Evaluation of thermal stresses in the blast furnace hearth with consideration of refractory block contact

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Abstract

A thorough understanding of thermal stresses within the blast furnace hearth refractory is crucial for selecting an optimal lining design and ensuring the safe operation of the furnace. An inadequate lining design can lead to excessive thermal stresses, resulting in cracks and gaps that may accelerate wear or, in severe cases, cause sudden and hazardous failures. Therefore, thermal stress simulation models play a vital role in designing a robust hearth and extending the furnace's operational lifespan.

Key Words

Blast furnace hearth, thermal stresses, contact modeling, refractory linings, hearth design, finite element method.

Introduction

One of the main factors governing the campaign life of a blast furnace is wear of the hearth lining. The wear resistance of the hearth lining is basically defined by the quality of refractory material and the hearth lining design. The refractory blocks are subjected to chemical attack and high thermal stresses during blast furnace campaign. For example, inadequate use of ramming material may on one side result in high stresses, damages and premature wear. On the other side, excessive use of ramming material may result in formation of gaps between blocks and ramming material itself. These gaps later on enable penetration of alkalis, zinc and hot metal which may lead to formation of brittle layers and premature wear of lining [1].

Achieving the optimal balance between geometric design and material selection for refractory linings in large-scale industrial blast furnaces requires a thorough understanding of their thermo-mechanical behavior. Design engineers need an efficient tool for rapidly assessing the thermo-mechanical state of refractory linings under different conditions.

One of the primary challenges in simulation models is accurately computing the interactions between refractory blocks. While most conventional finite element programs include contact computation capabilities, they are not well-suited for blast furnace hearth linings due to the large number of refractory blocks in contact. Modeling thermal stresses in an assembly of hundreds or even thousands of lining blocks is particularly complex.

To simplify this challenge, simulation models often represent refractory blocks as monolithic rings, but this approach compromises accuracy. Conversely, incorporating individual block interactions significantly increases model complexity, requiring extensive computational resources while still facing convergence issues. Additionally, access to supercomputers is typically limited for most design engineers. The complexity of such models makes them impractical for real-time hearth monitoring in operational blast furnaces. Therefore, effective simplification strategies must be developed.

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One of the primary challenges in simulation models is accurately computing the contact interactions between refractory blocks. While most conventional finite element programs include built-in contact computation features, they are not well-suited for simulating blast furnace hearth linings due to the large number of refractory blocks in contact. Modeling thermal stresses in an assembly consisting of hundreds or even thousands of lining blocks is particularly complex.

To address this, many simulation models simplify the refractory lining into monolithic rings, which significantly distorts the accuracy of the results. However, incorporating individual contact interactions between refractory blocks increases the model's complexity, requiring extensive computational resources while still posing challenges in achieving convergence.

Moreover, high-performance supercomputers are typically inaccessible to most design engineers, making such detailed models impractical for real-time hearth monitoring in operational blast furnaces. As a result, developing effective simplification methods is essential.

Methods

Understanding the temperature distribution is crucial for designing the refractory lining. By making reasonable simplifications, an effective model can typically be developed with ease. Such a model primarily accounts for heat conduction within the refractory lining while incorporating boundary conditions like convection and radiation. Additionally, any discontinuities in heat flow caused by refractory block interfaces or gaps should be considered in the model.

A thorough understanding of the stress and displacement fields is crucial for optimizing the design of hearth linings. Engineers can develop effective strategies to manage crack and gap formation caused by uneven thermo-mechanical stress distribution only after gaining comprehensive insight into the system's thermo-mechanical behavior. The structured arrangement of refractory blocks in the lining walls simplifies contact stress patterns, making friction between the blocks negligible. While the contact interfaces efficiently transfer compressive stresses, they do not transmit tensile stresses. Additionally, the finite element software COMSOL® allows precise control over field equations, enabling the elimination of tensile stresses between blocks. For more details, please refer to the related conference proceedings [2] and the software's user guide [4].

