UTILIZATION OF THE POLYGONAL CONTACT MODEL FOR THE SIMULATIONS OF THE TILES MOVING THROUGH A KILN

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Main aim

To develop the computational model suitable for the numerical simulations of the tiles moving through a kiln by means of ceramic rollers.

Talk outline

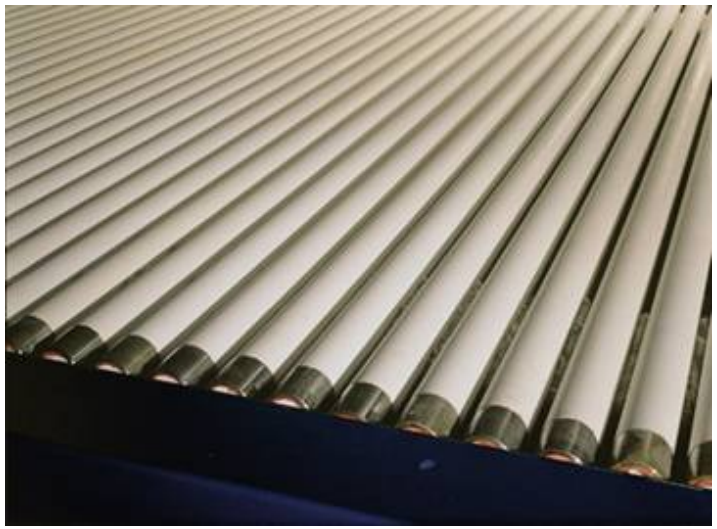
- Introduction and problem description
- Modelling using standard contact elements (FE18 approach)
- About the polygonal contact model (PCM)
- Utilization of the polygonal contact model
- Conclusion and comparison with LS-Dyna software

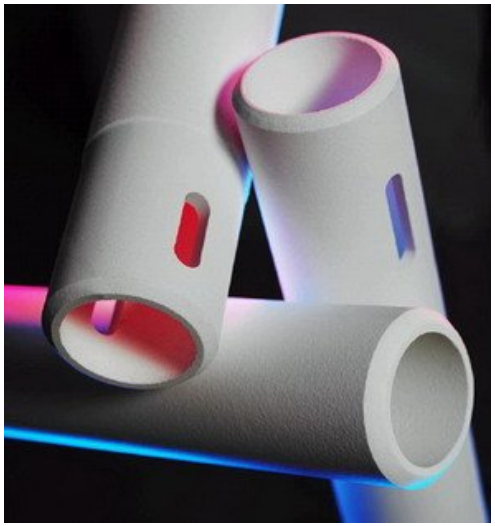
Introduction

- ŠKODA VÝZKUM s.r.o. (ŠKODA RESEARCH Ltd.)
  - Former part of ŠKODA HOLDING company (transportation, energy)
  - Hundred years of the research in Pilsen (1907 – 2007)
  - Today $\longrightarrow$ standalone research and testing company (computer-aided modelling, fluid mechanics, mechanical and dynamical testing laboratories, noise and vibration, . . .)
- Multibody dynamics in ŠKODA VÝZKUM s.r.o.
  - SIMPACK, **alaska**, in-house software (MATLAB)
  - Vehicle dynamics (trolleybuses, buses, rail vehicles), biomechanics, special problems (nuclear engineering – control assemblies, tiles, . . .)

Introduction

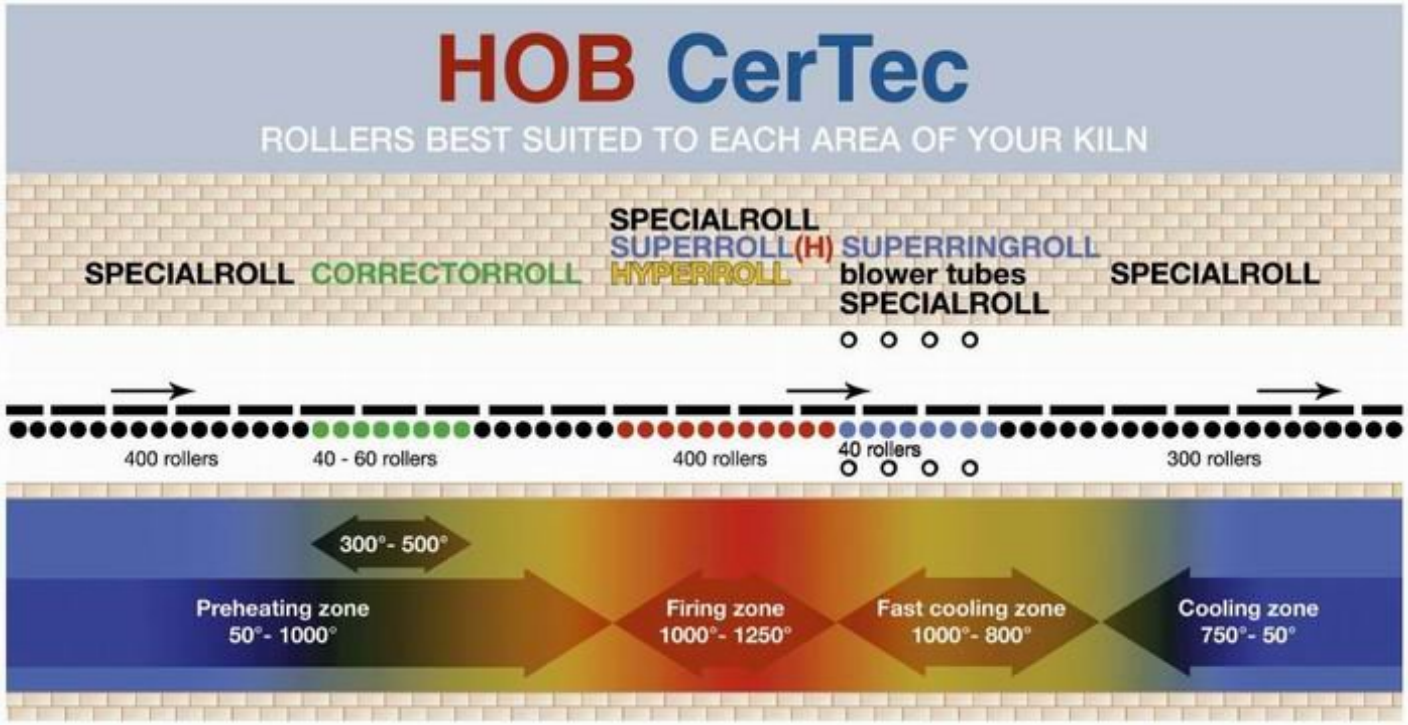
- HOB Cer Tec s.r.o.
  - Czech producer of ceramic rollers
  - Rollers are used in modern kilns in order to transport ceramic tiles through a kiln
  - Numerical simulations of the tile movement in a kiln were requested





