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Latest Evolution in Blast Furnace Hearth thermo-Mechanical Stress Modelling

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Abstract

Saint-Gobain has a long experience in the design and supply of blast furnace hearth linings. The Blast Furnace Hearth is arguably the most critical part within the whole integrated steel plant when considering overall potential profit/loss. Typical wear lines found in the BF hearth match closely with the areas subject to highest Thermo-Mechanical stresses. There is clear interest in being able to estimate the thermo-mechanical stresses experienced between different designs. Thanks to FEM tools, SG has a means of evaluating these stresses in the hearth and in order to complete their expertise, they have launched an ambitious program of material modelling and characterization aimed at designing a model as close to reality as possible. The last developments include:

- The identification of the mortar joint behaviour as a function of temperature. For that purpose, new compressive tests at high temperature have been developed;
- A modelling method with Equivalent Homogeneous Materials for pad as well as walls has been used. This calculation method makes it possible to take into account the behaviour of the very soft and numerous joints. As a consequence, the hearth stiffness is globally reduced;
- A precise and appropriate identification of the ramming mix behaviour through a Cap model, defining hardening behaviour in compression. Accounting for this specific behaviour is a key point considering its strain absorbing role due to lining expansion.

At the same time efforts are being made to register actual stresses found in the BF hearth. With the results from the improved model calculation and better knowledge of the actual stresses which are experienced, we will be better placed to make advances in the correct direction regarding design considerations.

Introduction

The BF Hearth is the most critical part within the whole integrated steel plant. A major incident with the hearth impacts all downstream activity resulting in serious loss. In some cases, such an episode can endanger overall viability of the whole site. When long, stable BF operation is achieved optimum operating conditions can be maintained throughout the process; efficiency and profitability can be maximised.

Problems above tuyere level can often be resolved with minimal disturbance, but not hearth problems. With Savoie/Saint-Gobain BF design and supply experience, the importance of the hearth was recognised, a major R&D programme (still ongoing) commenced and the first "Ceramic Cup" technology was pioneered in 1984.

Major improvements were also made in carbon quality around the same time resulting in finer pored structures (minimising metal penetration) and additions of ceramics (to improve erosion resistance). The graphite approach had limited success but the importance of freezing a protection layer on the carbon hot-face was recognised leading to further carbon quality changes (higher conductivity) and a reassessment of optimum wall thickness.

Even if all these improvements have been shown, it becomes more and more necessary to quantify their impact in terms of stress fields in the structure. It is in fact essential to bring the guarantee that new proposed materials and designs still allow to support the thermomechanical stresses in the BF hearth. In order to meet these requirements, Saint-Gobain has developed a thermomechanical model for the BF hearth.

This paper will summarise the specific behaviour laws implemented for the ramming mix and the masonries. The parameters of these models were all identified thanks to specific tests up to 1500°C. These behaviour laws were then validated and implemented in the final BF hearth model. The modelling of a hearth is compared with in-situ

instrumentation results. A good agreement is reached between these results.

The BF hearth

The blast furnace hearth is mainly composed of refractory materials to support strong thermo-mechanical loads. Indeed, there is a direct contact between its internal walls and the molten pig iron at 1500°C. As shown on figure 1, the hearth is divided into five parts which must be accurately modelled: a steel shell, a carbon ramming mix layer, carbon blocks and two kinds of masonries (bricks with mortar joints) called the bottom and the ceramic cup.

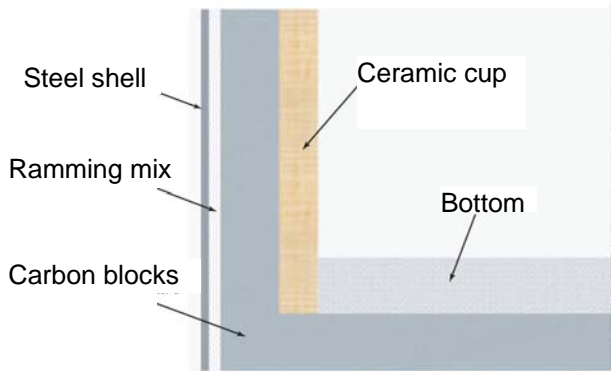


Figure 1: Constituents of the hearth.

