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MODELING OF REFRACTORY BRICK FURNITURE IN ROTARY-KILN USING FINITE ELEMENT APPROACH

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Abstract. Refractory brick lining in rotary kilns is an essential part that governs availability of a kiln. A severely damaged lining will eventually lead to an unplanned, long-lasting and costly production stop. A brick lining experiences various degrading mechanisms during its service life. Knowing and avoiding critical situations is of great importance to its life length. This work is focusing on a global mechanical behaviour of the brick lining at room temperature. Finite element method by the commercial software LS-Dyna is used as a tool. Fundamental challenges for a brick lining are presented and studied. Approximation of true kiln geometry and a method of sequenced bricklaying of a large-diameter rotary kiln is presented. Stresses in the lining in static and dynamic loading are evaluated. Maximum effective von Mises stresses experienced by the brick lining in static and dynamic loading were found to be approximately 1 and 6 MPa, respectively. Fast acceleration to working speed leads to extensive brick movement in the kiln. Careful ramping of the rotational speed makes the brick lining to keep its integrity. A conclusion

is that maximum stresses in the brick lining is rather unaffected by the rotational acceleration, but the relative positions between individual bricks can be affected. These results confirm necessity of avoiding cold rotation. Additionally, a general conclusion is that in terms of experienced stresses the brick lining is rather unaffected at room temperature.

1 INTRODUCTION

A rotary kiln is a large cylinder-formed furnace used in certain hot-process manufacturing industries. It is a slightly inclined, refractory lined steel container which rotates about its axis and where certain chemical and physical reactions take place by the influence of heat. The slope and the rotation make the material inside to move through the kiln from feed to discharge end. The heat is commonly generated by a flame in the discharge end from the combustion of coal, oil, natural gas or waste. The size of a rotary kiln can be as large as 180 m in length and 7.5 m in diameter, while service temperature can be up to 1800 °C. The kiln is commonly resting on two to five pairs of support rollers, depending on its length. Additionally, it is equipped with thick, tightly fitted steel tyres that are riding on the support rollers. There are many industrial users of rotary kilns, however most of them are found in the field of cement, lime and mineral production.[1]

In order to be able to operate at high temperatures, the inner part of a rotary kiln consists of one or several layers of refractory materials. This is required for heat protection of the steel casing of the kiln, surroundings (such as sensible equipment and personnel) and reduction of heat losses (lower drift costs). These materials are usually in form of castables or bricks and have varied chemical composition dependent on service conditions. Refractories are essential for a wide range of hot processes exceeding 1000 °C and the availability of a rotary kiln is highly dependent on the condition state of the refractory lining. Depletion of the refractory lining can lead to significant failures with fall outs of bricks or castables that may require shut-down of the production. Unplanned shut-downs can cause very high production losses and put company in a demanding situation.[1,2]

Refractory products are often used in harsh service environment and therefore are prone to degradation. Tolerance to temperature, mechanical loads, thermal cycling, wear and chemical resistance are some of the common requests.[3,4] As a matter of fact degradation of refractories in use is inevitable. Normal procedure in industry is that refractories in a kiln are controlled and/or replaced at a regular basis during planned maintenance shut-downs. The best case scenario is when refractory lining is degrading in a controlled manner without causing shut-downs in-between maintenance stops.

This work is focused on the problems influencing stability and reliability of refractory lining in rotary kilns. Some general aspects and basic concept of rotary kilns will be discussed. In order to better understand the different loads encountered by refractory lining, finite element analysis (FEA) is used. In this work, the commercial FE-software LS-DYNA is used for FEA calculations. The parameters used here (geometries, materials) are typical for grate-kiln plants in iron-ore pellet production. Mechanical aspects in cold condition are of main focus in this paper.