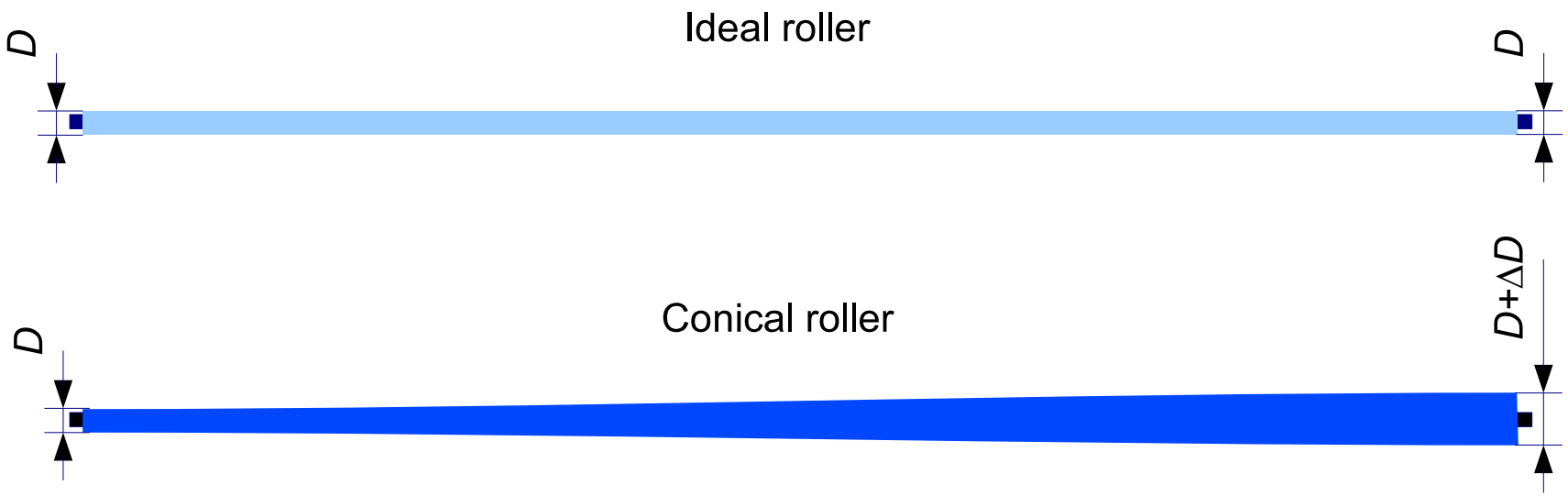
Introduction

- Kilns can be very long (100 – 150 meters)
- Various rollers (with respect to the shape and flexibility), different tiles (with respect to dimensions and weight)



