Combined Approach for High Temperature Concrete Simulations

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ABSTRACT

In the following paper a combined approach for the analysis of concrete structure under fire is presented. The coupled tool combines computational fluid dynamics (CFD) with structural analysis (FEM). At this first stage the coupling is performed with a one way strategy transferring the results from CFD to FEM. The thermal load on the structure and the water vapor in its surroundings are calculated in the CFD simulation, later these are used as boundary condition for the FEM code. The approach allows to set more realistic boundary conditions for the FEM code, which takes into account the fire scenario with a performance based approach. In order to show the influence of a fire scenario on the response of the structure a simple slab is exposed to fire. Different fires are simulated keeping the same heat release rate peak, but changing the size of the burner and the fire growth rate. The thermal load on the structure and the response of the concrete slab show different behaviors depending on the fire conditions.

INTRODUCTION

In the last decades computation fluid dynamic models have been developed to study the flow field induced by a fire [1-2]. At the same time also finite elements code have been developed for the analysis of concrete structures at high temperature. These two analysis are usually separated since some standard fire curves are used for assessing the mechanical response of the structure. These fire curves are not directly related to the fire scenario, rather they are designed on some experimental benchmark and applied with a prescriptive approach [3]. Therefore it is necessary to develop a new strategy for the structural analysis starting from thermal loads related to the specific fire scenario. For steel structure a coupled approach has been already proposed by Zhang in [4] which use the results coming from the CFD simulation in a thermo-mechanical solver. This approach models the material as pure conductive solid which may be appropriate in case of steel, but it is not sufficient to model the thermal response of porous media [5-6]. For a proper modeling of concrete, heat and mass transfer of gas and moisture must be taken into account as presented in [7]. Two initial attempts to perform a structural analysis basing on real fire scenario have been done in [8-9], but through an uncoupled analysis in the first case and without taking into account the radiation and the mass exchange with the environment in the second work. Due to development of CFD models for fire simulations, a new coupled tool able to consider all the most relevant phenomena involved, is necessary. In this new coupling the fire simulation provides the boundary conditions for both thermal input, convective plus radiative, and moisture exchange. In this manner the structural response is related to the real fire conditions, which leads to a safer design in case the fire condition are more demanding than the prescribed one. On the
other hand it allows to design a lighter and less expensive structure in case the fire condition are much less demanding that the prescribed one.

**FIRE AND FLOW-FIELD MODELLING**

With the development of computational fluid dynamics (CFD) alongside with the rise of the computational power it is possible to perform reliable simulations of fire scenarios. In this research work the code Fire Dynamic Simulator (FDS) is used due to the long term validation work on different cases [10] and its wide use in the engineering practice. In this sections some of the main features of FDS will be presented.

Navier-Stokes equations are solved using the large eddies simulations approach with a second-order accurate finite difference scheme on a Cartesian grid [11]. The first equation is the mass conservation, this has to be fulfilled for every species because of the chemical reaction occurring during the fire. The balance of mass takes into account also the diffusion among the different species and the mass flow generated by sub-grid particles. The second equation is the momentum equation which is written along the three axes. For the model closure the turbulent viscosity is modeled with the Deardorff eddy viscosity model. The last governing equation is the energy equation which takes into account the heat released by the fire and the heat losses through the gases and the structure.

In FDS, the fire produces different gas products and heat, the latter one can be exchanged with the surrounding structure or with the gases in the fluid domain. The heat flux exchanged between the solid and the fluid domain occurs due to radiation and convection. The radiative heat exchange is solved in FDS by solving the radiation transport equation (RTE), with a finite volume method [12].

The radiative heat flux exchanged at the surface is the difference of the incoming and outcoming heat flux:

\[
q_{\text{rad}} = e \int_{S_{w}} I_{w}(S') | s' \cdot n_{w} | d\Omega - e\sigma T_{w}^{4}
\]

Eq. 1

where \( e \) is the surface's emissivity, \( s \) is the Boltzmann constant, \( I \) is the intensity of radiation, \( n \) is the normal vector to the surface, \( s' \) the direction vector of the intensity, \( \Omega \) is the angle of integration and \( T_{w} \) is the wall temperature.