2 BACKGROUND AND DESCRIPTION OF THE PROBLEM

Producers of upgraded iron-ore products for the steel industry are common users of rotary kilns. Standard products such as iron-ore pellets undergo oxidization and sintering during heat treatment in order to be cost effective at future steps of the life chain, such as transport and steel production.[5] The heat treatment is typically performed in the grate-kiln systems. This process consists mainly of three parts: a pre-heater, a short dry rotary-kiln and a cooling section. The pre-heater zone has moving grates transporting green pellets to the kiln. The oxidation process starts on the grate-band, while sintering is completed in the rotary kiln. See Figure 1 for the illustration of the process. Common

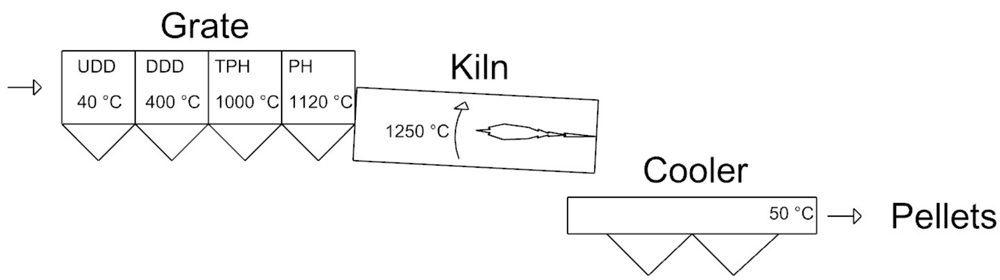

Figure 1: Schematic illustration of a typical grate-kiln process in iron-ore pellet production.

dimension of a rotary-kiln used for iron-ore pellet production is 30-45 meters in length and 5.0-7.5 meters in diameter. The steel casing is usually lined with a single layer of refractory bricks and is resting on two pairs of support rollers. The thickness of the steel casing is typically 50-100 mm depending on the diameter and the axial position (e.g. the casing is commonly thicker close to the tyres). Figure 2 illustrates a typical rotary kiln for iron-ore pellets production. The filler pads, placed between the casing and the riding tyre, function as sacrificing abrasion material. Most of the grate-kiln plants for iron-ore pelletizing in the world use traditional alumino-silicate based bricks, derived from e.g. bauxite, andalusite, clay or chamotte. The base material controls the final alumina (Al_2O_3) and silica (SiO_2) content in the brick, phase composition, and therefore many of its properties.[3,8] The lifetime of a refractory lining is influenced by mechanisms of different severity of thermal, mechanical and chemical character. If the bricks technical limits are violated during usage, degradation will be speed up. Therefore, it is very important that all the relevant steps of any process, either during production or a maintenance stop, are well adjusted to the technical limitations of the brick lining.

The state of the refractory lining is one of the most significant factors influencing the availability of a rotary-kiln. Brick furniture of a rotary kiln is in direct or indirect symbiosis with the rest of the system. To some important factors influencing brick lining

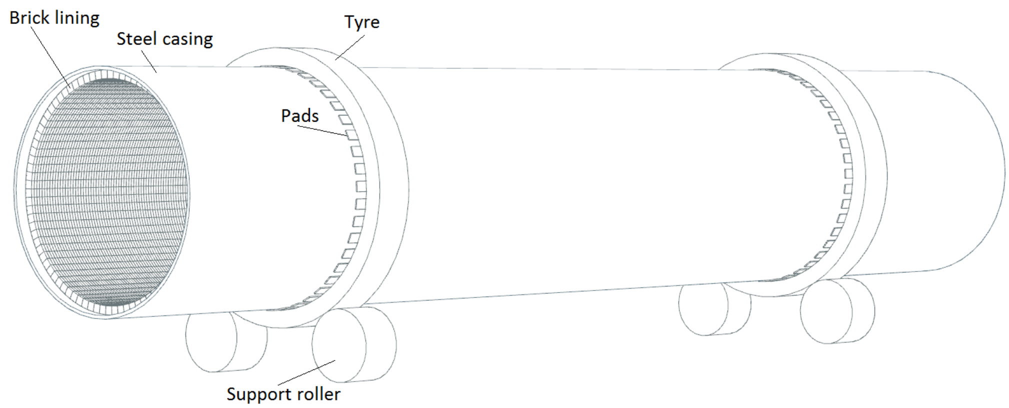

Figure 2: Illustration of a typical short dry-kiln used in iron-ore pellet industry (true proportions).