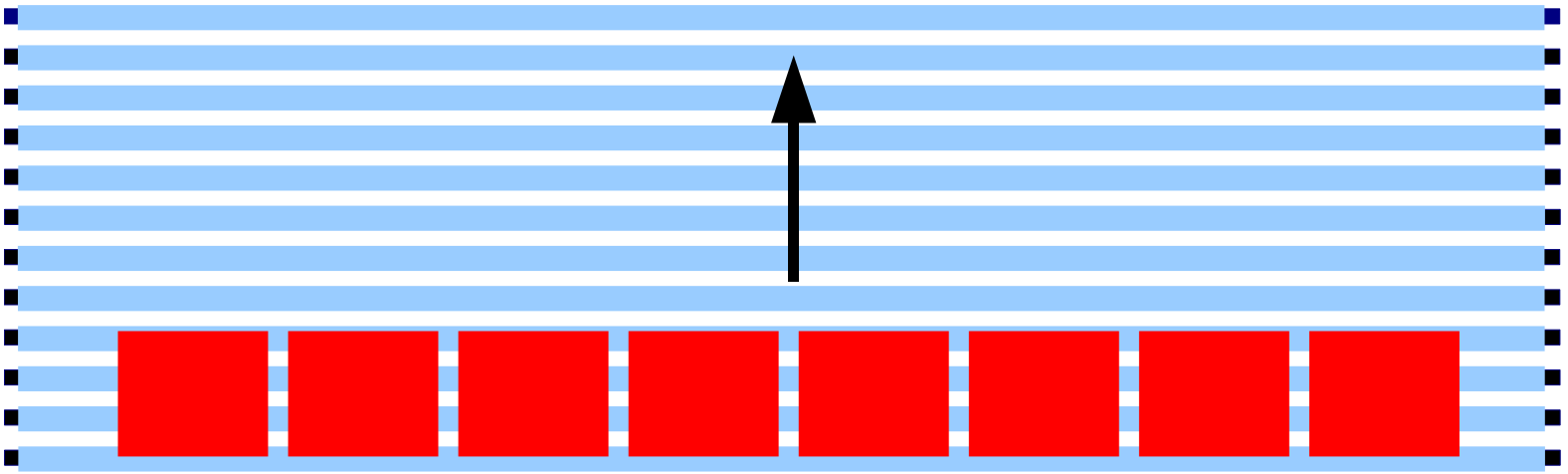
Introduction

- Due to the production technology the rollers can be of a conical shape
- Owing to cooling in vertical position the lower end can be wider
- Length $l = 3.9$ m, supported on the ends, outer diameter $D = 0.052$ m, inner diameter $d = 0.04$ m



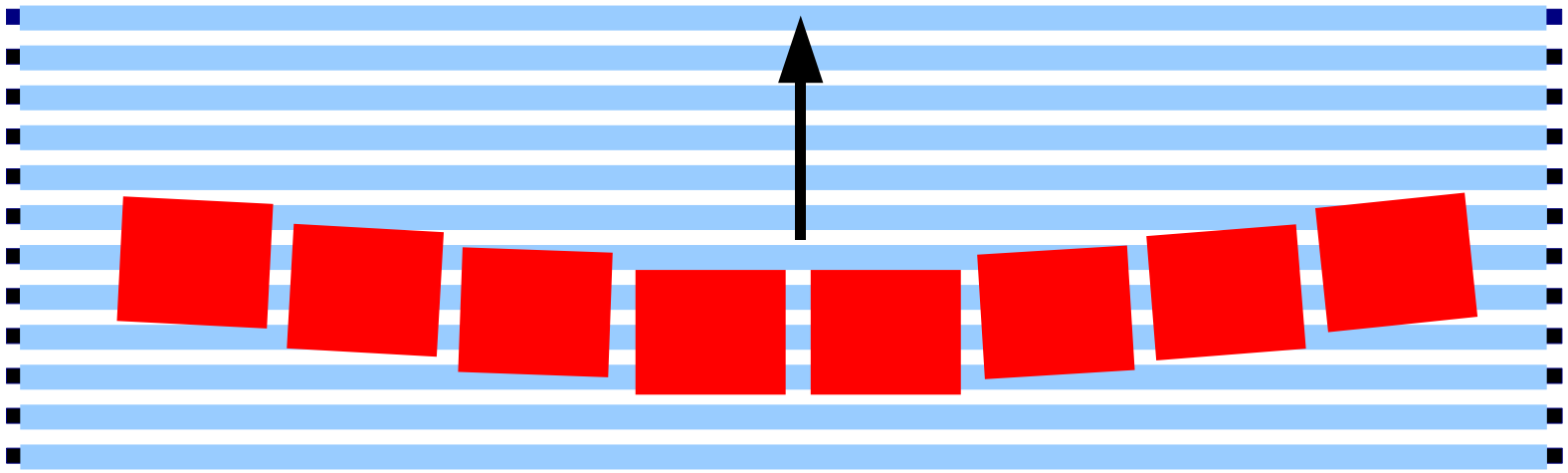
Problem description

- Tiles are transported by means of rollers in the rows (depending on the width of tiles)
- The reference velocity of tiles $\longrightarrow$ 150 meters per hour (0.0417 m/s)