The convective heat transfer is solved with a simplified approach by considering the temperature and the Reynolds number near the surface. The convective heat transfer is calculated as follows:

\[
q_{\text{con}} = h(T_{g} - T_{w})
\]

Eq. 2

where \( h \) is the convective heat transfer and \( T_{g} \) is the gas temperature near the wall, at the first cell. Inside the solid a pure conductive one dimensional model is implemented, the governing equation can be written as follows:

\[
\rho_{s} c_{s} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k_{s} \frac{\partial T}{\partial x} \right) + q_{\text{reac}}
\]

Eq. 3

where \( \rho_{s} \) is the solid density, \( c_{s} \) is the specific heat of the solid, \( k_{s} \) is the conductivity of the solid and \( q_{\text{reac}} \) is the heat generated inside the solid.
CONCRETE MODELLING

The structural analysis are carried out with an in house built FEM code, Comes-HTC, which has been specifically developed for the analysis of concrete structure at high temperature. The mathematical model used for the analysis of concrete behavior in fire conditions is described in detail in [7,13-15]. Here, for the reader convenience, a brief summary of its main features is presented. Concrete is modeled as a multi-phase porous material. Pores are filled partly with liquid water and partly with a gas phase. The liquid phase consists of bound water, which is present in the whole range of moisture content and temperature, and capillary water which appears at temperatures below the critical point of water. The gas phase is an ideal mixture of dry air and water vapor. The model considers the physic-mechanical interactions between phases, the exchange of mass, energy and linear momentum between phases and their components, the most important chemical reactions (e.g. dehydration), thermo-chemical and thermo-mechanical degradation processes that can take place in concrete under such severe conditions, various mass and energy transport mechanisms (among others: convection, advection diffusion on different forms, etc.).

The primary variables of the model are: gas pressure $p_g$, capillary pressure $p_c$, temperature $T$, displacement vector of the solid matrix $u$. The mathematical model consists of seven equations: two mass balances (continuity equations), enthalpy (energy) balance, linear momentum balance (mechanical equilibrium equation –written in terms of the effective stresses tensor) and three evolution equations (for the process of dehydration, thermo-chemical damage and mechanical damage). The governing equations of the model are discretized in space by means of the finite element method and the time discretization is accomplished through a fully implicit finite difference scheme.

COUPLING STRATEGY

In order to evaluate the response of a structure in case of fire it is necessary to use both tools that have been presented earlier. In this coupled approach the results from the fire simulation are used as boundary condition for the structure with a one way coupling strategy, without transferring back the structural results to the CFD. This approach may have some limits in some cases since it assumes that the wall modeling has no influence on the fluid domain, but it is considered to be sufficient as first attempt.

Comes-HTC code needs a set of boundary conditions to simulate the concrete behavior at high temperature, the thermal load, the moisture content near the wall and the gas pressure. The thermal load applied to the structure is imposed using a Robin boundary condition. The incident heat flux, radiative plus convective, evaluated in FDS is imposed on the surface, while outcoming flux is calculated basing on the wall temperature evaluated Comes-HTC.

$$ q_v = q_{FDS,in} - q_{HTC, out} = q_{FDS,in} - \left( e \sigma T_{w,HTC}^4 + h T_{w,HTC} \right) $$

Eq. 4

where $q_{FDS,in}$ is the incident flux on the surface, $h$ is the convective heat transfer coefficient and $T_{w,HTC}$ is the wall temperature. The heat flux in FDS is calculated by means of the adiabatic surface temperature AST. This approach has been already proposed by Wickström in [16] since it releases the calculation from the wall temperature calculated in FDS. To compute the incident
heat flux, convective and radiative, also the convective heat transfer coefficient is calculated in FDS, while the emissivity has to be the same in the two codes.