can be included ovality of steel casing, burner conditions, fit of the tires and alignment of kiln. All of which can have negative influence on the life time of the refractories. Too large ovality of the steel casing can cause unhealthy load peaks in the brick lining when shifting position during rotation. Misaligned burner or badly controlled power output of the burner can cause critical temperature peaks in parts of the lining leading to mismatched thermal expansion. Too tight riding tyre can inhibit expansion of the brick lining leading to failure of the lining or even the tyre. Misalignment of the kiln can cause unnecessary stresses to the rollers, tires and the brick lining. Severe damage of the lining is usually presented by the fall outs or dramatic thickness reduction of the bricks. This leads to the formation of hot spots on the surface of the steel casing, risking a partial permanent deformation of the shell and making it less perfect. Bad perfection of the steel casing causes a less perfect brick lining, which additionally augments the risk of future fall outs. Thus, when hot spots are detected the production is stopped for emergency maintenance. Due to the need of slow cooling and heating of the kiln, and the repairing the process is time-consuming (5-14 days).[2,6]

3 METHOD AND MODEL APPROACH

A full scale model of a brick lined rotary kiln requires large computational power and effort. In this paper a three dimensional model of a 100 mm thick section of the kiln made at the position of support rollers will be brick lined and evaluated. The model dimensions according to the Figure 3.

3.1 Approximation of shell geometry

Emphasize that a rotary kiln is a massive construction. The total operational mass of a large rotary kiln used in iron-ore pellet production is at least 1 500 tons (including steel

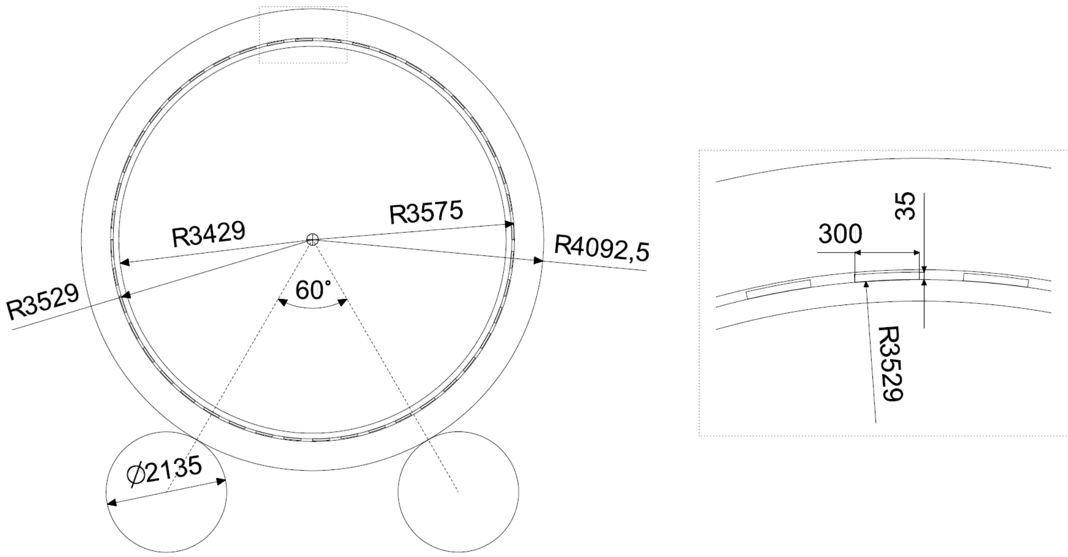

Figure 3: Dimensions (mm) of the unstrained kiln cross section used in the FE-model.

casing, refractory lining, pellets and slag). The effect of gravity on a hollow construction with such mass cannot be neglected. For simplicity a kiln shell is often regarded as circular with some given nominal diameter. However, a well-known and understandable fact is that cross-section of a rotary-kiln casing is not perfectly circular, but flattened due to gravity force.[2,7] The influence of gravity is schematically represented in Figure 4.

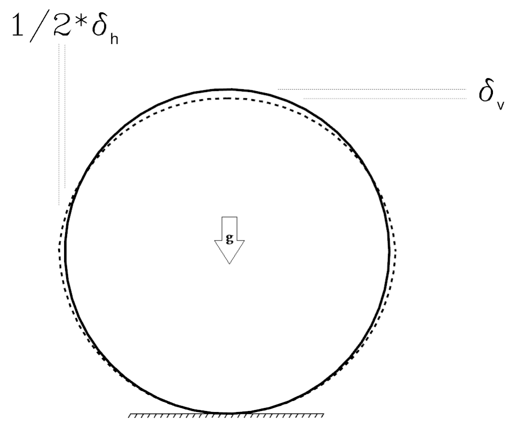

Figure 4: Arbitrary representation of unstrained (solid line) and strained (dashed line) kiln shell profile.