Problem description

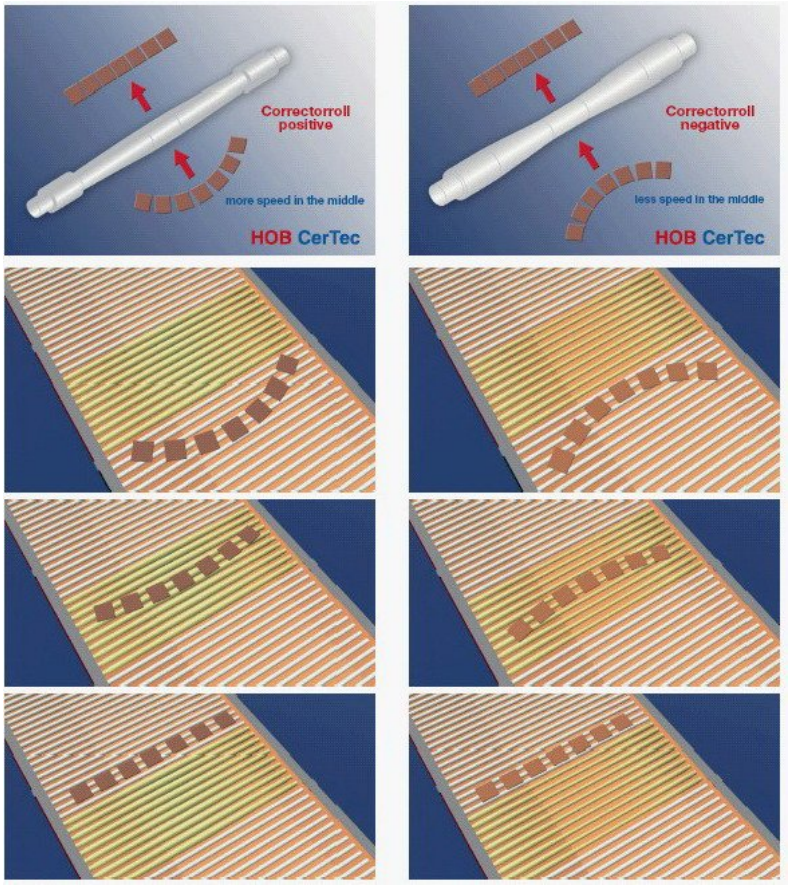
- After the passage of the tiles through a kiln $\longrightarrow$ the originally straight row of tiles becomes curved
- It is undesirable phenomenon for the kiln operators



Problem description

- Why does it happen?
- Is it caused by conical shape rollers?
- What parameters most influence the problem?

- Complex unusual mechanical system (many contacts, rollers flexibility, neglecting influence of temperature changes, . . .)

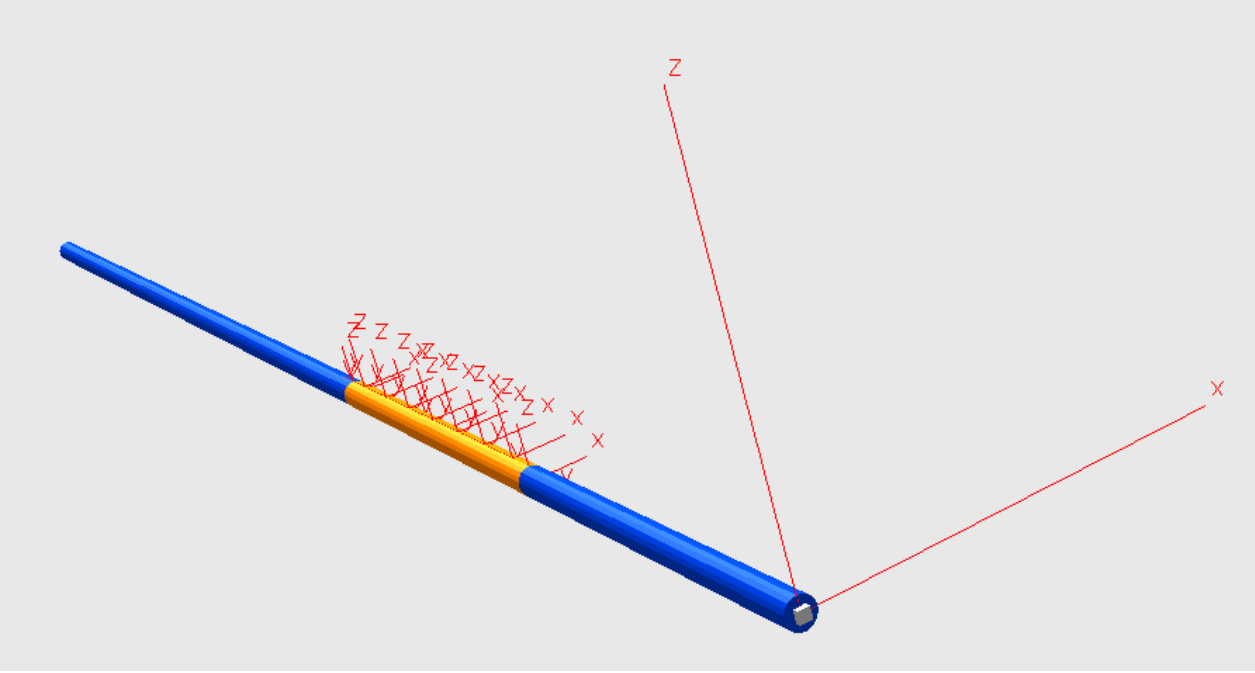


Model based on the FE18 element

- Multibody approach can be suitable for the solution (in ŠKODA VÝZKUM limited to rigid bodies)
- Contact modelling possibilities in SIMPACK
  - The SIMPACK Contact module
  - Single point contact (moved markers, force elements)
  - Multipoint contact (FE45 – two separate curves)
  - Hertzian contact (FE222, ball, cylinder, plane)
- Tiles and rollers $\longrightarrow$ multipoint contact, but FE45 not suitable
- Solution $\longrightarrow$ set of moved markers + unilateral spring-damper elements (FE18)