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

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

These three parts were studied by Saint-Gobain to build this new BF hearth model.

The ramming mix

A particular attention was paid to the modelling of the ramming mix whose hardening behaviour allows absorbing the thermal expansion of refractory bricks and so protecting the steel shell. This material is porous with voids filled with fluids (air, hydrocarbon binder). That is why during a compaction step, plastic deformations appear leading to volume changes and increasing stiffness. For this kind of materials, a cap plasticity model seems to be the best way to take into account the hardening behaviour [6]. Moreover, when submitted to shearing conditions, the material can reach a critical state in which shearing occurs without any changes in stress or volume. Both behaviours under shear and compression loads will be simply

reproduced thanks to the “modified Cam-Clay” material model of ABAQUS finite element software [7]. This model is an extension of the theory developed by Roscoe [8] for geotechnical materials.

The modified Cam-Clay model

This model is composed of non-linear elastic and plastic behaviours. The inelastic behaviour is activated when the yield function F_{CCM} 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.

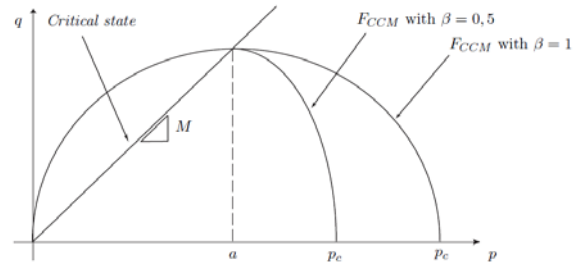


Figure 2: Modified Cam-Clay model.

The model (figure 2) is based on the following yield surface:

$$F_{CCM} = \frac{1}{\beta^2} \left(\frac{p}{a} - 1 \right)^2 + \left(\frac{q}{Ma} \right)^2 - 1 = 0$$

where

$p = -\frac{1}{3} \text{trace } \underline{\underline{\sigma}}$ is the equivalent pressure stress;

$q = \sqrt{\frac{3}{2} \underline{\underline{s}} : \underline{\underline{s}}}$ is the Mises equivalent stress;

$\underline{\underline{s}}$ is the deviatoric stress;

M is a constant that defines the slope of the critical state line;

a is the size of the yield surface;

p_c is the yield stress in hydrostatic compression;

β is a constant which can modify the shape of the cap. The parameter is used to take into account the influence of temperature on the hardening behaviour.

When this surface is reached for values of q upper than the product Mp , the material has a softening behaviour. In the other case, a hardening behaviour is defined.

As shown on figure 3, the hardening law is written in the $(e, \ln(p))$ plane, where e is the void ratio of the

material. For a sample of mass m , volume V and real density ρ_r , the void ratio is calculated as:

$$e = \frac{\rho_r V}{m} - 1$$

Linear relations for the elastic and inelastic parts are described.

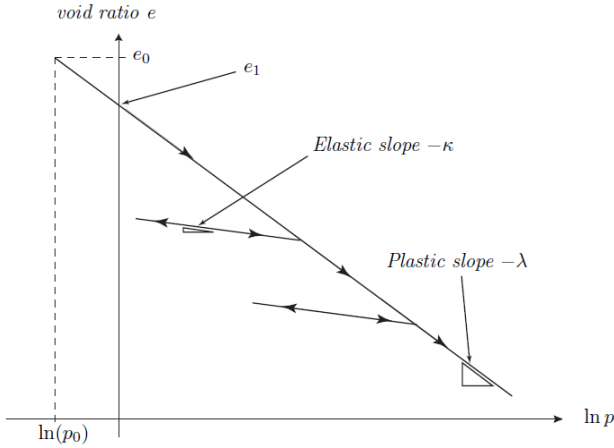


Figure 3: Hardening behaviour.

The different parameters of the hardening behaviour are:

- κ the logarithmic bulk modulus for the elastic behaviour;
- λ the logarithmic hardening constant for the plasticity;
- e_1 the void ratio for a hydrostatic pressure of 1 MPa;
- e_0 and p_0 the initial conditions of consolidation of the material.

Parameters identification

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 and the parameters identification method are described in [9]. The identified parameters of the modified Cam-Clay model allow to accurately reproduce the shearing (figure 4) and hardening behaviours (figure 5) of the ramming mix.