The proposed method builds upon the fundamental principle illustrated in Figure 1. While refractory blocks can withstand compressive forces, they are unable to endure tensile stresses when the load is applied perpendicular to the contact plane. By dynamically adjusting the initial stress state in tensile regions based on the orientation of refractory blocks within the lining wall, this approach effectively captures the behavior of refractory separations and contacts. Compared to conventional contact models, this method significantly enhances model preparation and solution efficiency, as it eliminates the need for explicitly modeling individual refractory blocks and their interactions. Instead, only directional information related to tension resistance is required. Benchmark simulations comparing this method with traditional contact models have demonstrated its high level of accuracy.

Benchmark Simulations

The proposed simulation method is evaluated on a conventional circular refractory wall, which consists of multiple lining blocks enclosed by a thick outer steel shell. A single layer of the lining wall is depicted in the upper sketch of Figure 2. To ensure compatibility with a standard PC, the model is further simplified by utilizing symmetry planes that pass through the center of the blocks in the radial direction (refer to the enlarged section of the upper sketch in Figure 2).

However, it is important to note that such simplifications are strictly applicable to ideal symmetrical conditions, where the overall behavior can be reduced to the interaction between two adjacent refractory blocks.

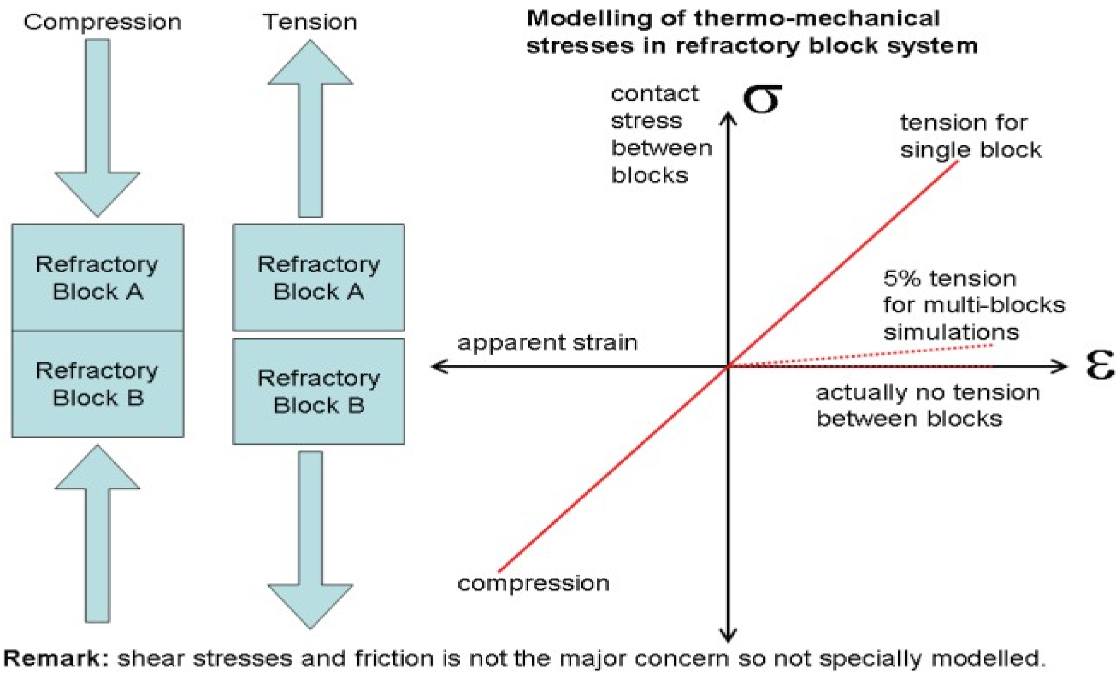

Figure 1: No Tension Concept

As the furnace temperature rises, the refractory blocks expand and exert pressure on one another. A thick steel shell encases the assembly, experiencing circular tension. Standard simulations that account for contact interactions indicate the development of gaps at the outer edges of the initially well-fitted refractory blocks (as illustrated in the enlarged section of the lower sketch in Figure 2). If a simulation model includes assumptions that fail to capture the formation of these gaps and their impact on stress and displacement, the results may be inaccurate or unrealistic.