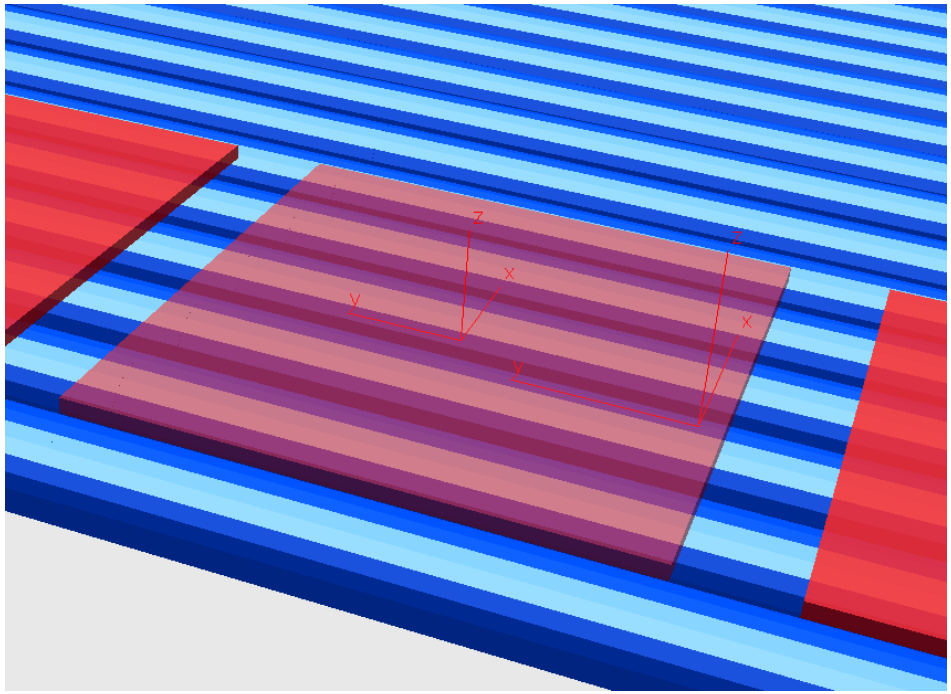
Model based on the FE18 element ...

- Roller model (substructure)
  - Flexibility $\longrightarrow$ N segments (rigid bodies), allowed bending (FE13, compared with FE model), closed loop (constraint)
  - Rheonomic joint on one end (defined angular velocity ω_{roller})
  - Set of moved markers for the contact definition (MM94, rotation)



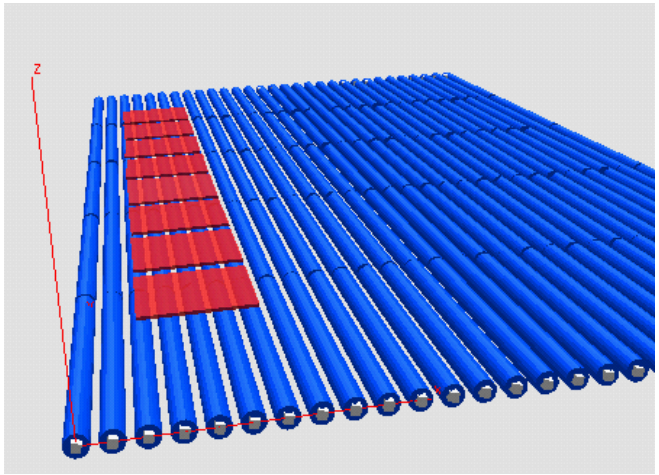
Model based on the FE18 element ...

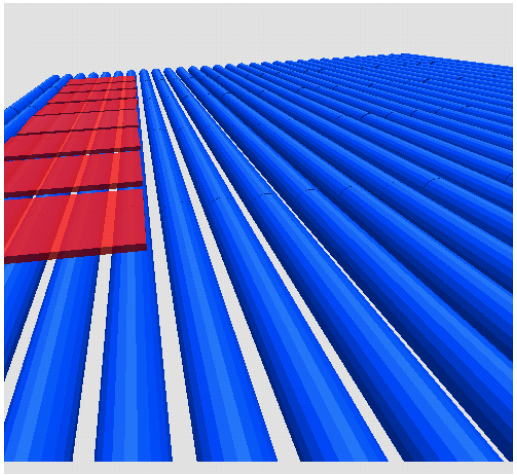
- Tile model ⟶ one rigid body, 6DOF joint
- Contact model ⟶ moved marker + FE18 (unilateral spring-damper)
- Friction force (lateral direction), "driving" force (based on rolling condition) ⟶ FE50 (component force by expression)



Model based on the FE18 element ...

- Many bodies and many contact elements $\longrightarrow$ automatic generator of SIMPACK source files (MATLAB, acronyms for element names, ...)
- Results of the numerical simulations were not sufficient (not realistic enough due to the contact model, especially roller shape description, very long computational time due to the many force elements, ...)
- Movies $\longrightarrow$





About the polygonal contact model (PCM)

- Developed and implemented in SIMPACK by Dr. Gerhard Hippmann
- References

[1] G. Hippmann: *Modellierung von Kontakten komplex geformter Körper in der Mehrkörperdynamik*. Dissertation, TU Wien, 2004.