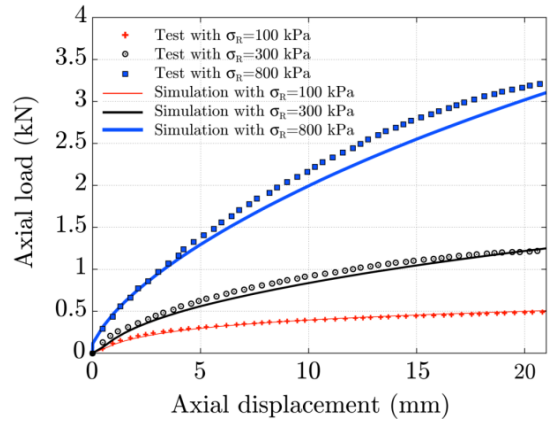


Figure 4: Triaxial tests for different radial pressures.

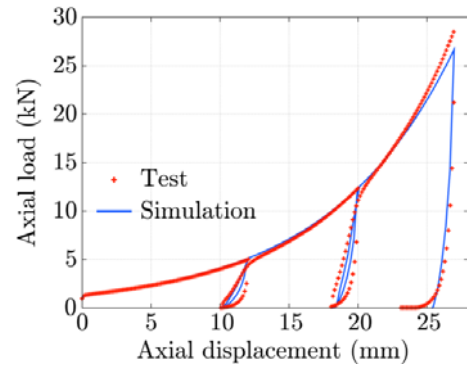


Figure 5: Die compaction test at room temperature.

The ability of the model to fit with the elastic and plastic parts of the hardening behaviour was shown as well.

Validation of the model

In order to validate the previous results, another die compaction at a variable temperature is performed. As shown on figure 6, it confirms the faculty of this model to reproduce the temperature effect on the hardening behaviour.

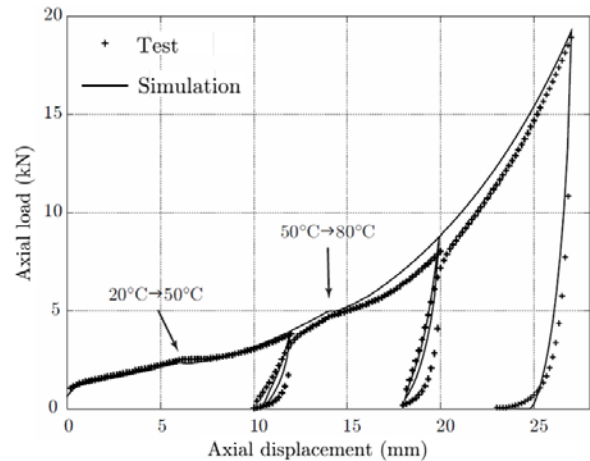


Figure 6: Die compaction test at variable temperature.

It is the influence of the parameter β which is pointed out. The stresses applied on the sample decrease when the temperature increases. This phenomenon is also observed in [10] and induces a decrease of the yield surface (and so the elastic region) with temperature.

The behaviour of the considered ramming mix was described by a modified Cam-Clay model. The model parameters have been experimentally determined for different temperatures and velocities. A good agreement between results of simulations and tests is reached with this model.

The masonries

Accounting for the behaviour of masonries (bottom and ceramic cup) is also important because they are submitted to high thermal loads which can lead to the opening of mortar joints. So, it is essential to characterize the behaviour of bricks, mortars and their interfaces up to 1500°C.

Characterization of masonries

For that purpose, new compressive tests at high temperature on cylindrical samples have been developed (they were used to characterize the carbon blocks behaviour as well). They allowed to identify the Young modulus E of the linear elastic behaviour for bricks and mortars. A slight decrease of the Young modulus with temperature was observed. Moreover, the Young modulus of bricks was identified ten times stiffer than the mortars' one. These results clearly show temperature influence and mortar's role which lead to a softer behaviour for the masonry. This softening behaviour may be often due to joint openings, considering their small thickness. Specific shear and tensile tests on brick-mortar samples were built up to 1500°C. Thanks to the tensile tests, the brittle failure (figure 7) of the brick-mortar interfaces was observed.