Details of Benchmark Models

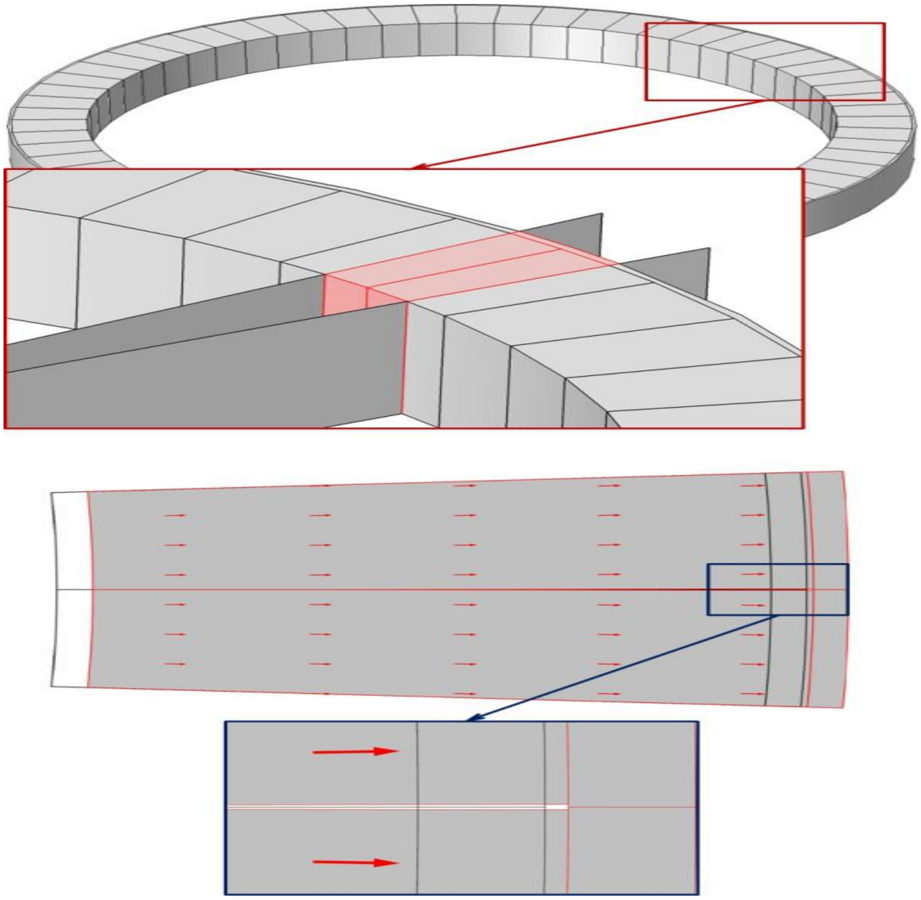

Figure 2: Separation and contact of block

The tube geometry depicted in Figure 2 represents the hearth lining wall of an industrial furnace. The thermo-mechanical properties of the materials are listed in Table 1. The refractory blocks are considered to exhibit linear elastic behavior, while the steel shell is modeled as elastic-perfectly plastic. The thermal boundary conditions involve convection heat transfer, with the inner surface maintained at 1500°C and a heat transfer coefficient of 300 W/(m²·K). The outer surface is at 30°C with a heat transfer coefficient of 1000 W/(m²·K). To simplify the model, perfect thermal contact is assumed between the refractory blocks and the steel shell, eliminating the need for an additional thermal resistance layer. Additionally, the tube's cross-section is treated as a plane strain condition, meaning no displacement occurs in the axial direction.