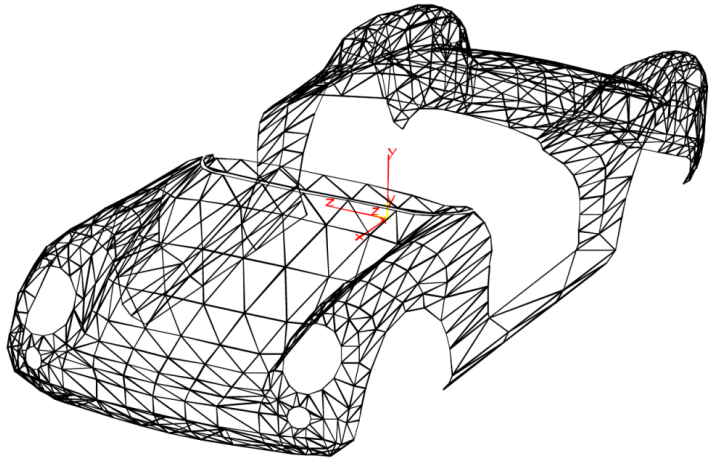
[2] G. Hippmann: An Algorithm for Compliant Contact Between Complexly Shaped Bodies. In *Multibody System Dynamics* 12, pp. 345–362, 2004.

[3] `http://www.pcm.hippmann.org`

- Available in SIMPACK as the force determined by an user subroutine (The SIMPACK User Module is necessary)

About the polygonal contact model (PCM) ...

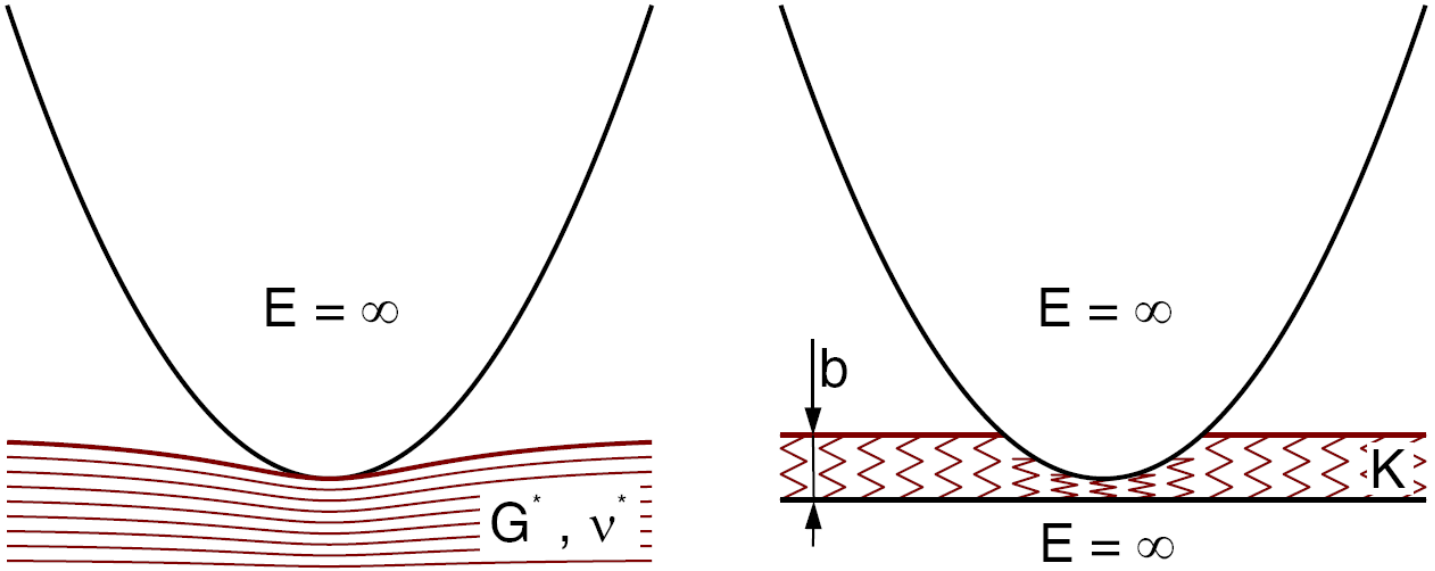
- Contact algorithm for multibody dynamics (rigid bodies, very robust)
- Body surfaces are represented by polygonal meshes
  - Vertices and faces
  - Complex surfaces can be represented
  - PCM requires $\longrightarrow$ any duplicate vertices, any cracks, consistent orientation



Example of polygonal mesh (taken from [1])

About the polygonal contact model (PCM) ...

