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THE CONTACT STRESSES BETWEEN CEMENT KILN TYRE AND SUPPORTING ROLLERS

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ABSTRACT
This paper presents an analysis of the stress field caused by the contact between kiln tyre and its supporting rollers. The analysis is simplified to the problem of the contact between full cylindrical bodies having parallel axes, and performed using both analytical solution and finite element simulation. Contact force is calculated assuming that the kiln is a simply supported, indeterminate beam subjected to statical and symmetrical loads. The results obtained give a promising sign for predicting the stress field in more complex situations such as in reality (dynamic conditions, heated environment, crack propagation, etc.)
Keywords: kiln, support reactions, Hertzian contact stress

1. INTRODUCTION
Cement kiln (Fig.1) is used for pyroprocessing stage of manufacture of cement in which calcium carbonate reacts with silica-bearing materials to form a mixture of calcium silicates. The kiln is the heart of cement production process and its capacity defines the capacity of cement plant. It consists of a tube made from steel plate, and lined with firebrick. The tube slopes slightly (1–4°), and slowly rotates on its axis at between 0.5 and 4 revolutions per minute. Rawmix is fed in at the upper end, and the rotation of the kiln causes it to gradually move downhill to the other end of the kiln.

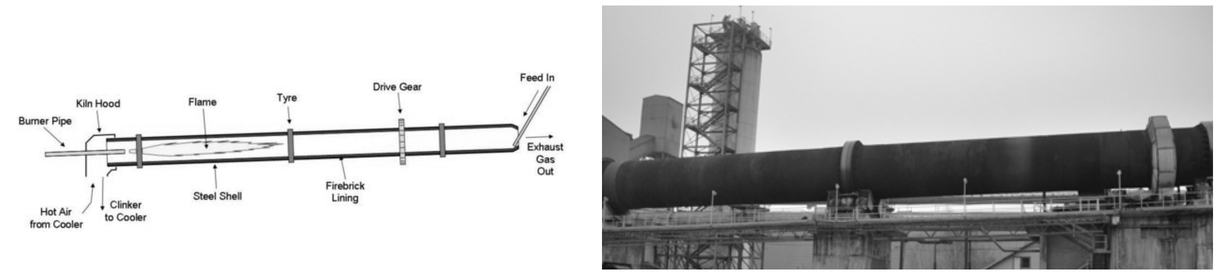

Figure 1. Rotary kiln: left - general layout[1], right – cement plant Kakanj

Figure 1-right shows such a kiln in the cement plant Kakanj. Rotary kiln is 70 m long and its inner diameter is 4.4 m. Slope is 3.5°, and it has 2 rev/min. The mass of kiln in Kakanj, including refractory line and feed, is around 1100 tones and is carried on three tyres and set of rollers, spaced along the length of the kiln. The capacity of the plant is 120 tone of rawmix per hour.

Tyres, sometimes called riding rings, usually consist of single annular steel casting, machined to a smooth cylindrical surface, which attach loosely to the kiln shell. The tyre rides on pairs of steel rollers, also machined to a smooth cylindrical surface. The roller must support the kiln, and allow rotation that is as nearly frictionless as possible. In some situations, such as in the cement plant Kakanj, the rollers have a short operating life (about a year) and a proper analysis is needed to prevent this to happen (rollers crack at their surface and huge pieces of roller material can be torn off).

There is a little attention paid to this problem in literature. Xiao et. al. [2,3] gives general mechanical model for indeterminate kiln with variable bending rigidities, arbitrary supports and complex loads. Correlation between roller forces and axis deflection is established. Del Coz Diaz et. al. [4], used Finite Element method (FEM) to the nonlinear analysis of cement rotary kiln in Algeria. A reduced model, consisting of shell section with its corresponding tyre and roller station, has been constructed. The model has been developed in Ansys 5.7.1. Some conclusions are that augmented Lagrange method is adequate for contact simulation and sliding stresses are negligible in comparison with normal ones.
This paper presents results from the first step in the analysis of this complex problem by examining the loads acting on the rollers and kiln tyres, and thus the stress field in them. Only elastic analysis (Hertzian theory) is used in order to determine whether the stresses in rollers are high enough to affect their short operating life. Both analytical and numerical (FEM) solutions are presented.

