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Thermomechanical Modelling of a Blast Furnace Hearth

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Abstract

The goal of this work is to develop a thermo-mechanical model of a blast furnace hearth able to estimate the stress state in service. To identify the behaviour of bricks, mortars and ramming mix, characterization tests have been developed for temperatures up to 1500°C. A modified Cam-clay model is identified for the ramming mix. The masonry modelling is based on a macroscopic approach where bricks and mortars are replaced by a set of equivalent homogeneous materials accounting for the different joint states (open or closed). The non linearity of the behaviour is reproduced thanks to a stress criterion, allowing the transition from one state to another. The final modelling of a hearth is compared with in-situ instrumentation results.

1. Introduction

The blast furnace (BF) hearth is the most critical part within the whole integrated steel plant. Whatever are the improvements of the last decades, it becomes more and more necessary to quantify the impact of materials or shape changes in terms of stress fields in the structure to be able to validate an evolution before the starting of the design task. This goal requires a validated method to build a predictive thermo mechanical model of a BF hearth. The method developed herein proposed the replacement of the ceramic cup masonry by an equivalent homogenized continuous medium and the use of a non-linear law to reproduce the ramming mix behaviour. The parameters of these models were all identified thanks to specific tests up to 1500°C. These behaviour laws were then validated before being implemented in the final BF hearth model. Then, the modelling of a hearth is compared with in-situ instrumentation results.

2. The blast furnace hearth

The blast furnace hearth is mainly composed of refractory materials that support strong thermo-chemo-mechanical loads. Indeed, there is a direct contact between its internal walls and the molten pig iron at 1500°C. As shown on **Fig. 1**, the hearth is divided into five parts which must be modelled: a steel shell, a carbon ramming mix layer,

carbon blocks and two kinds of jointed masonries called the bottom and the ceramic cup.

Although the temperature distribution has been for a long time the only important result to compute^(1,2,3), thermomechanical models for the BF hearth progressively appeared^(4,5). These ones have shown the main efforts which must be made in order to build a model closer to reality:

- The temperature-dependent behaviour of bricks and mortars must be known up to 1500°C;
- An accurate modelling of the ramming mix is essential in order to reproduce its hardening behaviour under compaction;
- The effect of joints in masonries must be taken into account.

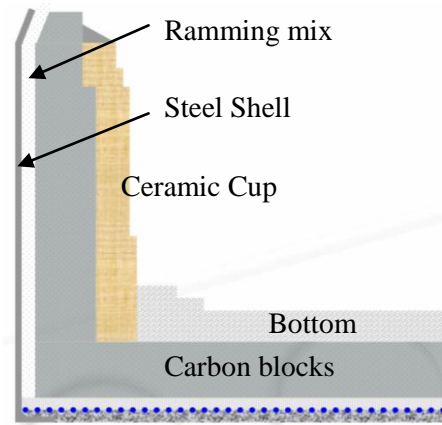


Fig. 1: Constituents of the hearth.

3. Modified Cam-Clay model for ramming mix

The ramming mix is a porous material with voids filled with air and hydrocarbon binder. That is why during a compaction step, plastic deformations appear leading to volume changes and increasing stiffness. Moreover, when submitted to shearing conditions, the material can reach a critical state in which shearing occurs without any changes in stress and volume. Both behaviours under shear and compression loads will be simply reproduced thanks to the “modified Cam-Clay model” which is an extension of the theory developed for geotechnical materials⁽⁶⁾.

This model is composed of non-linear elastic and plastic behaviours. The inelastic behaviour is activated when the yield function is reached. A

strain hardening theory allows the size of the yield surface to change according to the inelastic volumetric strain. The plastic strain rate is defined by an associated flow assumption. A constant which can modify the shape of the cap is used to take into account the influence of the temperature on the hardening behaviour⁽⁷⁾.

An instrumented floating die compaction test was developed to identify the parameters of the hardening behaviour and their evolution with temperature. Triaxial tests were carried out to determine the parameter M which defines the critical state in shearing. In these tests, the ramming mix sample is a cylinder submitted to an increasing axial stress. The radial stress applied is kept constant in the triaxial test although it increases in the die compaction test. Accounting for the loads applied on the ramming mix in the BF hearth, these tests were done for temperatures lower than 80°C and velocities lower than 1 mm/min. The details on these tests, on the model and the parameter identification method are described in reference (7).

In order to validate the implementation of the temperature effect and the identified parameters, a die compaction test with variable temperature has been performed⁽⁷⁾. As shown on **Fig. 2**, it confirms the faculty of this model to reproduce the behaviour of the ramming mix under complex thermomechanical loading.