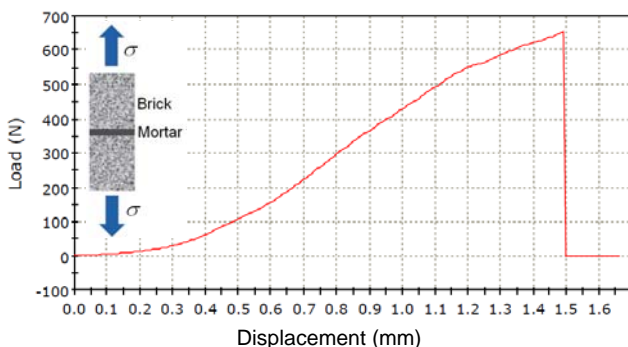


Figure 7: Brittle failure from a tensile test.

The tensile strength f_t of the brick-mortar interface is therefore identified. Shear tests carried out on brick-mortar samples with an inclined mortar plan permit to identify the cohesion c and the friction

angle ϕ , the two parameters of a Mohr-Coulomb

criterion defined by: $|\tau| = c - \sigma_n \tan \phi$

In fact, the load applied on the sample leads to a shear stress τ and a normal compressive stress σ_n on the interface.

It is worth noting that a high decrease in tensile strength and cohesion is observed as temperature increases. It reinforces the need to take into account these possible joint openings which will lead to stress softening in the masonry.

Masonry modelling

Considering the high number of joints in the masonries of the BF hearth, instead of a discrete approach which could lead to numerical problems, a micro-macro approach with homogenization method was developed. It allows to replace bricks and mortars by an equivalent homogenous material. To that end, the masonry is first studied at the microscopic level, considering a representative elementary volume loaded with homogeneous boundaries conditions [11]. Due to the periodicity of the studied masonries (bottom and ceramic cup), a periodic homogenization method is applied [12]. The periodic elementary cell is composed of two components whose behaviours were experimentally identified as previously explained:

- The brick with a linear elastic behaviour;
- The mortar with a linear elastic behaviour and a yield surface in tension and in shear (figure 8).

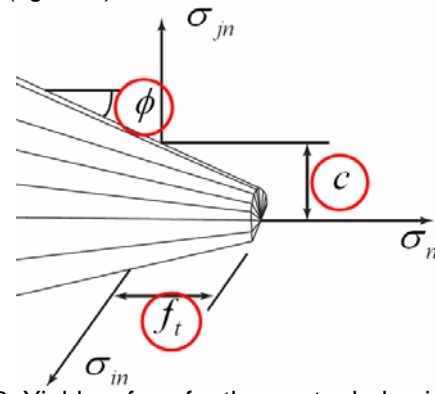


Figure 8: Yield surface for the mortar behaviour.

Once the mortar yield surface is reached, a loss of stiffness is defined.

The macroscopic model built from this microscopic approach is thus based on the assumption that the failure will occur in the mortar due to its small thickness. It defines a joint states model inspired from [13]. The proposed model is an extension of previous works [14,15,16] dealing with the modelling of mortarless masonries.

Working on a periodic elementary cell with head and bed joints, 4 states can be reached according to the joint openings. For each one of them, an Equivalent Homogeneous Material (EHM with orthotropic elasticity) must be obtained. Moreover as shown on

figure 9, a stress criterion is defined between these states.

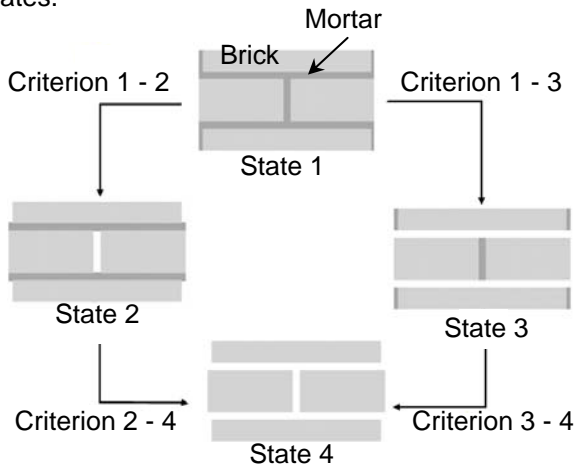


Figure 9: Macroscopic joint states model.

