

NUMERICAL SIMULATION OF TILES TRANSPORTATION IN A KILN BY MEANS OF CERAMIC ROLLERS

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Summary: *The paper deals with the multibody modelling and simulation of a very unusual problem motivated by the real industry task. The aim of the simulations was the verification of the problems arising from the tile movement through very long kilns. The row of tiles that is initially straight at the kiln beginning is coming out curved at the kiln end. The SIMPACK simulation tool was chosen for the solution of this problem. Two approaches to the modelling of the complex system of tiles and rollers are shown in the paper. The more suitable one is based on the polygonal contact model developed for the fast and efficient contact analysis between complexly shaped rigid bodies. The simulation results obtained using the SIMPACK simulation tool are compared with the results calculated by the LS-DYNA software.*

1. Introduction

HOB CerTec s.r.o., the Czech producer of ceramic rollers, which are used in modern kilns in order to transport ceramic tiles through a kiln, requested numerical simulations of the tile movement in a kiln. The rollers are arranged longitudinally one beside other, supported on their ends and driven by a drive system on the end. Tiles are placed on the rotating rollers and it causes the moving of the tiles through the kiln.

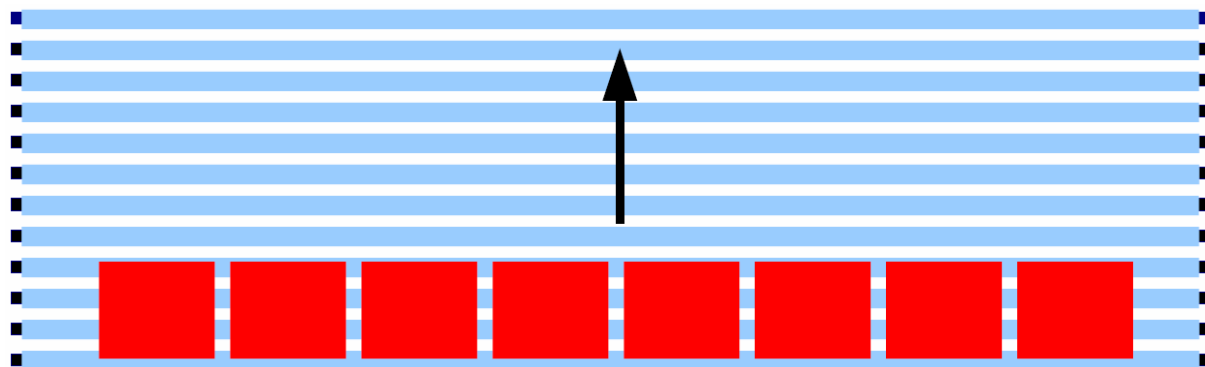


Fig. 1: View from above of the initially straight row of tiles placed on the rollers.

The aim of the requested simulations was the verification of the problems arising from the tile movement through very long kilns (more than one hundred meters long). The row of tiles,

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which is initially straight at the kiln beginning (see Fig. 1), is coming out curved at the kiln end or after the passage through a certain part of the kiln (see Fig. 2). This fact brings undesirable influences on different aspects of the tile burning. The purpose of the computational models was also the investigation of the roller design sensitivity and the manufacturing inaccuracy sensitivity on the studied effect.

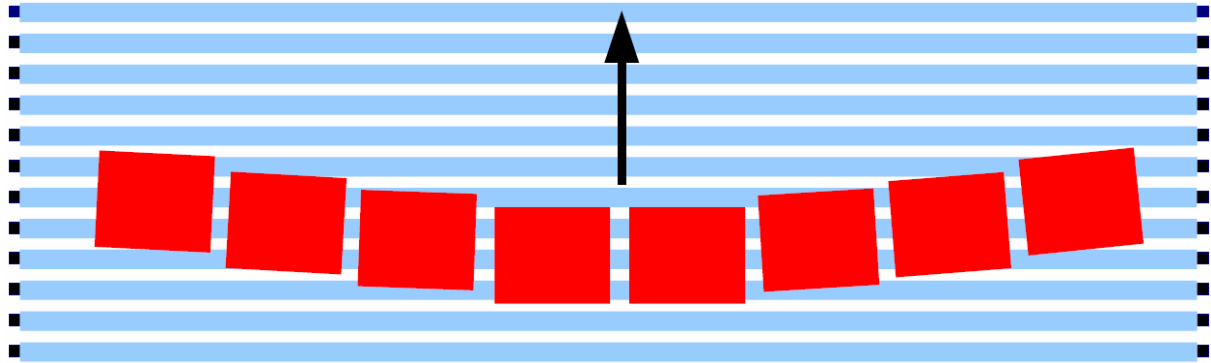


Fig. 2: View from above of the curved row of tiles after the passage through a part of the kiln.

The HOB CerTec s.r.o. company produces many types of rollers with respect to the shape and flexibility intended for different tiles (with respect to dimensions and weight). Due to the production technology the rollers can be of a conical shape (see Fig. 3). Owing to the cooling in vertical position the lower end can be wider (usually 0.001 m or 0.002 m difference of the end diameters) and therefore the goal of the modelling was also to verify if the tiles problem can occur also for ideally shaped rollers. Typical dimensions are length $l = 3.9$ m, outer diameter $D = 0.052$ m, inner diameter $d = 0.04$ m. Reference tile velocity is 150 meters per hour (0.0417 m/s).