Table 1: Material properties

Property	**Refractory**	**Steel**	**Unit**
Elasticity Modulus	70	200	GPa
Yield Stress	1500	250	MPa
Poison’s Ratio	0.25	0.30	-
Density	2500	7800	kg/m^3
Thermal conductivity	15	70	W/(m·K)
Heat capacity	800	450	J/(kg·K)
Thermal expansion	8	12	10^{-6} 1/K

Three distinct simulation methods were evaluated in the benchmark simulations. The first method follows the continuum approach, where the refractory block assembly is modeled as a unified, monolithic structure resembling a ring. To simplify the analysis, an axisymmetric model is employed, as illustrated in Figure 3. In COMSOL®, the geometry should be defined using the “form assembly” setting, which facilitates the representation of contact interactions between the refractory blocks and the steel shell at internal boundary 4 (Figure 3). The necessary contact pairs must be specified in the solid mechanics module, while the corresponding heat continuity pair should be established within the heat transfer module. Additionally, boundaries 2, 3, 6, and 7 in Figure 3 should be designated as symmetry boundaries.

The second method incorporates the contact interactions between individual blocks within the model. Due to the complexity of simulating block contacts, the simple axisymmetric model shown in Figure 3 is not suitable. Instead, a planar geometry, depicted in Figure 4, is utilized under the plane strain condition. Similar to the first approach, the geometry should be set as “form assembly” in COMSOL® to accurately represent contacts at internal boundaries 2, 4, and 8, as well as continuity at boundary 10 (Figure 4). The corresponding contact pairs must be assigned in the solid mechanics module, and the heat continuity pairs should be defined within the heat transfer module. Furthermore, boundaries 1, 5, 9, and 13 in Figure 4 should be specified as symmetry boundaries.

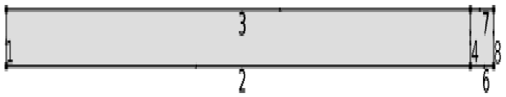

Figure 3: Layout of geometry for axis-sym. Models

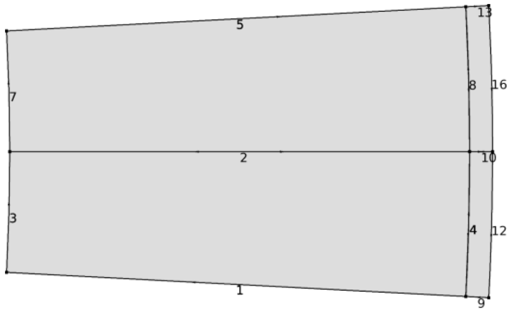

Figure 4: Layout of geometry for contact model

The third simulation approach introduces a novel method that incorporates the effects of refractory contacts within a simplified model, where the assembly of refractory blocks is treated as a continuum. By making a minor adjustment to the model used in the first approach, this method achieves highly accurate results while eliminating the need for complex contact computations. The "no tension concept," illustrated in Figure 1, can be implemented in COMSOL® through the use of initial stresses and strains. In this approach, the hoop stress is calculated separately and stored in a user-defined variable, referred to as S22. The expression for S22 in this specific case is given by:

$$S22 = D12*eel11 + 2*D24*eel12 + 2*D26*eel13 + D22*eel22 + 2*D25*eel23 + D23*eel33$$

Where, D_{ij} denotes the components of the elasticity tensor, while eelij represents the components of the elastic portion of the strain tensor (i, j = 1,2,3). When the hoop stress is positive (i.e. $S22 > 0$), a negative initial stress (-S22) is applied to counteract its influence on the actual stress tensor. This adjustment ensures the removal of unrealistic tensile stresses in the hoop direction between refractory blocks with minimal effort. The first approach follows the conventional method used by standard design engineers. However, the second approach may be too complex for accurately modeling a real blast furnace hearth. To address this, a third approach has been introduced, where simplified monolithic models are adjusted to replicate contact behavior.