The second boundary condition is the water vapor content near the wall, where the Robin boundary condition is imposed as well. The water mass flow is calculated starting from the density of the water vapor at the first cell near the wall and on the wall's surface. The density near the wall is evaluated in FDS while the density on the wall is calculated in the Comes-HTC code. The mass flow balance can be written as follows:

\[
\dot{m}_w = \beta (\rho_{g,W} - \rho_{w,W}) \tag{Eq. 5}
\]

where \( \rho_{g,W} \) and \( \rho_{w,W} \) are the densities of the water vapor in the gas and on the wall and \( \beta \) is the mass transfer coefficient calculated basing on the convective heat transfer coefficient. The pressure boundary condition is imposed as constant value on the whole structure, because in case of fire without explosions the pressure shows small fluctuations. With this approach it is possible to impose on the structure boundary conditions that are non constant on the surface and which are related to the specific fire scenario.

An important issue related with the data transfer from FDS to Comes-HTC is the difference between the geometries used in the two programs. FDS employs a Cartesian grid which does not allow to draw rounded surfaces while Comes-HTC use a common structured grid. This problem has been already tackled by Silva [17] combining the adiabatic surface temperature together. However in this new coupling the incoming heat fluxes are combined together in order to preserve the total heat flux coming form FDS and transferred to Comes-HTC:

\[
\sum q_{fds} \cdot A_{fds} = \sum q_{fem} \cdot A_{fem} \tag{Eq. 6}
\]

The heat flux evaluated at one node in Comes-HTC must be calculated starting from the fluxes in the surrounding elements of FDS. The elements in FDS are chosen in order to give a local information on the fluxes, but also to approximate the geometry of the structural element. To reproduce the incoming flux on a sloped geometry different Cartesian elements must be combined together in order to rebuild the geometry's orientation. Different number of element can be chosen in FDS, at the limit for a local information just one element is required, but to reproduce correctly a sloped geometry an infinite number of elements is required. The orientation of the node in Comes-HTC can be approximated to some reference angles in order to use a small number of elements from FDS. A set of angle, 0°, ±30°, ±45°, ±60° and ±90°, has been selected in order to use maximum three elements from FDS to rebuild the orientation of the FEM node. This approximation allows to impose a smooth distribution of heat fluxes on a rounded surface starting from the Cartesian geometry of FDS. It important to stress that this approach is theoretically correct only for radiative heat flux. For convective heat flux the different components of the velocity which may affect the heat transfer coefficient can introduce some approximations. These have been considered acceptable since for fire problems the radiative component is the main one in the heat exchange process [18].

**THERMO-STRUCTURAL ANALYSIS WITH A PERFORMANCE BASES APPROACH**

In the following section the above-mentioned tool is applied to a simple case in order to show the importance of a coupled approach for structural analysis. In many practical applications the maximum HRR is the only information available about fire. This may not be sufficient to
understand the interaction between the fire and the structure, since many other factors affect the structure response. Using a test case with a fixed maximum heat release rate (HRR) it is possible to understand the effect of different fire scenarios on the response of the structure. The case deals with a simple two dimensional burner heating a concrete slab for 900 s, where the burner is 1.2 m wide and it is placed 1.8 m beneath the slab. Due to its well know properties n-heptane fuel is used generating a power of 600 kW/m. The slab is 2 m long and 0.2 m thick and it is made of concrete, whose properties in FDS are set as prescribed by the Eurocode. [19]

Mesh independence

Since there is no experimental data for this particular case just a grid sensitivity analysis is carried out in order to evaluate the effect of the mesh in the FDS simulations. The mesh has a regular shape and four different element's sizes are tested: 20 cm, 10 cm, 6.67 cm, 5 cm. In order to easily compare the results from different mesh in steady state conditions the HRR is set as constant at the maximum value since the beginning of the simulation. The results for the gas temperature and the temperature on the slab surface are presented in figures 1 and 2. The comparison of the results shows that the third mesh provides results in good agreement with the fourth one, therefore it will be used for the later calculations.