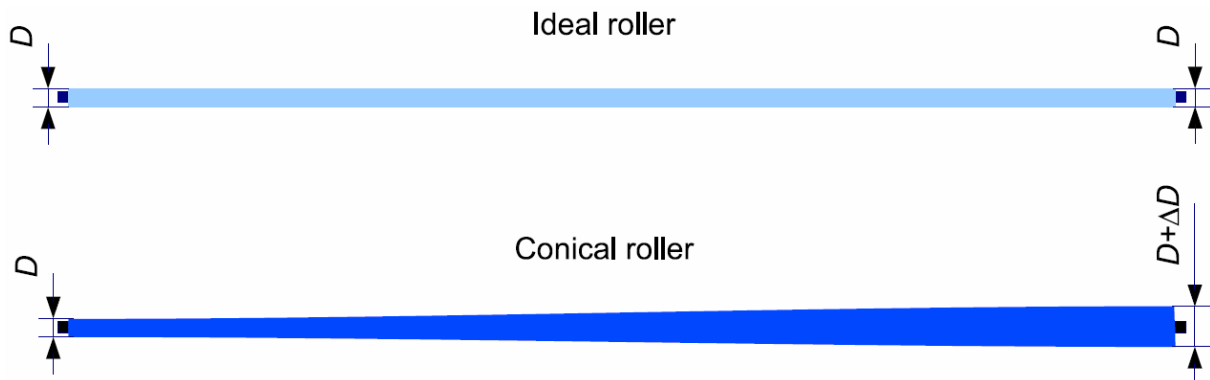


Fig. 3: Shapes of ideal and conical rollers (not in a real scale and ratio).

It was found after the literature review that such problem had not been solved and published yet. Because of the nature of the system of tiles and rollers it is complex dynamic problem with the presence of multiple contacts and friction forces. Moreover the rollers have to be considered as flexible bodies with their bending behaviour. Hence it was decided to use the commercial multibody code rather than to develop some special purpose modelling tool with respect to the complexity of the problem. The SIMPACK simulation tool was chosen for the model development and numerical simulations.

Another possibility was the selection of a finite element incremental explicit solver (e.g. LS-DYNA). This option will be discussed further on.

2. Briefly about the SIMPACK simulation tool

The SIMPACK simulation tool (INTEC, 2007) is being developed in INTEC GmbH, Weßling, Germany. Similarly as other MBS software it is intended for investigating kinematic and dynamic properties of a nonlinear three-dimensional coupled mechanical system consisting of many bodies. The approach to solving the tasks in the field of mechanics using computer models, which is based on the systems of bodies, enables to solve substantially more general problems than the approach based on the finite element method because it is not dependent on the continual model of the investigated system. As this approach is more general and due to character of studied mechanical systems the demands for the computing time of the solution of the nonlinear equations system are growing. When creating a multibody model it is necessary to pay attention to choosing the number of bodies, the number of kinematic pairs and especially the total number of degrees of freedom in kinematic pairs of a mechanical system, i.e. to optimally interpret the physical substance of the solved problem. The total number of degrees of freedom in kinematic pairs determines the number of constructed nonlinear equations of motion, solution of which should be within a real period of time.

Multibody models are created by a finite number of bodies connected by kinematic pairs and massless force elements, which enable to model spring-damper structural parts. With respect to the multibody models creating methodology and automatic generating of the differential equations in the SIMPACK simulation tool kinematic pairs are classified into two types (two separate groups within the framework of modelling in the SIMPACK simulation tool) – *joints* and *constraints*. Exactly one joint with a given number of degrees of freedom belongs to each body, which enables a body motion considering the previous body in a kinematic chain. Constraints are utilized for the closing of kinematic chains, i.e. for creating kinematic loops, and constraining the relevant degree of freedom. Bodies can move in space in the framework of joints, constraints, force elements, the way of coupling to the reference frame and boundary conditions. Each body is defined by inertial properties (mass, centre of mass coordinates and moments of inertia). It is possible to bind different *markers* to the bodies. A marker is a point, in which a local coordinate system is defined. Markers can be used to locate reference frames, to define the centre of mass. Through the markers it is possible to couple bodies by joints, constraints and force elements, it is possible to act on bodies by applied forces and torques, etc. After creating a multibody model it is possible to simulate the modelled system motion. In simulating motion with multibody models in the MBS software non-linear equations of motion are generated. The equations are solved by means of numerical time integration. Generally, displacements, velocities and accelerations of the individual bodies, forces and torques acting in kinematic pairs and force elements are the monitored quantities. It is possible to obtain results in the form of time series, in the form of graphs or in the form of multibody model visualisation (static or with animation). In outputs in the form of graphs it is possible to compare e.g. influences of changes of various parameters of the multibody model on the simulations results, it means to operatively evaluate influences of permitted design adjustment on the desired kinematic and dynamic properties of the real structure.

Besides the basic SIMPACK Kinematics & Dynamics module it is possible to buy additional SIMPACK simulation tool modules and data interfaces with other software. In ŠKODA VÝZKUM s.r.o. there are at disposal the SIMPACK Automotive+ module (support of road vehicles modelling including tire models), the SIMPACK Wheel/Rail module

(support of rail vehicles modelling including wheel-rail contact models) and the SIMPACK Contact module (support of contacts between bodies modelling).

