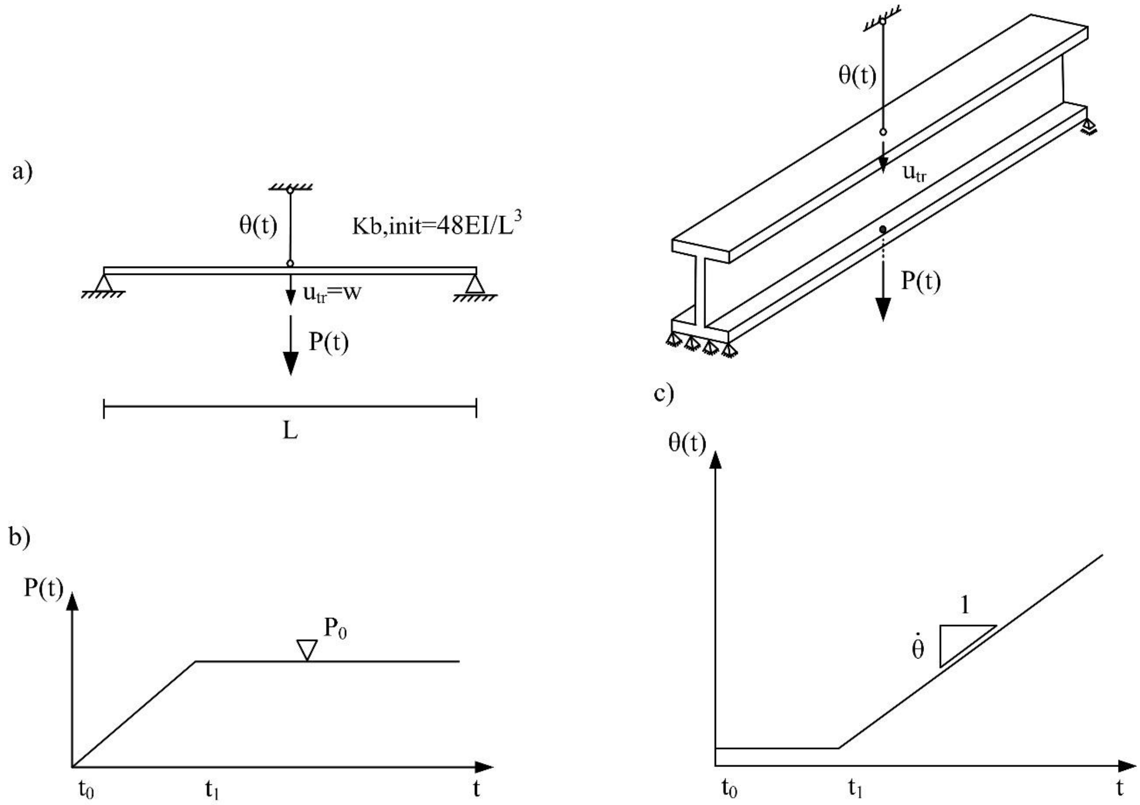

Figure 3: a) Benchmark system; b) Mechanical load application on system; c) Temperature increase history of the rod

3.2 Physical and numerical substructures of the benchmark problem

Both substructures of hybrid fire simulation are modeled numerically in ABAQUS. The first numerical model which is representable for numerical substructure is the global structure of the benchmark. The beam element is modeled with a 3D solid element to be able to assign temperature degrees of freedom in ABAQUS (DC3D8). The dimensions of the global structure are considered according the realistic dimensions for the physical substructure, which will be an experimental specimen e.g. implemented in a furnace in the laboratory scale. The fire-exposed substructure in the global model is a user-defined element (UEL) which its properties are specified. It acquires its properties through an automated interaction with the physical element in the fire compartment. In this study, the physical component is demonstrated also as a numerical model which simulates a dog bone shaped solid model representing the shape of the specimen in the laboratory scale that can be used in the testing equipment for the next step of coupling a numerical simulation with an experimental testing. In this context, the physical substructure model corresponds to a dog bone shaped specimen in laboratory dimensions of 5·10 mm from steel grade S235. These two FEM models have to interact in an automated way with each other with the help of a middle-ware server, which creates communications with two FEM model as a threading network. The physical substructure model is analyzed by a transient fully-coupled thermal-stress analysis and it gives the temperature, thermal expansion and actual force of the specimen in each increment as an output. These measured data have to be transferred to the global model. So in global model the displacement compatibility is checked, and the heat flux vector at the interface point of two substructures is determined according to the temperature of physical substructure and the reference temperature at the adjacent substructure and then the equation of displacement and the equation of heat are solved either with fully coupled analysis or either with static analysis having a predefined temperature history in adjacent substructure as the second step of sequentially coupled analysis, so the iteration convergence in both approaches have to be checked for the equilibrium in each increment.

Requirement of an automated communication interface between two substructures demands the physical component model to be equipped also with four user-defined subroutines to be capable of achieving the temperature, displacement and sending the measured elongation and restoring force respectively. Figure 4 demonstrates the computational implementation of the numerical model representing testing element with the automated server.