2. KILN SUPPORT REACTIONS

Kiln shell with multiple two-roller supports is loosely fitted in kiln tyres and can be regarded as simply supported beam whose supports are equivalent to simple supports. Under common condition, kiln inlet and outlet do not support shell, therefore kiln can be taken as a cantilever beam. To calculate support reactions, a simplified procedure is used and certain presumptions are taken:

- Raw-mix in kiln is evenly distributed along kiln length. Using the full kiln capacity (120 tones), angular speed and its incline, distributed load from raw-mix is calculated: Q=36.47 kN/m.
- Raw-mix is symmetrically distributed around vertical axis of kiln (Figure 2-left). This means loads from material weight are equally distributed on each roller in a pair. Real distribution is shown in Figure 2-right, ie. raw-mix causes uneven load distribution between rollers due to inertial effects.

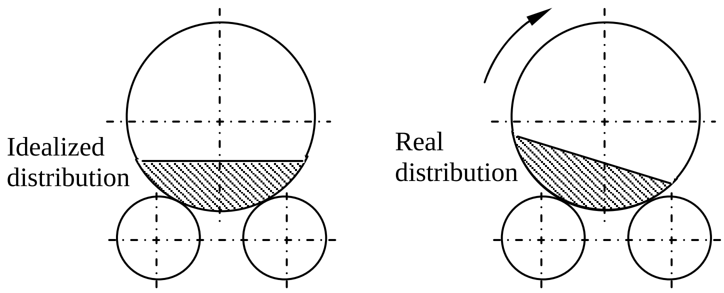

Figure 2. Distribution of raw-mix around vertical axis

- Temperature does not effect shell rigidity.
- Specific weight of line bricks on inlet side is 44 kN/m for the length of 18.2 m. The remaining part of the kiln has line bricks with specific weight of 73.78 kN/m.

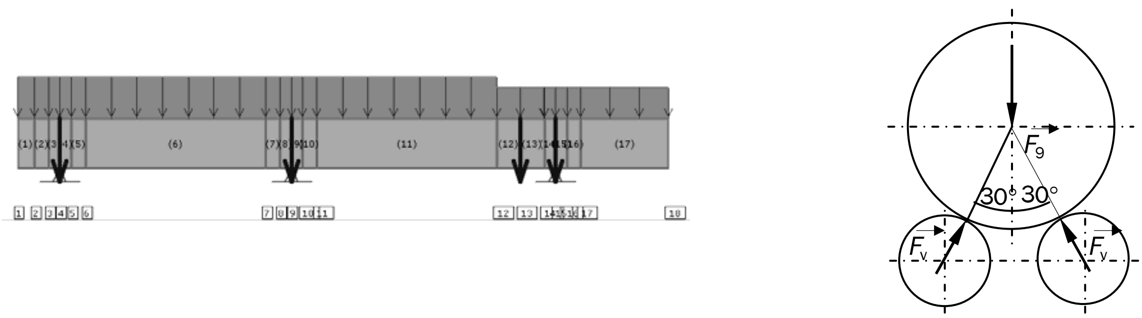

Figure 3. left - Kiln modeled as a cantilever beam, right - roller stations with reactions

Due to different shell rigidity, supports, drive gear, distributed loads, kiln is divided into 17 segments. For every shell segment, axial moment of inertia is calculated. To obtain support reactions software MdSolids3.2 is used. A simplified model of the kiln is given in Fig.3-left. Support reactions on nodes 4, 9 and 15, ie. on the rollers are as follows.: F_4=1875 kN, F_9=3767.7 kN and F_{15}=2944 kN. As expected, the highest force acts on the middle rollers (support 9) and the force on each roller can be obtained from Fig.3-right and is equal 2177.8 kN.