Due to the ovality the steel casing and the refractory lining will undergo repeatable deformation during kiln rotation since they are tightly fitted together. Knowing true geometry of steel casing is necessary in order to correctly reflect behaviour of the refractory lining. In order to estimate this geometry FEA is used.

3.1.1 Validity of casing model

Consider a circular shell with some nominal inner diameter and wall thickness resting on a flat ground (see Figure 4). The vertical and horizontal displacements caused by gravity force can analytically be found by:

$$\delta_h = 0.429 \frac{12 \cdot \rho g r^4}{E t^2} \tag{1}$$

$$\delta_v = 0.467 \frac{12 \cdot \rho g r^4}{E t^2} \tag{2}$$

Where δ_h and δ_v are horizontal and vertical displacements respectively, as can be seen in Figure 4. ρ is density, g is standard gravity, r is the nominal inner radius, E is Youngs modulus and t is the thickness of the casing (SI-units).

A finite element model was created in order to evaluate this basic case and validated towards analytical solutions. A comparison of deformation found by analytical and numerical solutions for different thickness and diameters of steel casing is graphically represented in Figure 5.

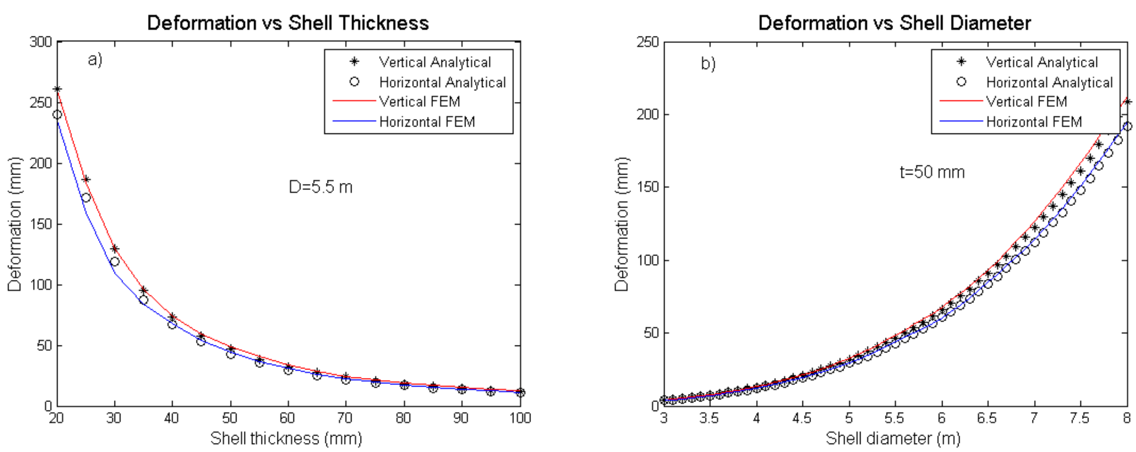

Figure 5: Graphical representation of analytical versus numerical calculations of steel shell deformation when: a) shell thickness (t) varies and b) inner shell diameter (D) varies.

The numerical response of this case is very close to the analytical solution. This confirms validity of the numerical model. The assumption is made that the casing model can be used for the more complex load cases.

3.2 Bricklaying

Refractory brick lining cannot be regarded as one homogeneous unit of the structure. The number of bricks in circumference directly influences flexibility of the refractory lining and steel casing during rotation and thermal load. Therefore, every brick in a section has to be taken into account in a simulation.

The quality of the brick lining is directly influenced by the skill and quality control of the craftsmen. There is no definite way of quantifying the quality of a brick work. Two different occasions will generate two different brick linings. However, generally a good brick lining is fitted tightly to the shell, it is not twisted, number of cut bricks is restricted and use of mortar and chims is limited. In this work the bricks are added to the model by following the edge of the shell and the neighbouring brick with a distance of less than 0.1 mm. The used brick dimensions used in the model can be seen in Figure 6. The last brick in the circumference is slightly wider than the rest. This is according to a

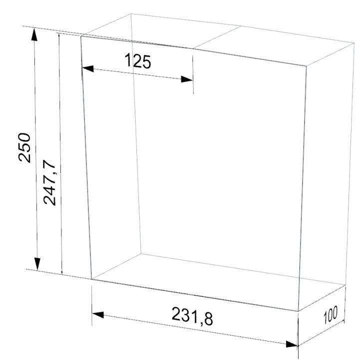

Figure 6: Brick dimensions (mm) used in the model.