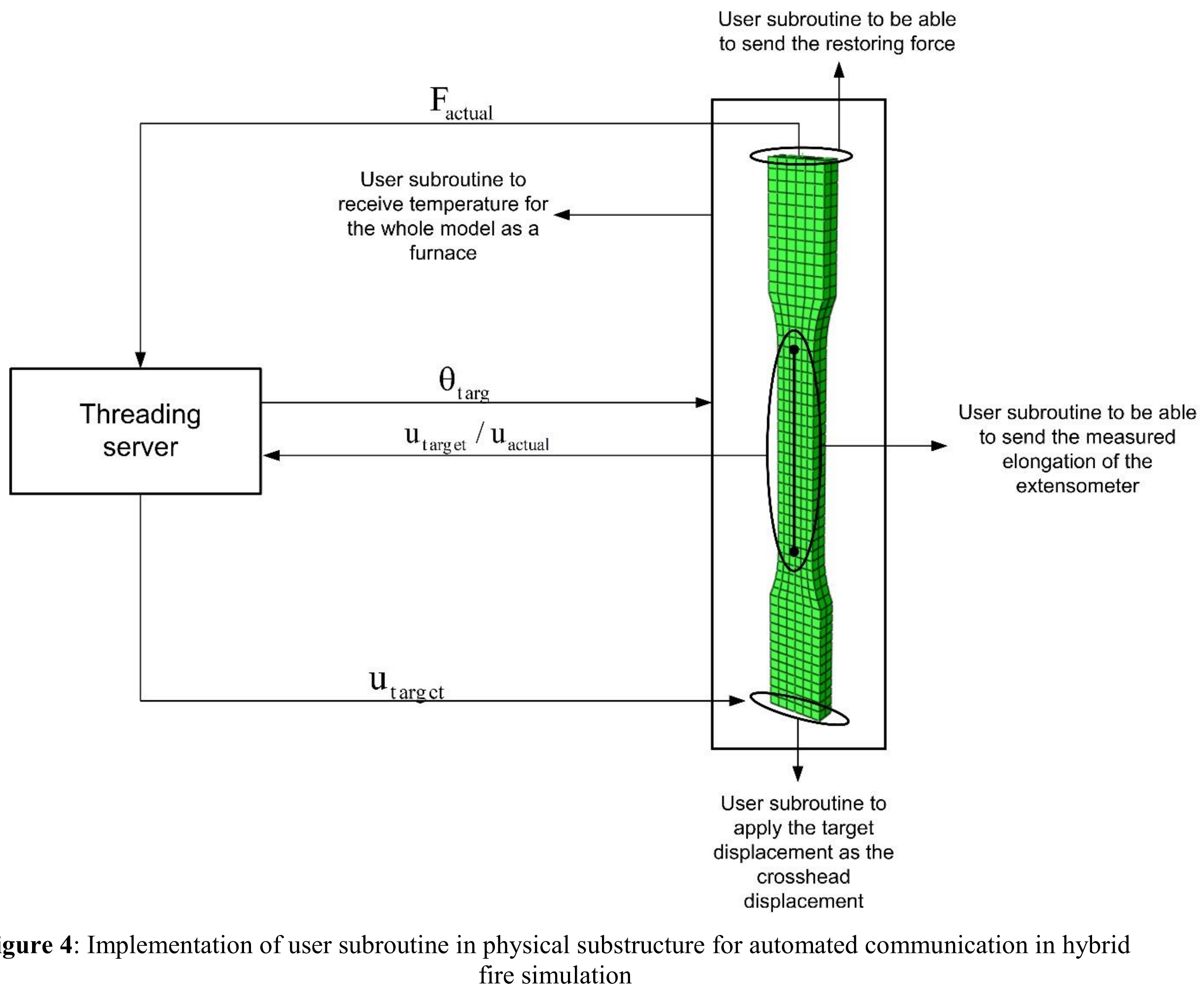

Figure 4: Implementation of user subroutine in physical substructure for automated communication in hybrid fire simulation

3.3 Computational procedure of the solution

To perform a purely numerical hybrid fire simulation with an automated middle-ware server, it is crucial to make the receiving and sending of the measured values at the interface between both substructures compatible and synchronized. Therefore, it is important to apply sending and receiving socket functions in user subroutines of FEM models and server with the property of blocking mode to be able to synchronize the two-way automated communication. When the global model achieves the thermal expansion due to increase of temperature from another numerical model, the solver has to suggest a new target displacement since displacement compatibility will get out of balance at the interface point. The displacement is applied on physical element model as the displacement command in testing machine may be performed and then displacement in the gauge length of specimen model and respecting force have to be sent back to update the stiffness matrix of the fire-exposed user-defined element and check the convergence for the equilibrium of forces. This procedure is iterated until the convergence is fulfilled and a new increment of global model is started. Therefore, the controlling parameter for the automated communication of hybrid fire simulation for two purely numerical models, has to be each iteration of the global model. In other words, each iteration of simulation time of global model can include one or more increment of the simulation time of the physical substructure model.

4 CONCLUSIONS

In this paper a framework for thermo-mechanical coupling of the hybrid fire simulation has been presented which studies the heat transfer and its effect on the behavior of global structure in fire. In particular, the effect of heat flux and temperature distribution in the hybrid fire simulation from fire-exposed experimental component to adjacent substructures for a specified benchmark problem are considered. This consideration provides a more rigorous study of the thermal coupling in hybrid fire simulation.

Two different approaches for thermal coupling are presented as sequentially coupled and fully-coupled analysis and the outcomes applying each method in hybrid fire simulation are discussed.

It is important to investigate the application of this advanced aspect regarding thermal coupling of hybrid fire simulation, in later stages in a coupled numerical simulation-experimental fire test. This accompanies further challenges in adjusting the numerical simulation time increments with physical time scale, especially in the evolution of temperature during the transient analysis and in convergence of the mechanical equilibrium with plastic material properties.

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