In order to identify the various EHM and stress criteria (at different temperatures), the periodic elementary cell is submitted to chosen strain fields \underline{E} (uniaxial, biaxial en shear strains). For each applied strain field, the strain energy is computed by the ABAQUS software. The knowledge of the applied strain and the computed energy allows to deduce the macroscopic stress $\underline{\Sigma}$ (direct identification from energetic equivalence). From this one, the macroscopic stress criterion between the states and the effective orthotropic stiffness tensor of each state $\underline{\tilde{C}}$ (from $\underline{\Sigma} = \underline{\tilde{C}} : \underline{E}$) are identified.

The developed masonry model, accounting for temperature effects and joint openings, was implemented in Abaqus/Explicit thanks to a VUMAT subroutine.

Validation of the model

A shear wall test available in the literature [17] was chosen for the validation of the developed model. As described on figure 10(a), the masonry is first submitted to a vertical pressure ($p=0.3$ MPa). Then, a monotonic horizontal displacement of the upper steel beam is imposed in a confined way (figure 10(b)). The upper beam is kept horizontal during the whole test. This test is particularly interesting for the validation of our model because joint openings in tension occur in the corners of the wall as a diagonal opening in shear (figure 11(a)).

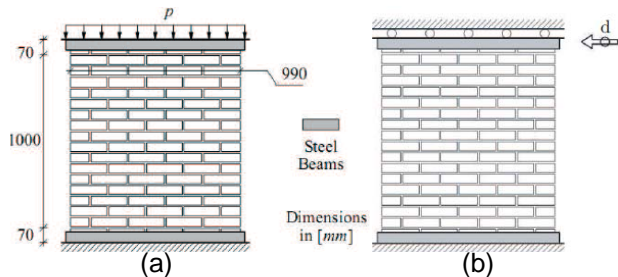


Figure 10: (a) Vertical pressure; (b) Horizontal displacement.

As shown on figure 11(b), the crack patterns initiated are detected. Horizontal joints (state 3) opened in the corners due to tensile stresses although horizontal and vertical joints (state 4) opened in the diagonal due to shear stresses.

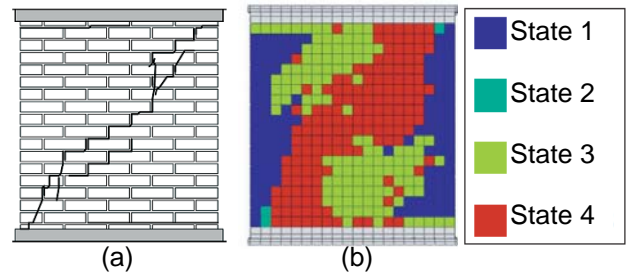


Figure 11: Crack patterns comparison: (a) Experimental result; (b) Numerical result.

Figure 12 presents the evolution of the horizontal load applied on the upper beam needed to impose its horizontal displacement. This result clearly shows the ability of the developed model based on a homogenization approach to reproduce the non-linear behaviour of masonry.

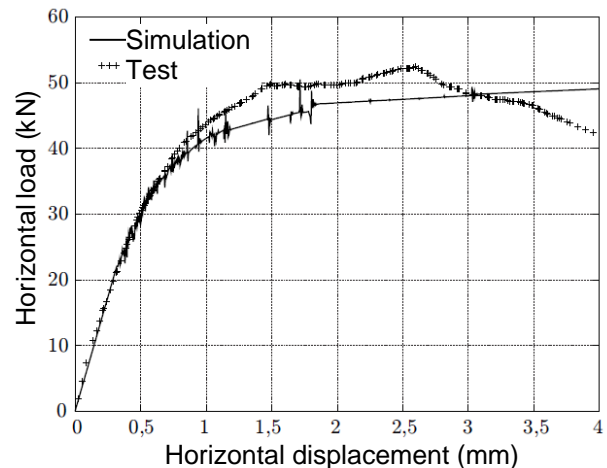


Figure 12: Experimental and numerical evolutions of the horizontal load applied on the upper beam.