Benchmark Model Results

Figure 5 presents a comparison of hoop stress variations in the refractory blocks across three different simulation methods. The dotted line represents results from the standard axisymmetric model, which does not account for contact between blocks. In this approach, the refractory assembly is treated as a continuous monolithic structure, leading to significantly high stress values and unrealistic tensile hoop stresses on the steel shell side of the blocks (5.5 < r < 6.0).The true contact model, depicted by the dashed gray line for the block centerline and the solid gray line for the contact boundary, effectively removes these unrealistic tensile stresses and captures the formation of small gaps between blocks (5.3 < r < 6.0). Additionally, stress values at the block center and contact boundary are observed to be quite similar, making them reliable reference points for benchmarking.

Lastly, the newly proposed method, represented by the solid black line, produces hoop stress results comparable to those obtained from the true contact model. This indicates that it can accurately simulate both stress and displacement fields without significant loss of precision. Moreover, the new method is computationally more efficient and easier to implement compared to the true contact models.

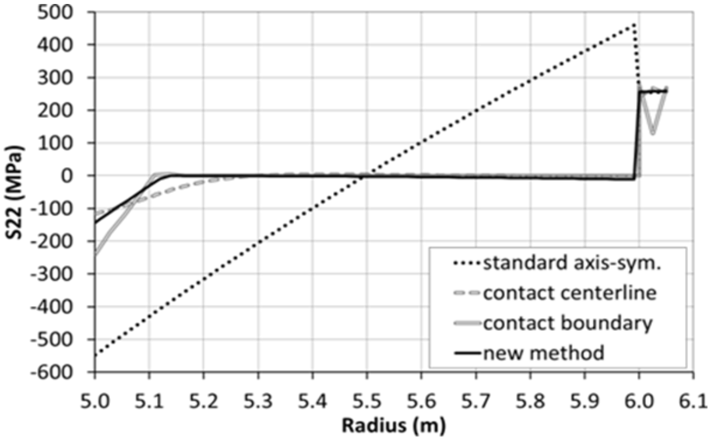

Figure 5: Comparison of hoop stresses

The radial displacements of the steel shell are:

- 39.7mm for the standard axis-sym. model,
- 65.4mm for the centerline of contact model,
- 65.8mm for the boundary of contact model,
- 65.3mm for the new method.

A newly developed model has been utilized to simulate thermal stresses in the hearth lining of BF4 at ROGESA, located within Dillinger Hüttenwerke. The design of the simulated blast furnace is illustrated in Figure 6. As depicted, the hearth features a ceramic cup along with large carbon blocks. For additional insights into thermal stresses in this blast furnace, please refer to [1] and [3]

An axisymmetric simulation model has been constructed to analyze thermal stresses. The impact of incorporating the no-tension concept within the simulation is examined. Figure 7 presents the thermal and mechanical boundary conditions applied to the axisymmetric model. The hearth contains molten metal maintained at a uniform temperature of 1500°C, which induces convective heating on the inner surface with a heat transfer coefficient of 300 W/(m²·K). Meanwhile, the outer side of the hearth is cooled using 30°C water circulating at the shell, with a heat transfer coefficient of 1000 W/(m²·K). Structurally, the hearth is constrained at its base while remaining unrestricted at the tuyere level. The computed results are provided along the designated cut-line.at z=3m as shown in Figure 7. The values of the material properties are listed in Table 2.