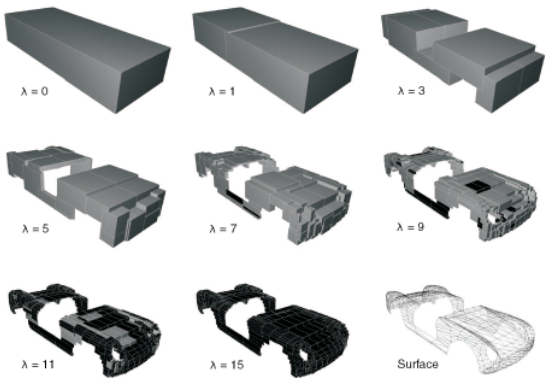
- Contact forces are determined using the elastic foundation model
  - Bodies are covered by thin elastic layer, shear stress neglected
  - Contact forces are implemented using discretized contact surface (contact patch)

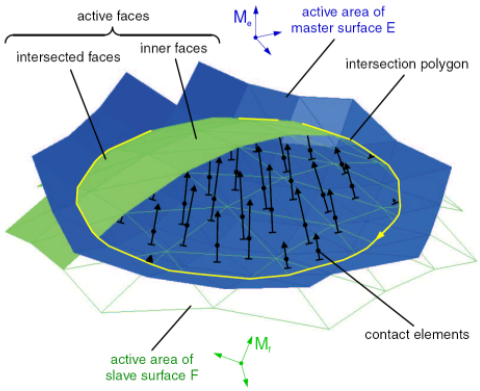


(taken from [1])

About the polygonal contact model (PCM) ...

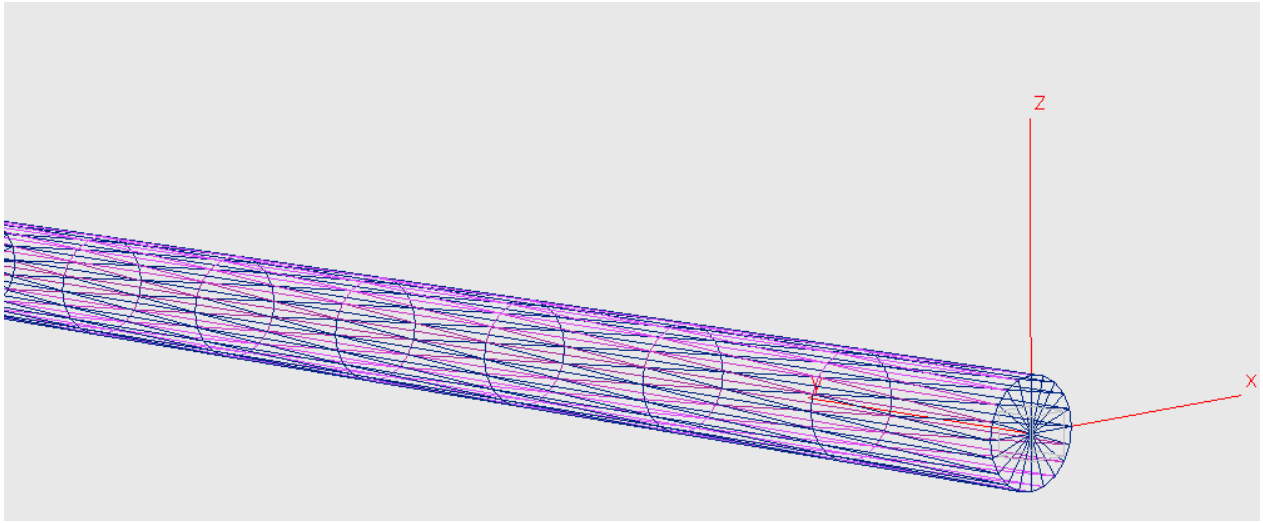
- PCM algorithm (see [1], [2]) $\longrightarrow$
  - Collision detection (based on bounding volume hierarchies, recursive algorithm, fast)
  - Contact element determination (intersection polygon $\longrightarrow$ active area $\longrightarrow$ contact elements)
  - Contact force determination (elastic + damping contact forces, regularized friction $\longrightarrow$ total force and torque on bodies in contact)





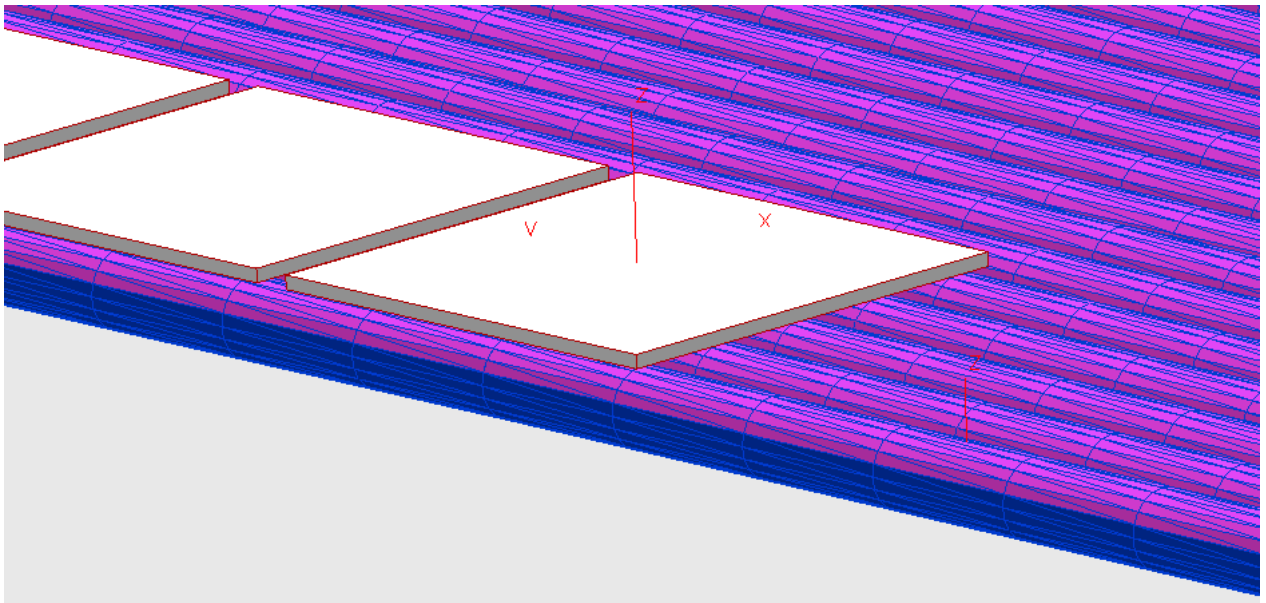
Utilization of the polygonal contact model (PCM)