3. Solution based on the standard SIMPACK Contact module features

At first the problem was solved by the standard elements of the SIMPACK Contact module. Several possibilities are available for the contact modelling:

- *Single point contact.* Two points, which can be in a contact, are defined on different bodies. The concept of moved markers that are moving according to potential contact points on the contact boundary is used. The force elements in order to compute a normal contact force and a tangential friction force are defined between the points.
- *Multipoint contact.* It is based on the usage of two separate contact curves between two bodies.
- *Hertzian contact.* The contact forces are determined for predefined contact situations (ball-to-ball, cylinder-to-cylinder, ball-to-plane, cylinder-to-plane contacts).

The problem of the tiles movement on the rollers is characterized by multipoint multiple contacts and therefore any of the standard methods was not suitable for the definition of the multibody model. Finally unilateral spring-damper elements and a set of moved markers were created in order to simulate behaviour of the tiles placed on the rotating rollers.

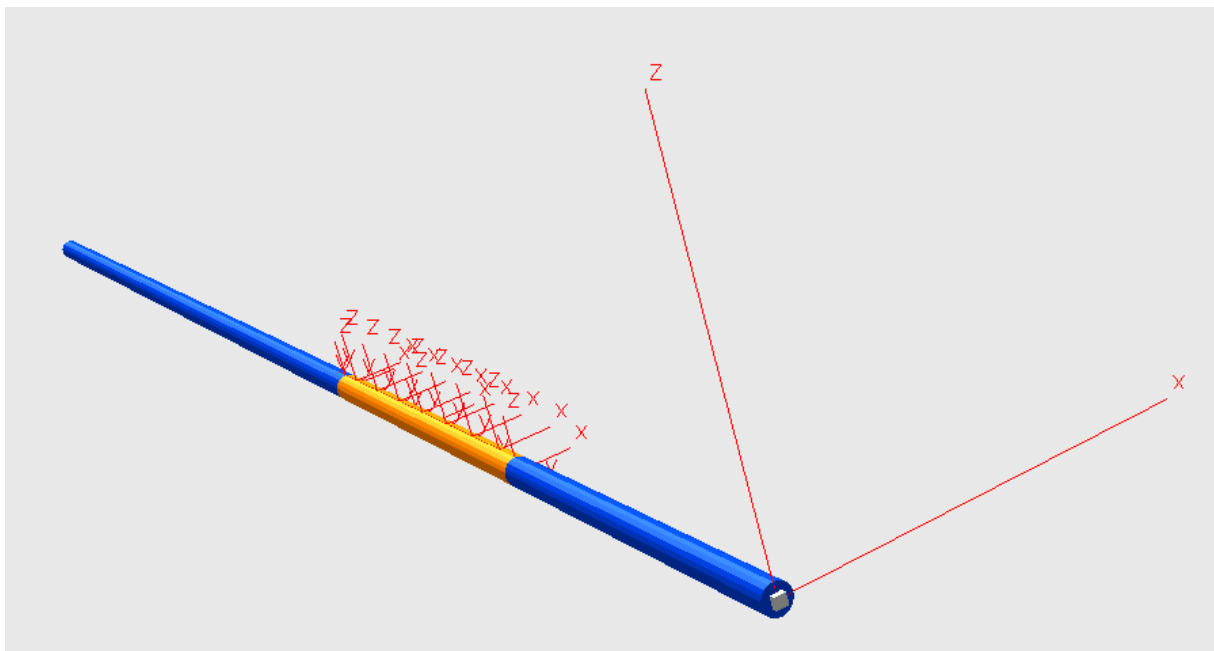


Fig. 4: Roller substructure with one emphasized roller segment and its markers (standard SIMPACK Contact module approach).

Because of the roller dimensions and boundary conditions (supported on the ends) the flexibility of the rollers is not negligible characteristics. The possibilities of the SIMPACK modelling in ŠKODA VÝZKUM s.r.o. are limited to the rigid body modelling so some special approach had to be used for the roller modelling. Each roller (flexible body) was

modelled using so called finite segment method (according to Shabana, 1997) that is based on the artificial subdivision of a flexible body into the system of rigid bodies coupled by particular joints with spring-damper force elements in order to represent the flexible behaviour. The stiffness and damping parameters can be calculated using the standard elasticity theory (Wittbrodt et al., 2006). Moreover the general nonlinear characteristics can be used instead of linear expressions and thus e.g. the plasticity can be defined. After the testing analysis and after the consideration of operational conditions and possible contact scenarios each roller was composed of five rigid body segments (see Fig. 4) coupled by universal joints with predefined spring-damper elements that represent flexible bending properties. Axial and torsional deformations were neglected with consideration of the problem nature. Both ends of the roller were supported in radial directions and one end was also supported in axial direction. This end was driven in the rheonomic joint in order to ensure the constant angular velocity of the roller. Each segment was equipped by the set of moved markers (see Fig. 4) that were rotating in the opposite direction with the same angular velocity as a roller. These markers were steady on the upper side of rollers in the global inertia coordinate frame and they could be used for the definition of the contact forces.