new trend in the bricklaying methodology, assuming it is better, if needed, to cut a wide brick than a standard-sized brick. The model does not include use of chims or mortar. Moreover, it does not consider compressibility of joints, which is primarily important during thermal expansion and is therefore not treated in this work.[9,10]

3.3 Assembling of FE-model

As previously shown the start geometry of an empty steel casing is oval. However, the ovality of an empty kiln casing will also gradually increase with addition of bricks. Consequently, a model of brick laying has to include stress and geometry updates in order to correctly reflect the final position of the bricks. Ideally the updates would be made after every new-coming brick. However, numerically this would be very time consuming. In the model presented in this paper the geometry and stresses were updated in four sequences. 86 bricks were used in the circumference. See Figure 7 for the illustration of the bricklaying sequences of the chosen kiln cross-section. In order to simplify the model also a rigid riding tyre has been tested. With this choice the support rollers can be removed and the thickness of the riding tyre reduced.

After assembling the model was tested in static and dynamic loading. Rotation of the kiln was divided into two cases, *slow* (30 s) and *fast* (7 s) ramping to 2 rpm. Rotation of a

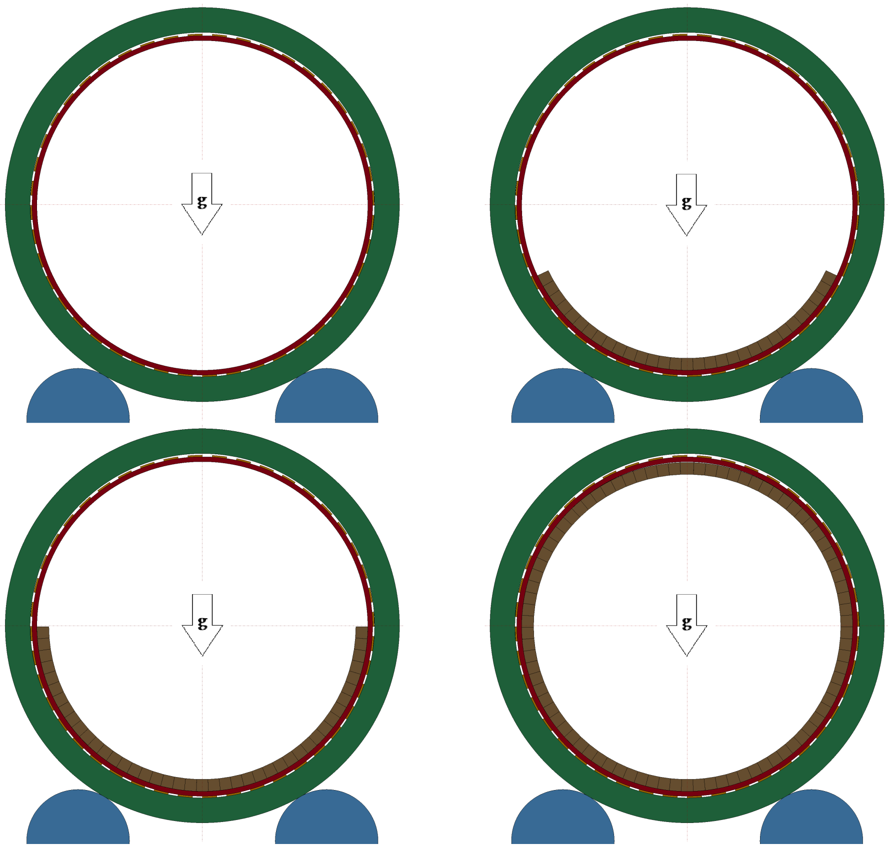

Figure 7: Illustration of the bricklaying sequences. Gravity load applied, followed by sequenced brick laying with geometry and stress updates in-between.

model with an *elastic riding tyre* and a model with a *rigid riding tyre* were also compared.