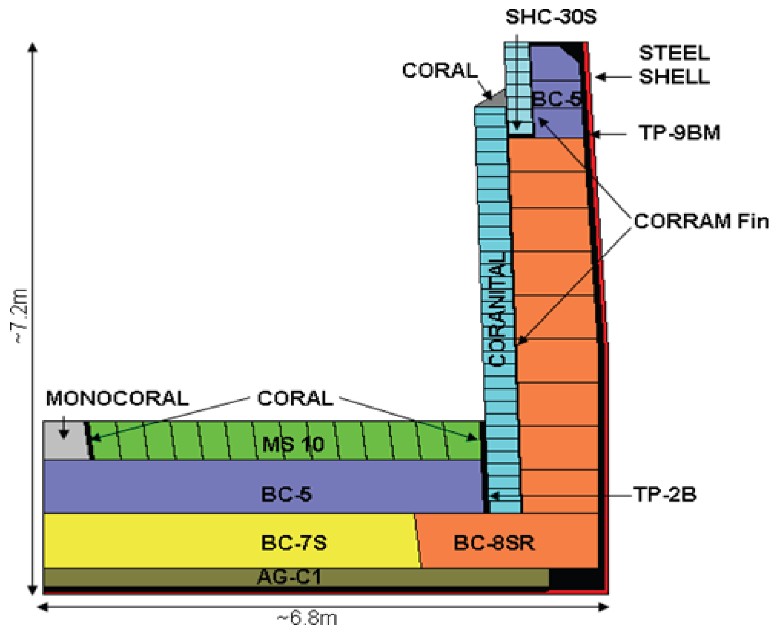

Figure 6: Design of BF4 at Dillinger Hüttenwerke

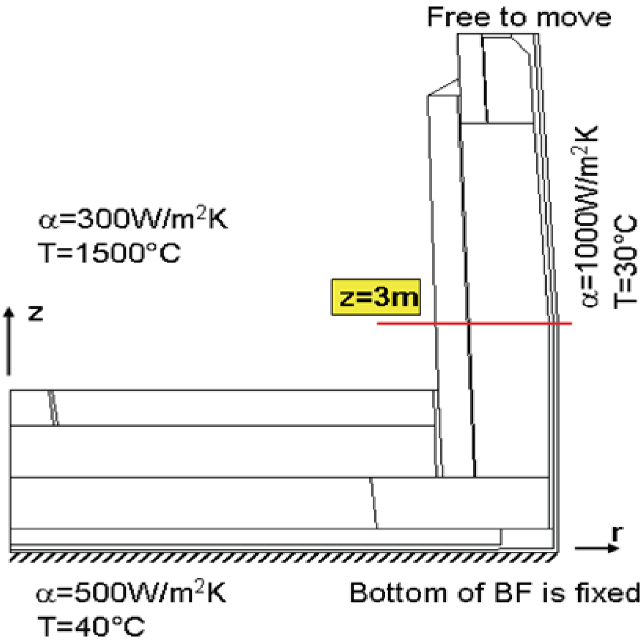

Figure 7: Simulated geometry and BCs

The results obtained using the new approach are compared with those from the conventional axisymmetric model. As anticipated, the temperature distributions remain identical in both models since the new method only affects stress and deformation calculations. However, a noticeable difference arises when comparing the stress fields.

In the hearth wall, the primary stress components include the hoop stress (S22 or $\sigma_{\phi\phi}$) and the vertical stress (S33 or σ_{zz}). The standard model (represented by dotted lines in Figures 8 and 9) predicts tensile stresses in the BC-8SR carbon blocks ($5.65 < r < 6.6$). However, since the wall consists of separate blocks rather than a continuous structure, these tensile stresses should not be present. A similar issue is observed in the ceramic cup (CORRANIT-AL, dotted line, $5.5 < r < 5.6$ in Figure 8), where the new approach correctly computes a near-zero stress level in those regions.

Additionally, there is a notable difference in the stress distribution within the steel shell and ramming mix. The standard model (dotted lines for $r > 6.6$ in Figures 8 and 9) underestimates stress levels because it assumes a monolithic structure, which can partially bear the load. In reality, as these components are made of individual blocks without tensile capacity, the entire load is transferred to the steel shell and ramming mix leading to higher tensile stresses in these areas.