The tile (eight tiles in a row) was modelled as one rigid body with defined inertia properties and dimensions that were used for the contact definition. The chosen pair of two contact markers is shown in Fig. 5. The frictionless contact force defined using the unilateral spring-damper force element was calculated by the vertical relative displacement of these markers. The special purpose forces had to be used for the pushing (driving) of the tiles in the longitudinal x -direction due to the rollers rotation. The expression for the force definition was developed such that the sliding velocity of the tile was the same as actual instantaneous velocity on the top of the roller. The penalty formulation was used in the expression. The friction force was defined in the lateral y -direction.

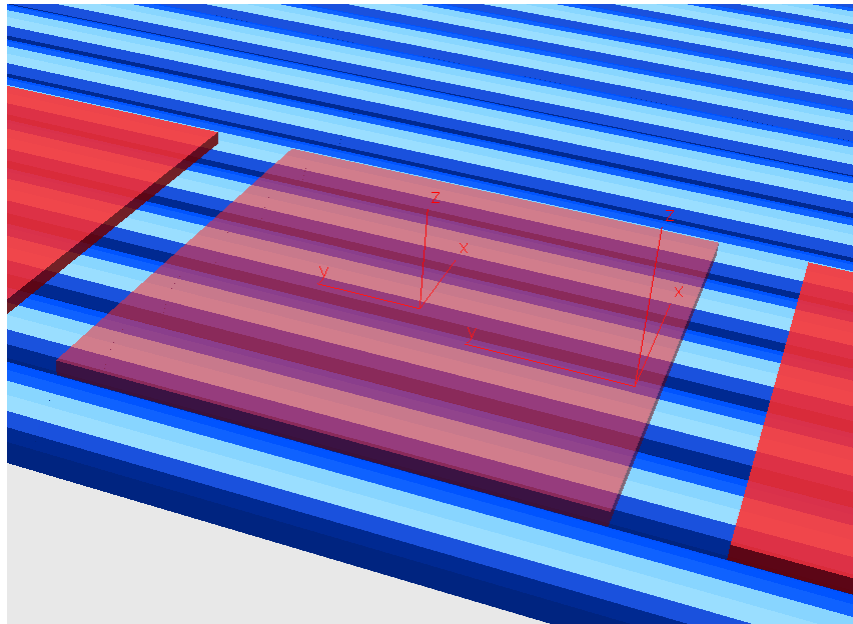


Fig. 5: Detail of the tile model with two markers defining a contact force.

Because there were many rigid bodies and also very large number of three types of force elements between the bodies it was inefficient to use manual method for the creation of the

SIMPACK model. The special parametric generator of the SIMPACK source code was developed in the MATLAB system for the purpose of the automatic model creation.

Due to the large size of the multibody model (mainly many contact and special purpose forces) only one row of tiles on several rollers could be simulated. Unfortunately the simulation results were not sufficient and realistic enough and therefore a different solution was searched. The problem was also very long computational times (in the range of days). Especially the rounded shape of the roller could not be represented by the approach with a set of moved marker on the top of roller segments.

4. Utilization of the Polygonal Contact Model

Another possibility was the usage of the PCM (Polygonal Contact Model) method (Hippmann, 2004a; Hippmann, 2004b) in connection with the SIMPACK User module. These tools were finally used for the creation of the multibody model of the row of tiles moving on the group of rotating rollers.

4.1. Generally about the Polygonal Contact Model

This modelling tool was developed independently of the covering multibody codes by Dr. Gerhard Hippmann (Hippmann, 2004a; Hippmann, 2004b). At first it was implemented by the author into the SIMPACK simulation tool and after that some other codes were also extended with user subroutines based on the PCM.

The PCM method is based on the body surface representation by polygonal meshes and on the usage of the elastic foundation model. It is a very robust algorithm for complexly shaped bodies. Complex surfaces can be described by polygonal meshes composed of vertices (points) and faces (triangles, quadrangles, pentagons). Most of graphic software tools and CAD system are able to export these graphic format and many Internet web pages with free polygonal meshes exist and could provide the source of mesh files. The PCM method uses the simplest representation of a surface by triangular mesh (in so called Wavefront format) and some restrictions are defined for particular meshes. The mesh should be without cracks, it should have any duplicate vertices and it should have a consistent orientation.

The algorithm of the PCM method that is implemented as a user defined force element in multibody codes can be summarized in three steps (Hippmann, 2004a):

- (1) *Collision detection*. It determines if the contact pair is in touch. The very fast collision detection is possible due to the bounding volume hierarchy approach used mainly in virtual reality applications. Several levels of bounding volume hierarchies are shown in Fig. 6 for the illustration.
- (2) *Contact element determination*. This step is intended to the finding of the intersecting polygons and constructing of so called contact patches (contact elements, see Fig. 7).
- (3) *Contact force determination*. The overall contact force of all contact elements is determined in the last step and applied as a force and a torque to the pair of the bodies in a contact. The expression for the contact force is based on the elastic foundation model (see Fig. 8). The regularized friction force is also generated.