3.3.1 FEM and model specifications

All the parts in the model are build with fully integrated solid elements. The model's depth corresponds to the thickness of the brick, 100 mm. Total number of elements for the model is 450 000 with *elastic riding tyre* and 135 000 for the model with *rigid riding tyre*. Support rollers are modelled with rigid material. The pads and the casing are modelled with elastic material, defined by typical low-alloy steel properties. The riding tyre is either elastic or rigid. For the bricks a material with predefined concrete behaviour, is used. Density of the brick material was set to 2700 kg/m^3, cold compression strength to 70 MPa and maximum aggregate size to 5 mm. The contact between parts is defined by mortar, penalty based segment-to-segment contact. The dynamic and static friction coefficients of bricks-bricks, bricks-casing and casing-tyre contacts are set to 0.5. The friction coefficients in support roller-riding tyre contact is set to 1.5. The rotation of the kiln is onset by prescribed rigid body motion, either by the rotation of rigid support rollers or the rigid riding tyre. In the numerical calculations implicit integration was used.

4 RESULTS AND DISCUSSION

Figure 8 is a zoom in of the upper part of the model when using elastic riding tyre. After applied gravity load a gap of approximately 35 mm is created at 12-o'clock-position between the filler pads and the riding tyre. Additionally a gap of around 25 mm is observed between the brick lining and the casing at the 12-o'clock-position, which is also commonly observed in reality. Effective von Mises stresses of the static case in the brick

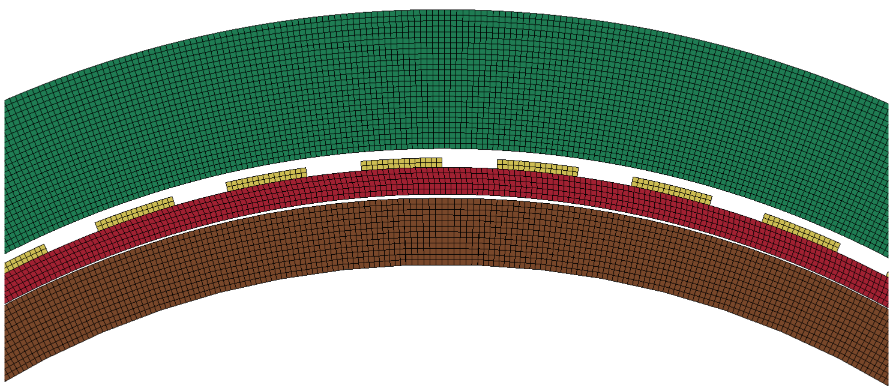

Figure 8: Zoom in of the upper part of the model. A gap between the filler pads and the riding tyre is revealed

lining are relatively small, reaching no more than 1 MPa, see Figure 9 a). That is far below the limitation of the bricks. In Figure 9 b) the effective von Mises stresses from the dynamic case with a fast ramping are shown for a model with *elastic riding tyre*. The maximum effective von Mises stress increases in average by a factor of six. Additionally, a substantial movement of the bricks is noticed in this case. This illustrates the importance of having a tight brick lining and avoiding rotation under cold conditions before the thermal expansion leads to proper self-locking. A slow ramping to 2 rpm does not change the stress distribution substantially, however the integrity of the lining is kept better. The case with *rigid riding tyre* show that the stresses are of the same order of magnitude as when using elastic riding tyre, see Figure 9 c).

For a case of a model with *rigid riding tyre* the solving time was approximately 20 hours at slow ramping, total simulation time of 60 seconds. The case was solved on 32 CPUs by massively parallel processing (MMP). When using shared memory parallel processing (SMP) the computational time increases by at least factor two on the same conditions. In the case of a model with *elastic riding tyre* the computational time reaches above 100 hours either by MPP or SMP on the same conditions. Explicit integration has been tested and was found to require much longer solution times, > 200 h.