3. ANALITICAL SOLUTION OF HERTZIAN CONTACT STRESS IN A SUPPORTING ROLLER

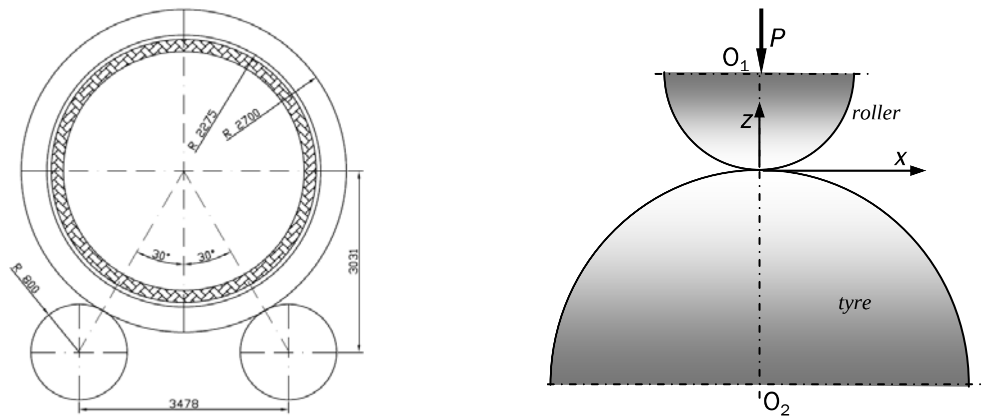

Figure 4. Tyre-roller contact: left – real geometry, right – simplified FE model

Hertzian pressure is the contact pressure between the roller and tyre. It is a function of their diameters but mostly the face width of the tyre – the wider the contact line between the tyre and roller, the lower the Hertzian pressure. When two cylindrical bodies, with their axes both lying parallel to the y axis in Oxyz coordination system, are pressed in contact by a force *P* per unit length (Fig.4-right), they make contact over a long strip of width 2*a* lying parallel to the y-axis. Force per unit length on roller in this case is 2222.24 N/mm. Now, using Hertz formulae [5] contact width *a* and contact pressure distribution, respectively, can be obtained as follows:

- $a = \sqrt{\dfrac{4PR}{\pi E^*}} = 3.89\text{ mm}$ .... (2)

where R is equivalent radius $R=(1/R_1+1/R_2)^{-1}$=617.1 mm, E^* is equivalent modulus of elasticity $E^*=((1-\mu^2)/E_1+(1-\mu^2)/E_2)^{-1}$=115385 N/mm^2. Indices 1 and 2 relate to tyre and roller, respectively.

- $p(x) = \dfrac{2P}{\pi a^2}\sqrt{a^2 - x^2}$ .... (3)

As can be seen from equation 3, pressure distribution is parabolic and maximum pressure is in the point of contact – p_0=363.7 MPa. Distribution of stresses σ_z, σ_x and τ_{xz} along the z-axis can be obtained from expressions given in figure 5, where their graphical representation is also presented. Maximum shear stress is at the depth z=0.78·*a* = 3.03 mm and its value is $\tau_{max}=0{,}3\cdot p_0$=109.11 MPa

$$\sigma_x(z) = -\frac{p_0}{a}\left[\left(a^2+2z^2\right)\sqrt{a^2+z^2} - 2z\right]$$