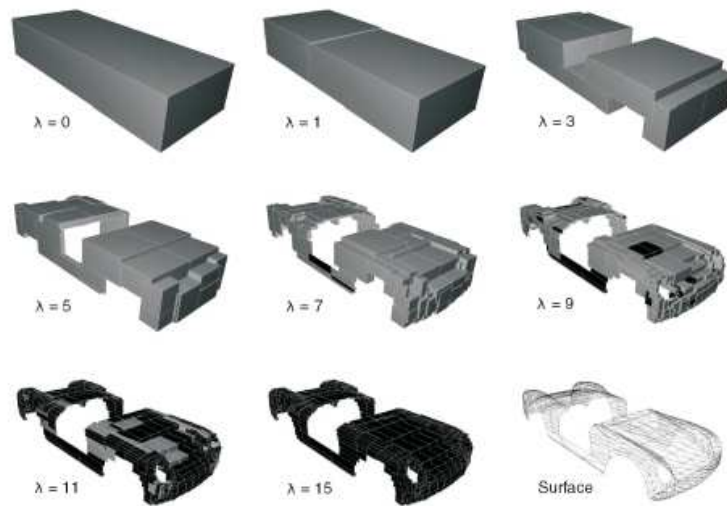


Fig. 6: Illustration of bounding volume hierarchies (taken from Hippmann, 2004a).

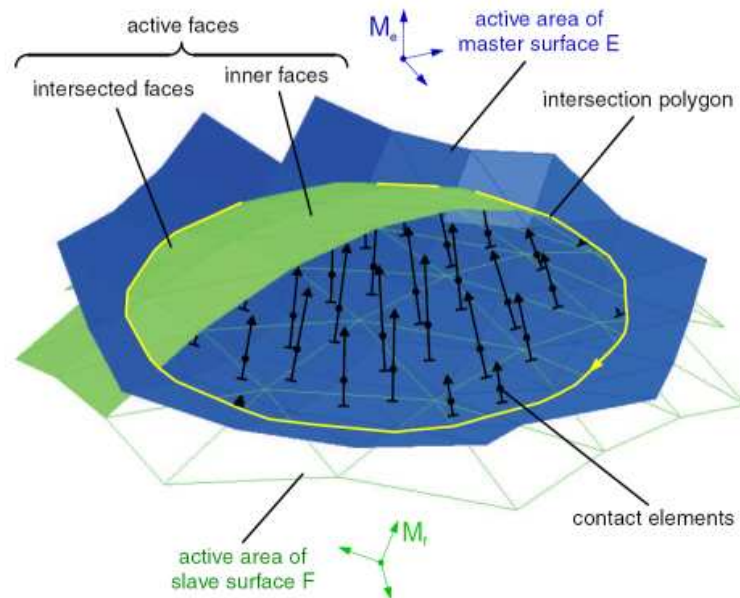


Fig. 7: Intersection polygon and contact force determination (taken from Hippmann, 2004a).

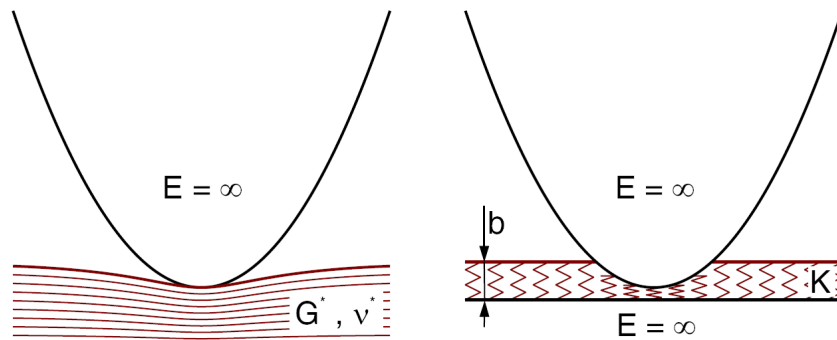


Fig. 8: Elastic foundation model (taken from Hippmann, 2004a).

4.2. Multibody model using the PCM and its dynamic response

The developed multibody model in the framework of the SIMPACK simulation tool using the PCM method consists (similarly as the previous model) of the roller substructures and of tiles in one row. A special user PCM force element was employed for the contact and friction definition between the tiles and the rollers.

The roller flexibility was considered as in the model presented in the previous chapter. The surface of each segment was described by the polygonal (triangular) mesh. Considering the regular shape of the cylinder the automatic mesh generator was developed and implemented in the MATLAB system for the parametric mesh creation. The sensitivity of the system dynamic response with respect to the mesh density was observed and the suitable mesh parameters were chosen for the final realization of the model (see Fig. 9).

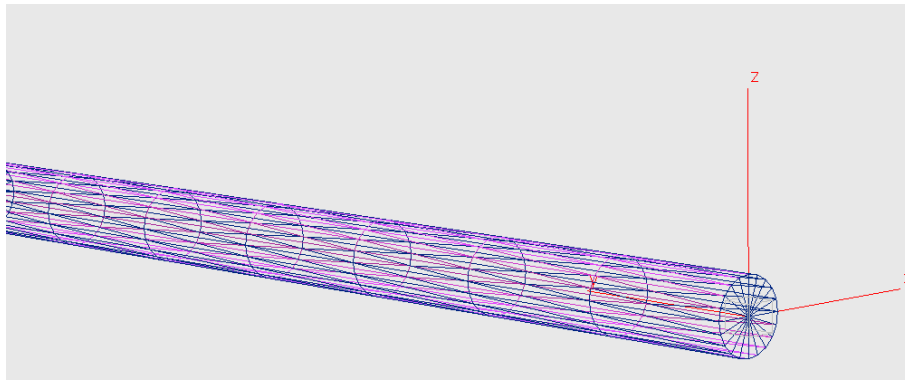


Fig. 9: Roller model for the PCM approach (triangular mesh).