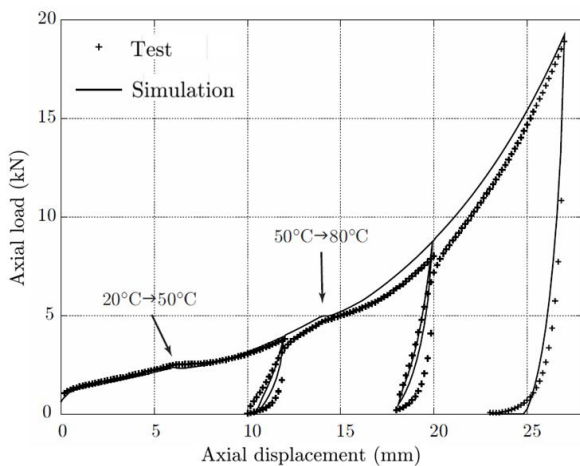


Fig. 2: Die compaction test at variable temperature.

3. Masonry modelling

Considering the high number of joints in the masonries of the BF hearth, a micro-macro approach with homogenization method was developed. It allows replacing bricks and mortars by an equivalent homogenous material. Due to the

periodicity of the studied masonries (bottom and ceramic cup), a periodic homogenization method is applied⁽⁸⁾. The periodic elementary cell is composed of two components: the brick and the mortar. Both materials are assumed to follow an isotropic linear elastic behaviour. Moreover, cracks occur most of the time at the unit-mortar interface because it is the weakest link of the assembly⁽⁹⁾. This observation leads to the development of a homogeneous equivalent material with a behaviour depending on the “joint state”: sound or broken^(10,11,12,13). Working on a periodic elementary cell with head and bed joints, 4 states can be reached according to the joint openings. These different local states are illustrated on **Fig. 3**. For each one of them, an Equivalent Homogeneous Material (EHM with orthotropic elasticity) is identified.

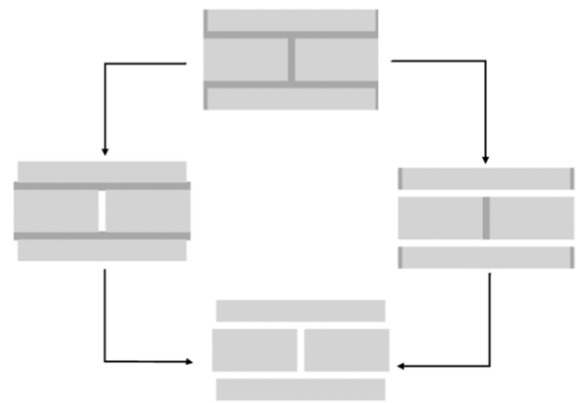


Fig. 3: Macroscopic joint state model.

Moreover, as illustrated on **Fig. 3**, a criterion has to be defined to pass from one state to another one. In this work, a macroscopic stress criterion is used. **Fig. 4** summarizes the criterion at the local scale: it is the combination of a 3D extension of the Mohr-Coulomb line with a Rankine tensile cut-off. To deduce the macroscopic criterion from local data, many numerical tests on a representative elementary volume were performed¹³. Before this, the cohesion c , the friction angle ϕ and the tensile ultimate strength f_t of the brick / mortar interfaces have been identified. To obtain these data, tensile tests and slant shear tests have been performed on couples made of bricks and mortar. Experimental details and results for this campaign are presented in reference (14).

To obtain the Young’s modulus for bricks and mortars, compressive tests at high temperature on cylindrical samples have been realized. A slight decrease of the Young’s modulus with temperature was observed. Moreover, the Young modulus of bricks was identified ten times stiffer than the

mortars' one¹³. These results clearly show temperature influence and mortar role which leads to a softer behaviour for the masonry.

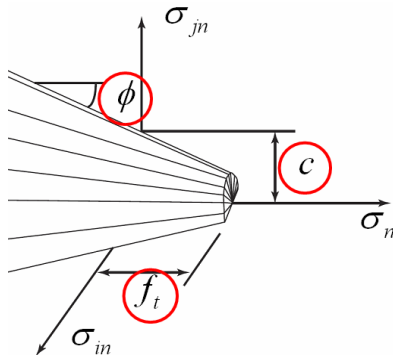


Fig. 4: Yield surface for the mortar behaviour.