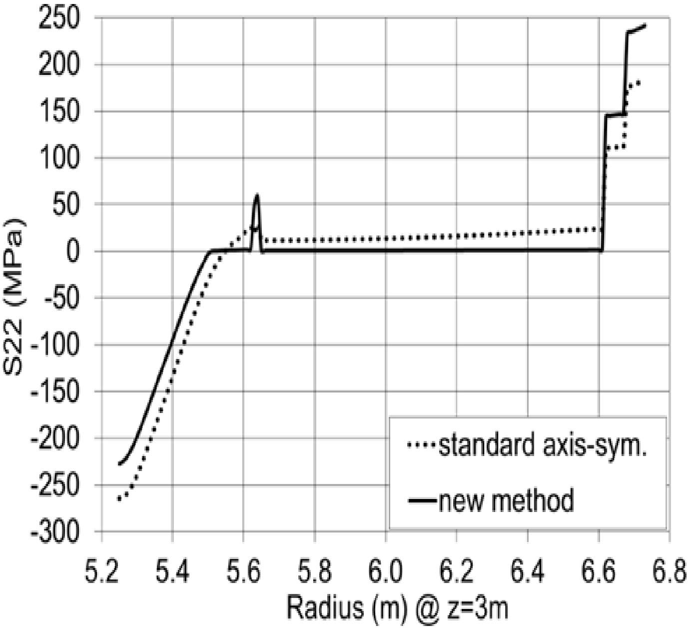

Figure 8: Hoop stress ($\sigma_{\phi\phi}$) at the cut line (z=3m)

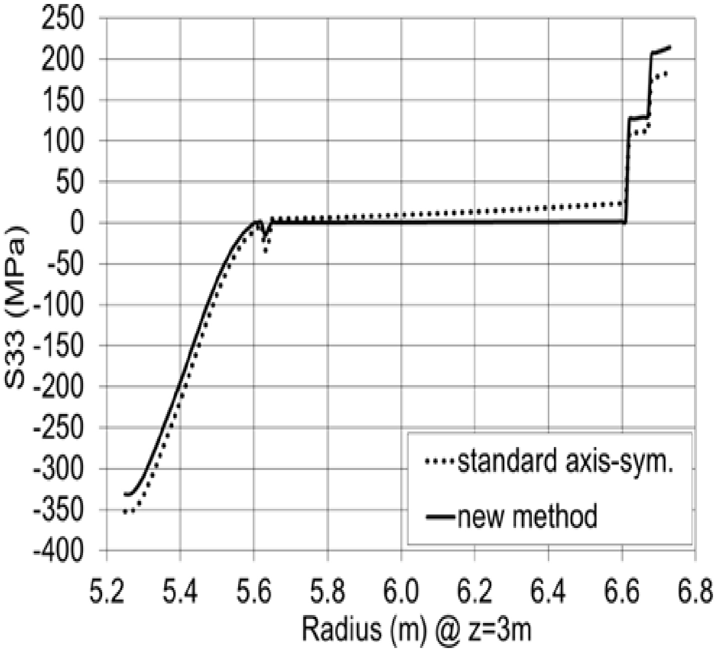

Figure 9: Vertical stress (σ_{zz}) at the cut line (z=3m)

Conclusions

A newly developed modified constitutive law effectively simulates the contact behavior between refractory blocks. This approach removes the necessity for an explicit contact model by seamlessly incorporating the effects of contact boundaries directly into the constitutive equations. The proposed method demonstrates high accuracy and efficiency. Its implementation, benchmarking, and application in an industrial blast furnace hearth are discussed.

The proposed method serves as an effective tool for calculating the thermo-mechanical state of refractory linings under different conditions in blast furnaces, converters, lathes, and similar applications. Due to its high computational speed, engineers can efficiently evaluate the performance of various lining designs and materials, enabling the development of improved refractory lining concepts. This solution is adaptable to both two-dimensional and three-dimensional simulation models

α : convective heat transfer coefficient
σ : stress
ε : strain
BF : Blast Furnace
D_{ij} : elasticity tensor components
eel_{ij} : elastic part of the strain tensor component
i, j : 1,2,3 for coordinate directions
S22, $\sigma_{\phi\phi}$: hoop stress component
S33, σ_{zz} : vertical stress component

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