BF hearth thermomechanical modelling

The new ramming mix and masonry behaviours are implemented in the axisymmetric BF hearth modelling. For the bottom and the ceramic cup, equivalent homogeneous materials with different states were identified at 20°C, 900°C and 1450°C, thanks to a large experimental campaign. The masonry behaviour evolves as a function of temperature and joint opening state. The thermomechanical modelling of the BF hearth was divided in 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 figure 13 is computed.

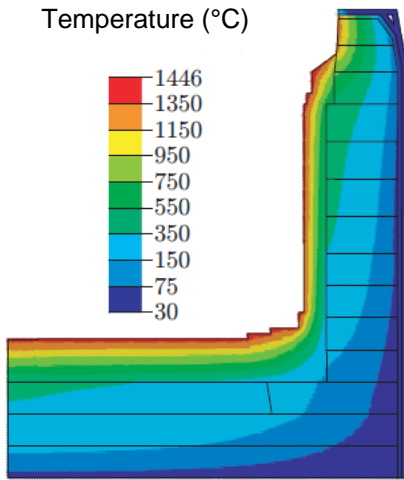


Figure 13: Thermal field in the BF hearth.

This result shows the insulation power of the ceramic cup which protects the carbon blocks from high temperatures (maximum of 500°C). In order to validate the temperature profile, 17 thermocouples were located in the carbon blocks: 12 around the ceramic cup and 5 below the bottom. Figure 14 shows the good agreement which is reached between measured and computed temperatures.

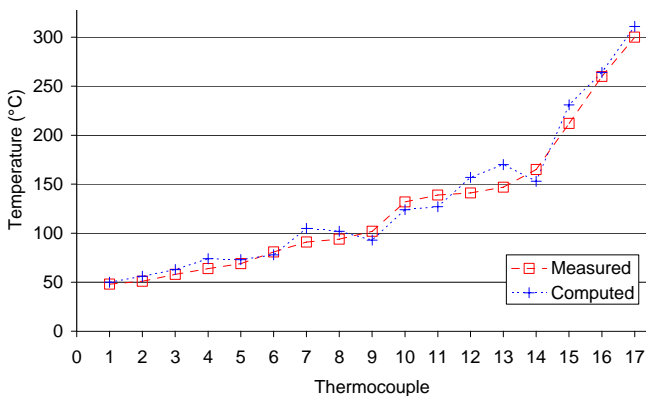


Figure 14: Comparison for 17 thermocouples between measured and computed temperatures.

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 behaviour laws for the ramming mix

and the masonries, four different cases are modelled. 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%). The relative density is linked with the void ratio by: $RD = \frac{1}{1+e}$

For each model, the evolution of the von Mises stress on the steel shell height is plotted on figure 15.

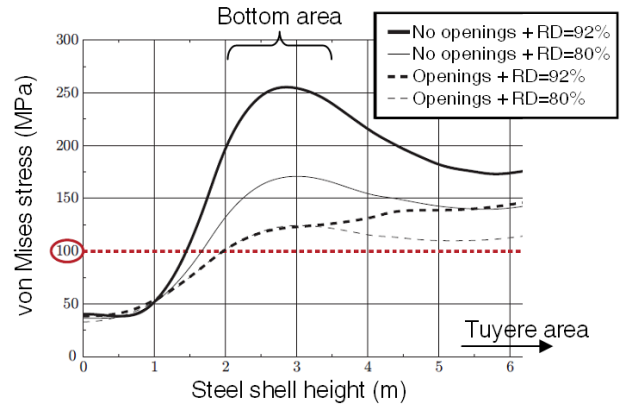


Figure 15: Comparison of the von Mises stress computed on the steel shell between four models.

Studying the stresses in the steel shell which is the external part of the hearth allows to demonstrate the influence of the improvements done. Thanks to the new 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 high 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 in-situ situations) is closer to reality (100 MPa is the highest authorized stress in the steel shell).

Conclusion

The materials and solutions proposed for the design of new BF hearths need to bring the guarantee they will support the thermomechanical stresses in the structure. For that purpose, Saint-Gobain has built a new model of BF hearth based on an ambitious program of material modelling and characterization. This work mainly concerns the ramming mix and the masonries for which specific tests were carried out. From these, the parameters of new behaviour laws were identified:

- a Cap model for the ramming mix which allows to reproduce the hardening behaviour in compaction and the temperature influence.
- a joint states 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 closer to reality.

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