3. BF hearth simulation

The ramming mix and masonry behaviours have been used in the axisymmetric BF hearth modelling. For the bottom and the ceramic cup, equivalent homogeneous materials associated with the different states of the joints were identified at 20°C, 900°C and 1450°C, thanks to a large experimental campaign¹³. The masonry behaviour evolves as a function of the temperature and joint opening states. The decoupled thermomechanical modelling of the BF hearth was divided into two steps. The thermal computation is first achieved, defining the thermal field which is then applied as a load for the mechanical computation. Results of simulations are compared with in-situ measurements.

Thermal computation

The BF hearth is submitted to high thermal exchanges. They are due to the cooling systems in the external part and to the molten pig iron in the internal part. From these loads, the thermal field presented on **Fig. 5** is computed.

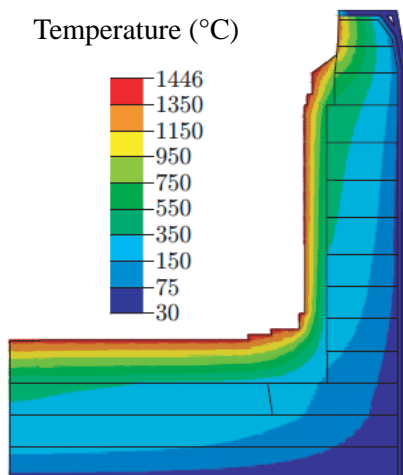


Fig. 5: Thermal field in the BF hearth.

In order to validate the temperature profile, numerical results were compared to values given by thermocouples located in the carbon blocks around the ceramic cup and below the bottom. A good agreement is reached between measured and computed temperatures¹⁵.

Mechanical computation

For the mechanical computation, the ramming mix and the masonries are modelled with the behaviour laws previously described. Moreover a linear elasticity with temperature dependence is considered for the carbon blocks. Between these blocks, contact conditions (friction for the tangential behaviour and no penetration condition for the normal behaviour) are defined. The BF hearth is submitted to the computed thermal field, gravity, gas and pig iron pressures. In order to check the improvements due to the developed constitutive equations for the ramming mix and the masonries, four different cases have been computed. They differ from the masonry model (with or without possible joint openings) and the initial relative density (RD) of the ramming mix in the BF hearth (80% or 92%).

For each model, the evolution of the von Mises stresses in regard to the steel shell height is plotted on **Fig. 6**.

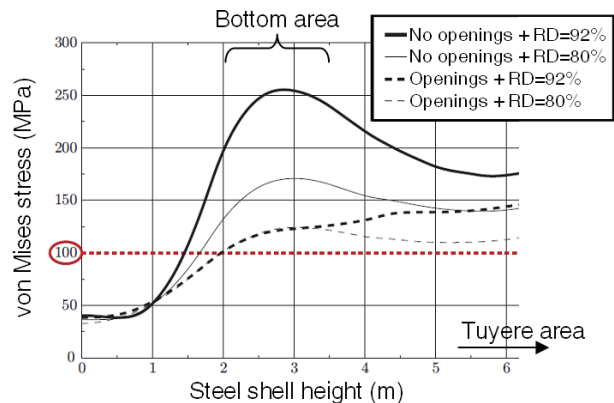


Fig. 6: Comparison of the von Mises stresses computed on the steel shell provided by four models.

Studying the stresses in the steel shell which is the external part of the hearth allows quantifying the influence of the different refinements of the model. Thanks to the ramming mix model, it is possible to quantify the impact of the initial state. In fact, the more the ramming mix is initially compacted, the less it can absorb thermal expansion of refractory blocks. In that case, a higher stress is computed in the steel shell. The effect of joint openings in masonries is clearly shown thanks to the stress

softening which occurs. Moreover, the result obtained with “Openings + RD=80%” (close to the in-situ situations) is closer to reality. Indeed, 100 MPa is the highest authorized stress in the steel shell.

Conclusion

The modelling of a complete complex structure such as a BF hearth requires a rigorous framework, including behaviour modelling development, numerical implementation, dedicated experimental set up development that account for the model parameters to be identified. These 3 years works between Laboratory PRISME and Saint-Gobain have produced interesting experimental techniques and numerical tools.

The characterization work mainly concerns the ramming mix and the masonries for which specific tests were carried out. From these, the parameters of new behaviour laws adapted to high temperature structures and materials were identified:

- a Cap model for the ramming mix which allows to reproduce the hardening behaviour in compaction and the temperature influence.
- a joint state model based on homogenization technique for the masonries. Stress softening due to temperature increase and joint openings are taken into account.

Finally the implementation of these models in the BF hearth modelling gave results close to reality. Nevertheless, improvements in the masonry modelling are still needed to account for brick crushing for example.

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