Due to the nature of the PCM method the tile surface could be represented by a very simple triangular mesh. Each tile was modelled as one rigid body and the inertia properties of the tiles were the same as in the previous model.

The big advantage of the PCM approach is that the contact between one tile and one roller segment was defined using only one force element (Fig. 10) in contrast with the previous moved marker approach. Although the number of force elements was still large and therefore the automatic source code generator in the MATLAB system was used.

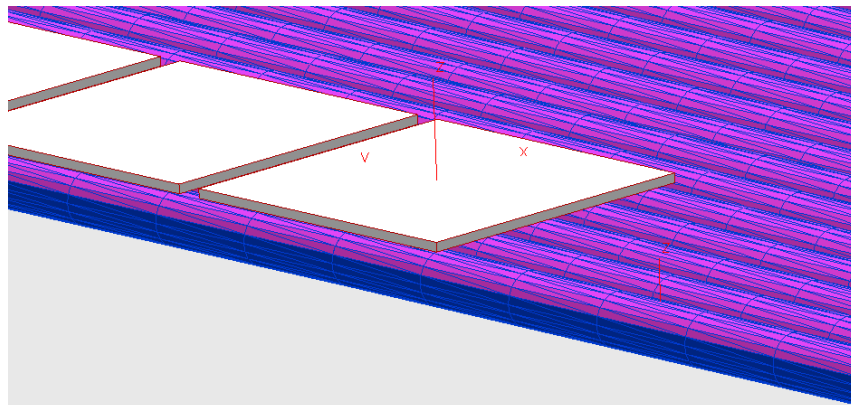


Fig. 10: Tiles and rollers model for the PCM approach.

The computational times for the tasks were in the range of tens of hours. The PCM model exhibits more realistic behaviour than the previous one based on the standard SIMPACK Contact module elements. The experimentally observed effect of the curved row of tiles (see Figs 1 and 2) was validated by the numerical simulations.

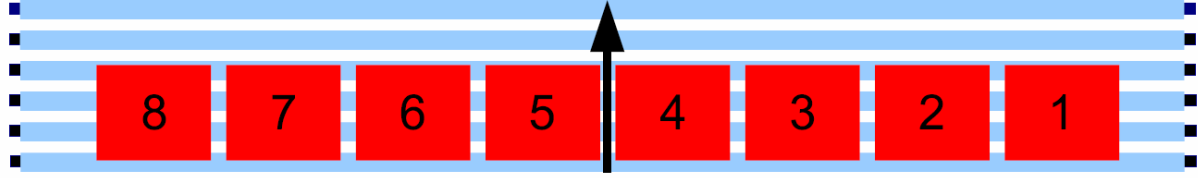


Fig. 11: Numbering of the tiles (SIMPACK).

Numbering of tiles can be seen in Fig. 11. The plot of the time history of the x -position difference between the motion of outer tile 8 and inner tiles 5 and 6 is shown in Fig. 12. It is obvious that the difference is increasing and therefore the curved row effect (Fig. 2) is verified. The similar plot for the motion of tile 1 is shown in Fig. 13.

After the analysis of the results and after the performed sensitivity analyses it can be concluded that the effect is caused probably by the difference between the motion of the inner and outer tiles because of the flexibility of long rollers, which are bent by the tile weights.