$$\sigma_z(z) = \frac{-p_0 a}{\sqrt{a^2+z^2}}$$

$$\tau_{xz}(z) = \frac{1}{2}\left[\sigma_z(z) - \sigma_x(z)\right]$$

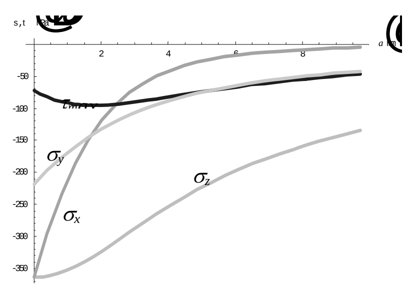

Figure 5. Stress distribution in the roller with corresponding expressions

4. FE ANALYSIS OF THE HERTZIAN CONTACT STRESS

In order to make a comparison between analytical solution and numerical analysis, 2D model of roller and tyre is modeled in ABAQUS. Only a half of both tyre and roller is considered. Both parts are made of steel and appropriate material properties are set-in. Total amount of cells is 150092 with 151046 nodes. Domains are firstly partitioned and then meshed in order to obtain denser mesh at the point of contact. The problem is linear, and the contact condition is modeled using contact pair approach. Discretization method is node to surface and sliding formulation is small sliding. Contact property is frictionless. Force per unit depth of $2222.24 \cdot 10^3$N/m is divided by roller diameter to obtain the pressure to be applied (p=1.39 MPa). Calculated stress distributions are given in Fig.6 for a small domain segment near contact area.

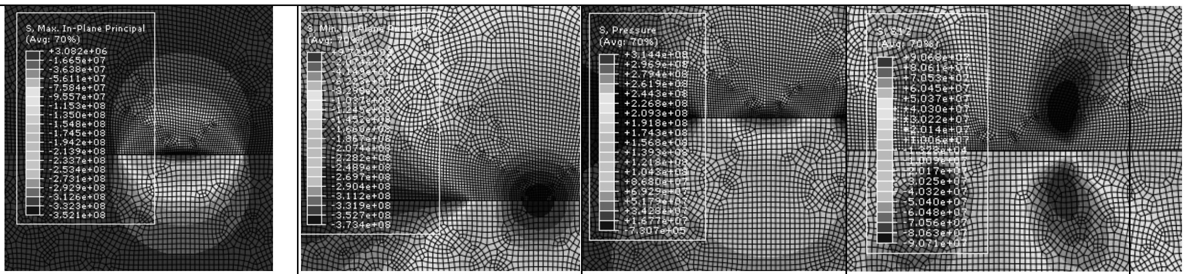

Figure 6. Stress distribution from numerical simulation: a) σ_x, b) σ_z, c) pressure, d) τ_{xz}

Comparison between stress values from FEM analysis and analytical method reveals following:

- Maximum pressure acts at the middle of contact length and its value from FEM is $p_{0\text{-FEM}}$=314.4 MPa, comparing to analitical solution of p_0=363 MPa. Deviation is 13 %.
- At the middle of contact surface stresses σ_x and σ_z have maximum values. Analytical solution is $\sigma_x=\sigma_z=p_0$=363 Mpa, whereas FEM method gives $\sigma_x(z=0)$ = -352.1 MPa and $\sigma_z(z=0)$= -373.4 MPa. Both values deviate for 3%.
- Shear stress τ_{xz} has the highest value for z=0.78a and for two-dimensional case analytical value is 109.11 MPa. FEM shows shear stress with maximum value of 90.68MPa. Deviation is 16%.

According to some sources [6], allowable Hertzian surface pressure is about 400-428 MPa. Calculated value using a simplified procedure is not far from it, suggesting that more detailed and complex analysis is needed, and FE analysis proved to be a good tool for achieving this.

5. CONCLUSION

This paper presents a simplified analysis of the contact stresses present in the rollers supporting the rotary kiln in the cement plant Kakanj. Thus, to obtain support reactions, kiln is considered as a cantilever beam. Highest support reactions are found to act on the middle supporting rollers. Contact stresses are calculated using Hertz theory and FE analysis. Agreement between results from both methods is satisfactory. The value of the highest stresses suggests that the stress field is high enough to cause failure (and fracture) of the rollers on the contact surface. The next step in the analysis will be to apply more realistic conditions, ie. dynamic, nonuniform and asymmetric loading, temperature effects, rolling contact, cyclic loading, etc. in order to find the reasons of rollers failure.

6. REFERENCES

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