Effect of the flame shape

In order to keep the same HRR, but changing the flame shape and the incident fluxes on the slab it is necessary to modify the size of the burner. The original burner size used for the mesh independence study is 1.2 m wide, now two other burner geometries are analyzed, a burner 0.4 m wide and one 2.0 m wide. In this comparison the fire curve is growing linearly from 0 to 600 kW/m in 450 s while in the second burning phase it is constant at 600 kW/m, the whole simulation time is 900 s.

The gas temperature profiles along the centerline of the fire are compared in figure 3 for the steady state burning phase showing also the original case. As expected reducing burner's size, the fuel flow rate per unit of area increases and the flame is stretched towards the slab. The two burners produce the same power in terms of HRR, but the thermal power dissipated through the
wall are quite different, figure 4. The effect of the different thermal load on the slab can be depicted also comparing the wall temperature on the surface of the slab above the fire centerline, figure 4. The wall temperatures show two diverging trends for the two burner confirming what has been found comparing the heat fluxes.

In order to evaluate the effect of the fire scenario on the slab the total damage [7], mechanical plus thermochemical, is compared in the two cases along the centerline of the slab as function of time and depth, as proposed in [20]. The total damage represents the material strength loss and it can be calculated as:

\[
D_{tot} = 1 - \frac{E}{E_0} = 1 - (1 - d)(1 - V)
\]

Eq. 7

where \(D_{tot}\) is the total damage, \(E\) is the Young's modulus, \(E_0\) is the Young's modulus for undamaged conditions, \(d\) is the mechanical damage and \(V\) is the thermochemical damage.

The damage as well influence the intrinsic permeability of the material [21]. As seen in figure 5, the damage in the two cases has a similar time history, but in case of narrow burner the values are generally higher, so the material is more degraded. A second parameter investigated with the same strategy is the gas pressure inside the material, figure 6, the gas pressure is related to spalling risk since an increase of pressure tends to open the cracks in the material [22-23]. The gas pressure is due to the pressure of the moisture in the pores of the material and due to the dry air pressure. When the temperature rises and the liquid water evaporates, an additional amount of moisture is produced with a subsequent increase of pore pressure which poses the material under tensile stress. The pressure distribution shows a stronger load in case of the narrow burner and the maximum value is higher if compared to the other case, leading to a greater risk of spalling. Besides the effect of the gas pressure also the stress in the material depicts the risk of spalling. In figure 7 the normal stresses along the X and Y axes are shown along the centerline of the slab. For sake of simplicity the stresses are presented only at 900 s, since the damage and the gas pressure are maximum under these conditions. The stress along the X axis is normal to the slab's centerline, while the stress along the Y axis is parallel to the slab's centerline. Near the surface a portion of material is subject to buckling because there is a compression stress in the X direction.
while a traction stress in the Y direction. This tensile stress summed to the effect of the gas pressure is considered to be one of the driving factors leading to spalling [23].

In the pictures the stresses have a similar pattern, but compressive stress is greater near the surface for the slab heated by the narrow burner. The tensile stress in the Y direction is greater on the surface for the slab heated by the wide burner. But in the slab heated by the narrow flame a larger portion of material is subject to traction and the stress peak is located in the inner part of the structure. It is important to stress that for a simple slab non heated by fire the lower part of the section is under traction stress instead of compression in the X direction. But in case of

Figure 5: Total damage distribution along the centerline of the slab at different time steps.

Figure 6: Gas pressure distribution [Bar] along the centerline of the slab at different time steps.
heated slab the material deformations due to temperature modify the stress distributions which expose part of the structure to buckling.

Effect of the fire growth rate

The rate of fire growth is another important parameter that usually is not taken into account or maybe not known when the fire simulation is performed. The maximum value of the HRR is not sufficient to describe the fire scenario and this has important consequences also on the thermal loads impinging the structure. In order to highlight this effect two opposite fire simulations are compared. The burner size in this case is equal to the reference case 1.2 m wide, but in one case the HRR is imposed as constant at 600 kW/m while in the other it grows linearly from 0 to 600 kW/m in 900 s.