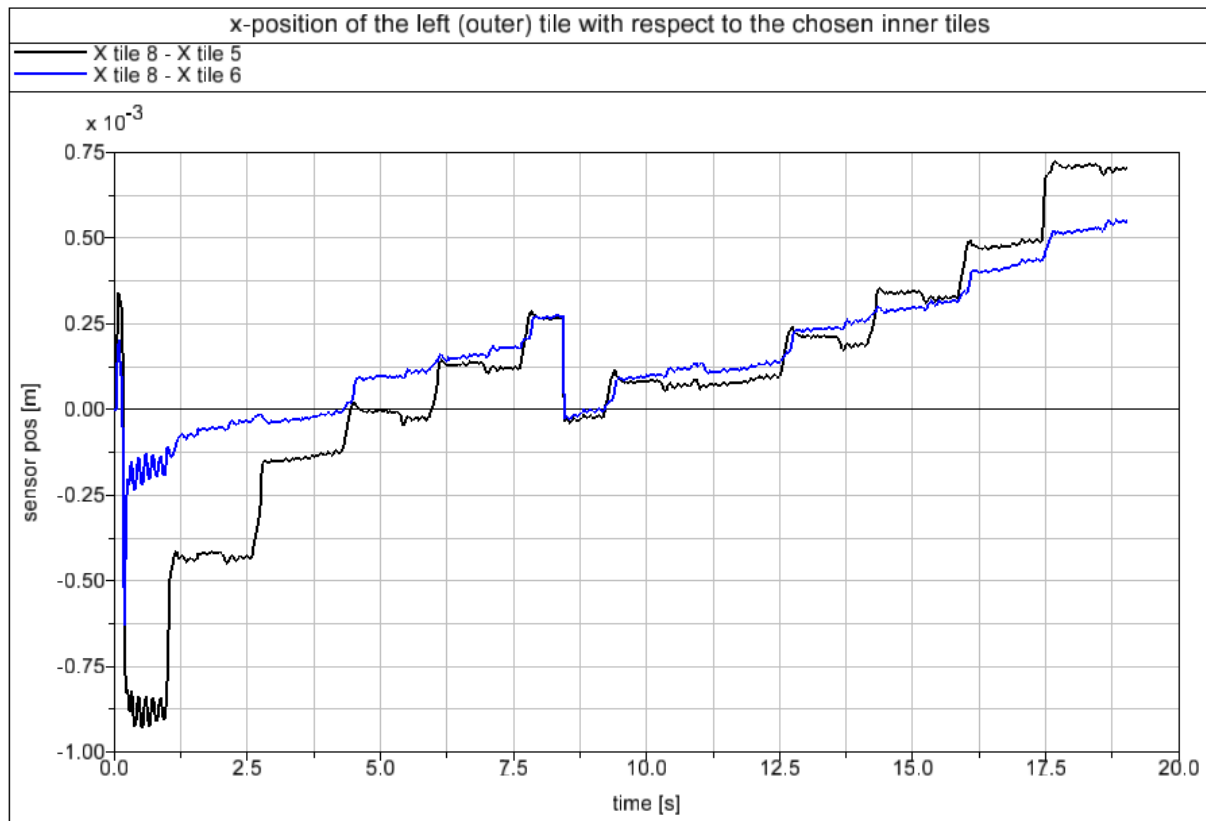


Fig. 12: Time history of the x -position difference for tile 8.

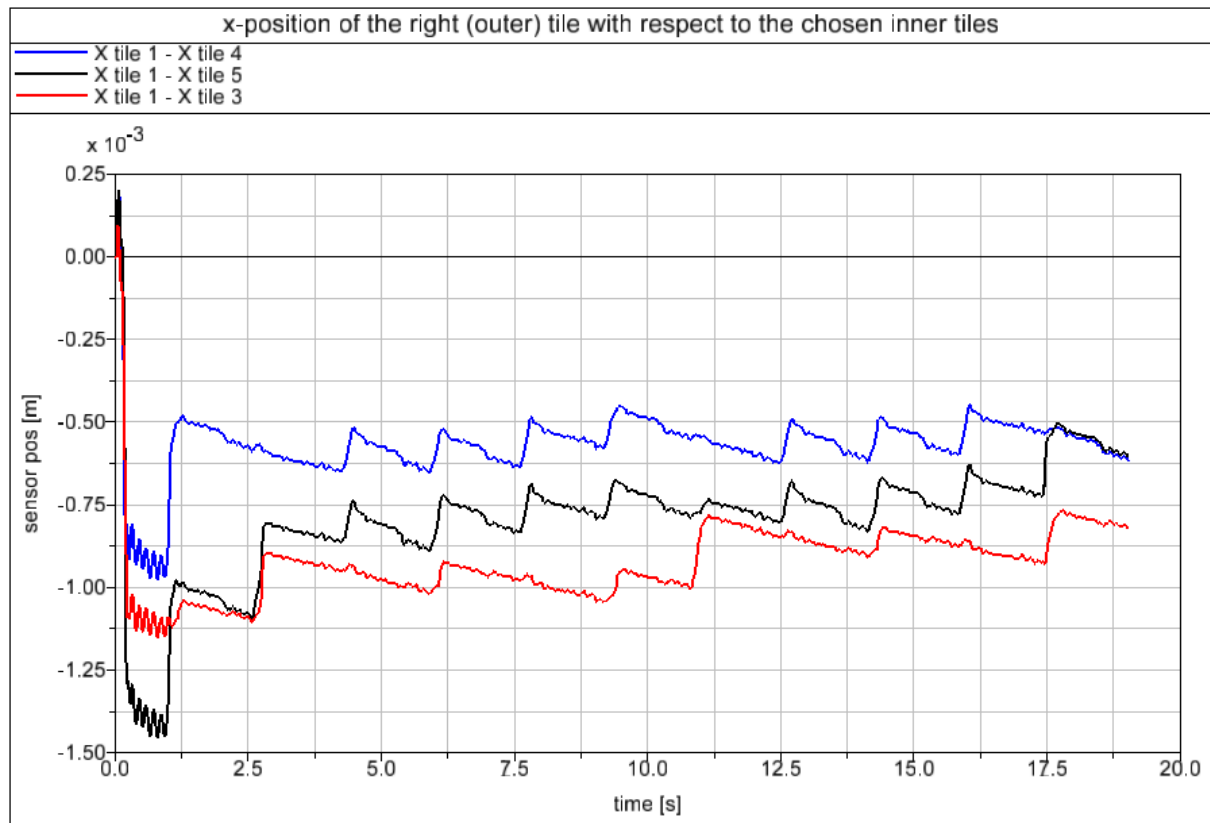


Fig. 13: Time history of the x -position difference for tile 1.

5. Comparison with the LS-DYNA software

The simulation results were compared with the results obtained by another simulation methodology using the LS-DYNA software, which is based on the explicit finite element solver. The results of these simulations were described and documented in Jankovec (2006). The overall view on the model is in Fig. 14. The tiles and the rollers were discretized by finite elements. As the LS-DYNA deals with short duration events some improvements in the model definition were necessary in order to simulate the tile movement problem (Jankovec, 2006) that is characterized by longer times.