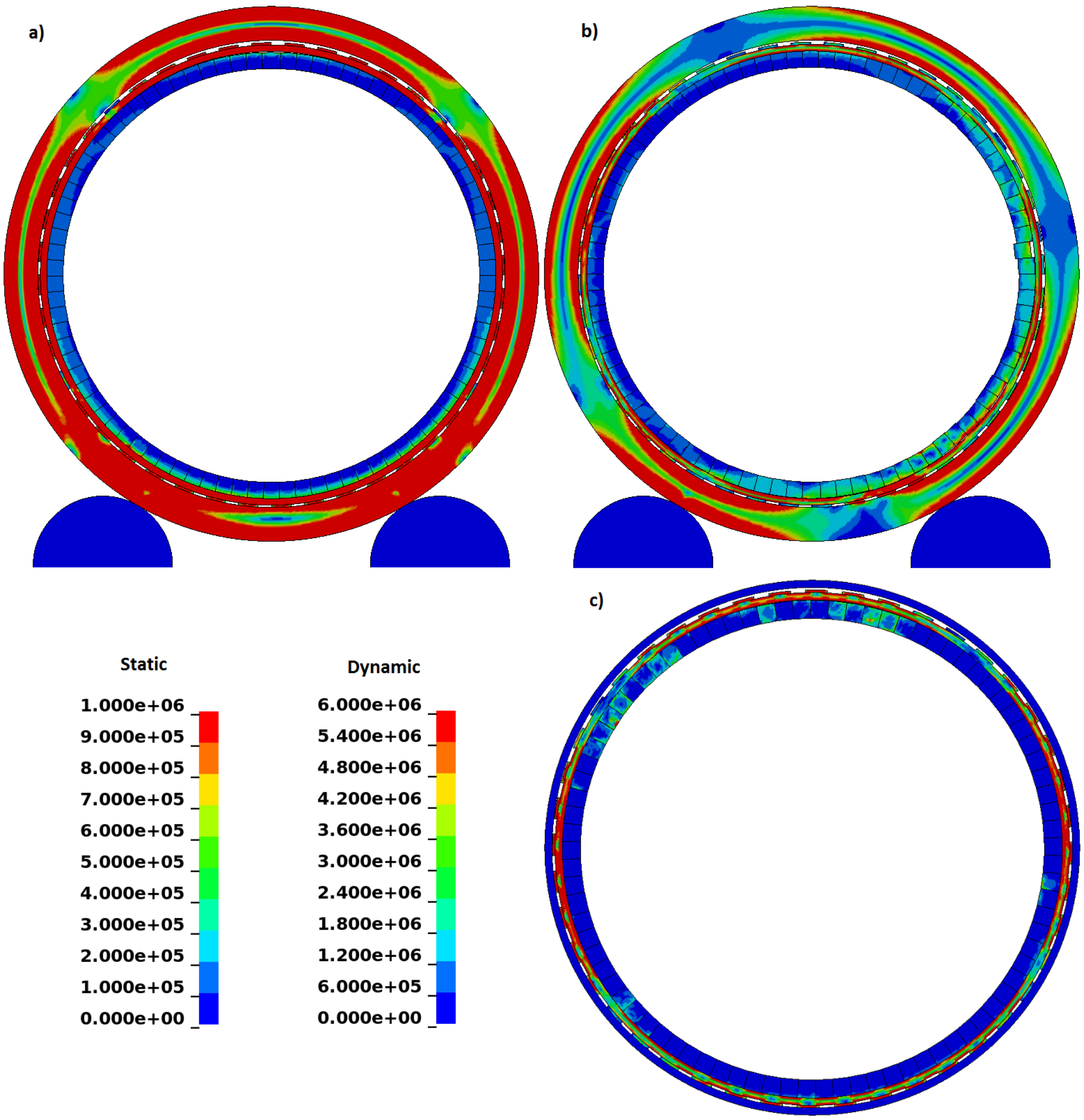

Figure 9: von Mises effective stress distribution in: **a)** Static case with *elastic riding tyre* **b)** Dynamic case with *elastic riding tyre*, fast acceleration **c)** Dynamic case with a *rigid riding tyre*, slow acceleration, and theirs corresponding fringe levels. (MPa)

5 CONCLUSIONS

A rotary kiln is a fairly simple construction. Nevertheless, it is a complicated task to create a realistic model of it. It would be unrepresentative to scale down the task, thus the large size of the rotary kiln leads to a demanding model in terms of computational power. Therefore it is important to create an effective model. Additionally, the large number of bricks creates a heavy contact task.

We have created a model of a cross section of a rotary kiln at the position of rollers. We have approximated the ovality of the shell and proposed a bricklaying method. We have evaluated static and dynamic von Mises stresses and have seen the difference. It can be concluded that in terms of von Mises effective stresses the brick lining does not experience critical situations at room temperature during static or dynamic loads. Nevertheless, in addition we can also conclude that a rotation in cold condition should be avoided due to risk of relative brick movement. Moreover, we have seen that we can assume the riding tyre as rigid, which reduces the number of used elements drastically.

There are reasons to believe that thermo-mechanical aspects contributes greatly to the stresses experienced by the lining. It is highly important to evaluated this contribution and recognize critical situations where the loads are close or above the limits of the bricks. It is our intention to investigate that in future work.

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