Figure 7: Stress along the centerline of the slab as function of the position.

Figure 8: Heat fluxes (FDS) and wall temperature (Comes-HTC) on the slab above the fire centerline.

Figure 9: Total damage distribution along the centerline of the slab at different time steps.
The heat flux exchanged through the slab above the fire centerline is presented in order to see the
different thermal load in the two cases, figure 8. The net heat flux in case of a fast burning rate is
always higher than the other case and it has a peak in the initial phase. The initial phase is
critical since the maximum heat flux is exchanged due to the maximum difference of temperature
between fire and slab's surface. As consequence the wall temperature increase with different
rates, figure 8. The fast rate curve is really steep in the first burning phase and later the slope
decreases while the slow rate curve has an increasing slope during the fire.
The consequences for the structure can be evaluated as done before comparing the damage
distribution and the gas pressure distribution along the slab's centerline. As expected the damage
is smaller when the fire grows slower and the increase of the damage is delayed in the whole
section, figure 9. Similarly also the gas pressure can be compared in the two cases, figure 10, and
it shows a much higher peak for the fast rate fire compared to the slow rate one. The stresses
along the X and Y axes are presented as well to depict the risk of buckling on the portion of slab
exposed to fire. The stresses are shown in figure 11 along the centerline of the slab. The
compressive stress along the X direction are similar in the two cases: for the fast heated slab, a
greater portion of the structural element is subject to compressive stress, while the peaks close to
the surface are really similar. The traction stress in the Y direction is greater on the surface for the
slowly heated slab, but as seen before, in case of more severe heating the peak is deeper in the
material. Therefore as expected a greater portion of material is subject to spalling in case of fast
heating rate considering also the greater magnitude of the gas pressure.

![Figure 10: Gas pressure distribution [Bar] along the centerline of the slab at different time steps.](image)

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greater portion of the structural element is subject to compressive stress, while the peaks close to the surface are really similar. The traction stress in the Y direction is greater on the surface for the slowly heated slab, but as seen before, in case of more severe heating the peak is deeper in the material. Therefore as expected a greater portion of material is subject to spalling in case of fast heating rate considering also the greater magnitude of the gas pressure.

CONCLUSIONS

In this paper a coupled tool for the analysis of concrete structures exposed to fire has been presented. The coupling strategy exploits the CFD capabilities to predict the flow field in the fire region and the thermal loads on the structure while a FEM code based on Multiphase Porous Media Mechanics is employed to evaluate the response of the structure. The code Fire Dynamic Simulator (FDS) is used to simulate the fire while the code Comes-HTC is used to simulate the concrete behavior. The coupled tool is then applied to a fairly simple case in order to highlight the importance of the fire scenario for the simulation of the structure response. A slab exposed to fire is simulated using the same HRR peak, but changing some features of the fire scenario. First, the size of the burner is changed keeping the same fire curve. Due to the different flame shape the heat fluxes on the wall can be more concentrated or distributed on the slab. If the thermal load is more concentrated the gas pressure and the damage of the material are higher in the slab. Therefore the impingement of the flame is important since it strongly affect the portion of the heat that is exchanged among the flame and the structure.

Secondly the burner's size is set back to the original size and the fire curve is changed. In one case the fire curve is constant at the maximum value while in the second case it increases linearly from zero to the maximum along all the simulations. Different fire curves obviously affect the energy released by the fire and which can be absorbed by the structure. If the fire grows fast in the initial stages, the heat exchange is enhanced because of the temperature difference between fire and structure. The peak of heat flux in the early stages of the fire lead to a steep rise of gas pressure and temperature in the material.

From the previous discussion it is clear that a coupled tool is necessary to perform a reliable and realistic analysis of concrete structure in case of fire. The CFD alone is capable to analyze the flow field induced by the fire, but the embedded thermal models are not sufficient to analyses properly the response of the concrete structure. On the other hand the structural analysis can not
be reliable if non-realistic boundary conditions are imposed. The boundary condition can be set only after a fire simulation which takes into account the real fire scenario.

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REFERENCES