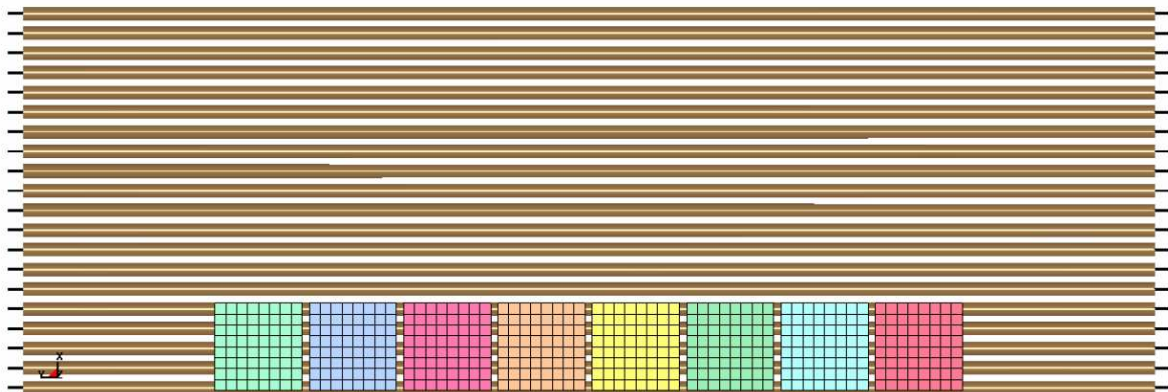


Fig. 14: Finite element model of the tiles and rollers (LS-DYNA).

The labels of the tiles used for the evaluation of the LS-DYNA results are clear from Fig. 15. The differences between the longitudinal motion of the chosen tiles are shown in Fig. 16. It can be concluded that the same effect as in case of the SIMPACK simulations was observed.

Time = 5998
max displacement factor=5

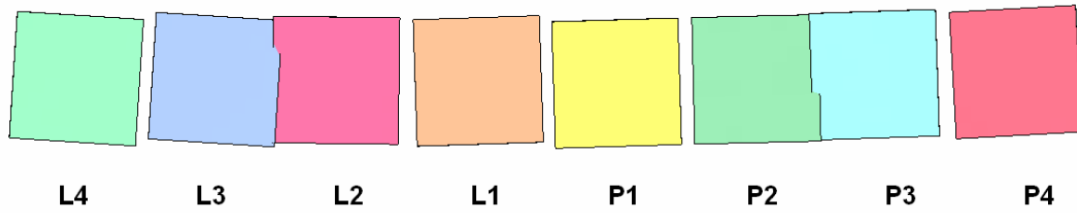


Fig. 15: Final displacements (scaled) and numbering of the tiles (LS-DYNA).

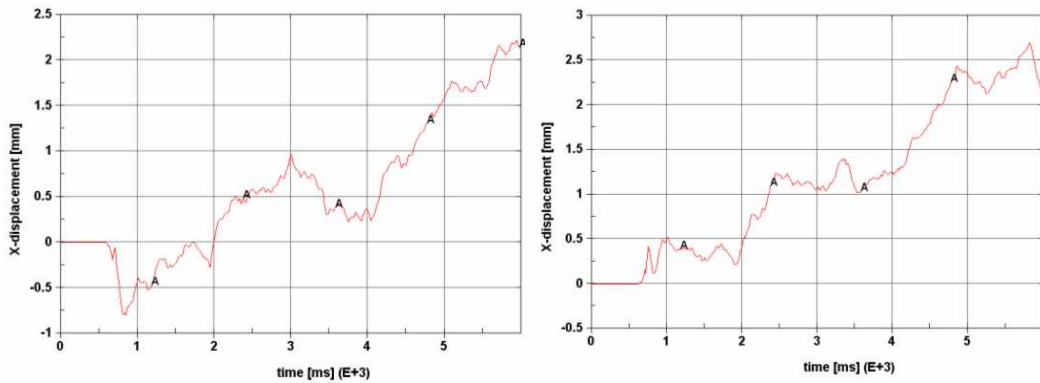


Fig. 16: Differences $x_{L4} - x_{L1}$ and $x_{P4} - x_{P1}$ of x -coordinates of the tiles (LS-DYNA).

6. Conclusions

This contribution deals with an unusual application of the multibody dynamics approaches in the ceramic industry. The problem of the row of tiles moving on the ceramic rollers, which is characterized by multiple multipoint contacts and by flexible behaviour of the rollers, was numerically simulated. The SIMPACK software was employed as the simulation tool.

Two approaches to the modeling of the contacts and particular forces were introduced. The more suitable one was the utilization of the Polygonal Contact Model developed by Dr. Hippmann and implemented to the SIMPACK using the SIMPACK User module. The PCM is very robust and efficient method for the solution of the contact problems in the framework of multibody systems. It is based on the polygonal mesh representation of body surfaces and on the contact force determination by means of the elastic foundation model. The simulation results were compared with the results obtained by another simulation methodology based on the LS-DYNA software and the problematic effect of the curved row of tiles was verified.

Acknowledgement

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