- Roller model (substructure)
  - Flexibility $\longrightarrow$ N segments (rigid bodies), allowed bending (FE13, compared with FE model), closed loop (constraint)
  - Rheonomic joint on one end (defined angular velocity ω_{roller})
  - Roller segment polygonal model (automatic generation, . . .)



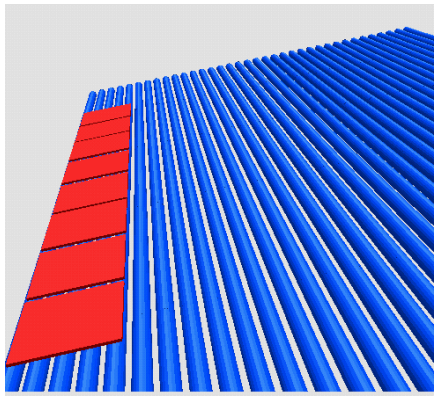
Utilization of the polygonal contact model (PCM) ...

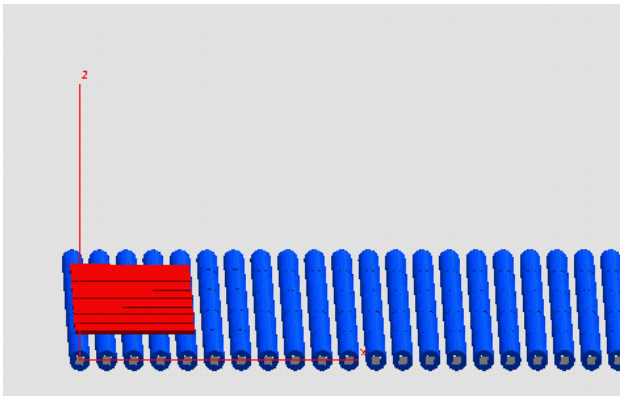
- Tile model ⟶ one rigid body, 6DOF joint, simple mesh
- Contact model ⟶ PCM user force (normal contact + friction)
- Master surface (roller) / Slave surface (tile)
- One tile–roller segment pair ⟶ one contact force

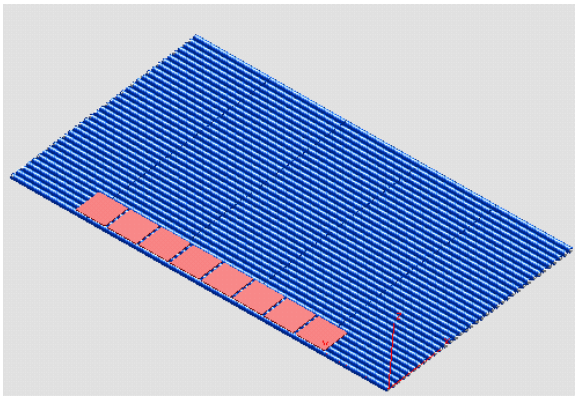


Utilization of the polygonal contact model (PCM) ...

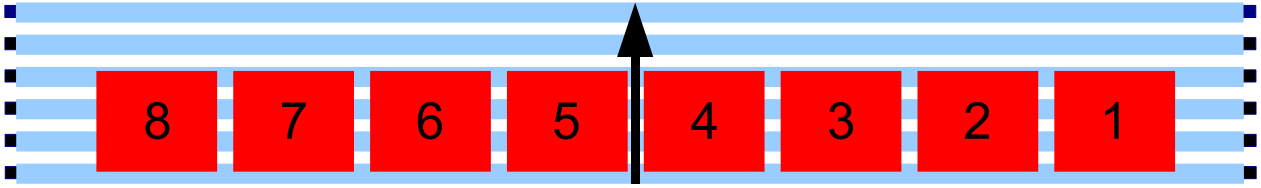
- Automatic generator of SIMPACK source files (MATLAB, ...)
- Ideal rollers case simulated, only limited number of rollers
- SODASRT integrator
- Movies $\longrightarrow$

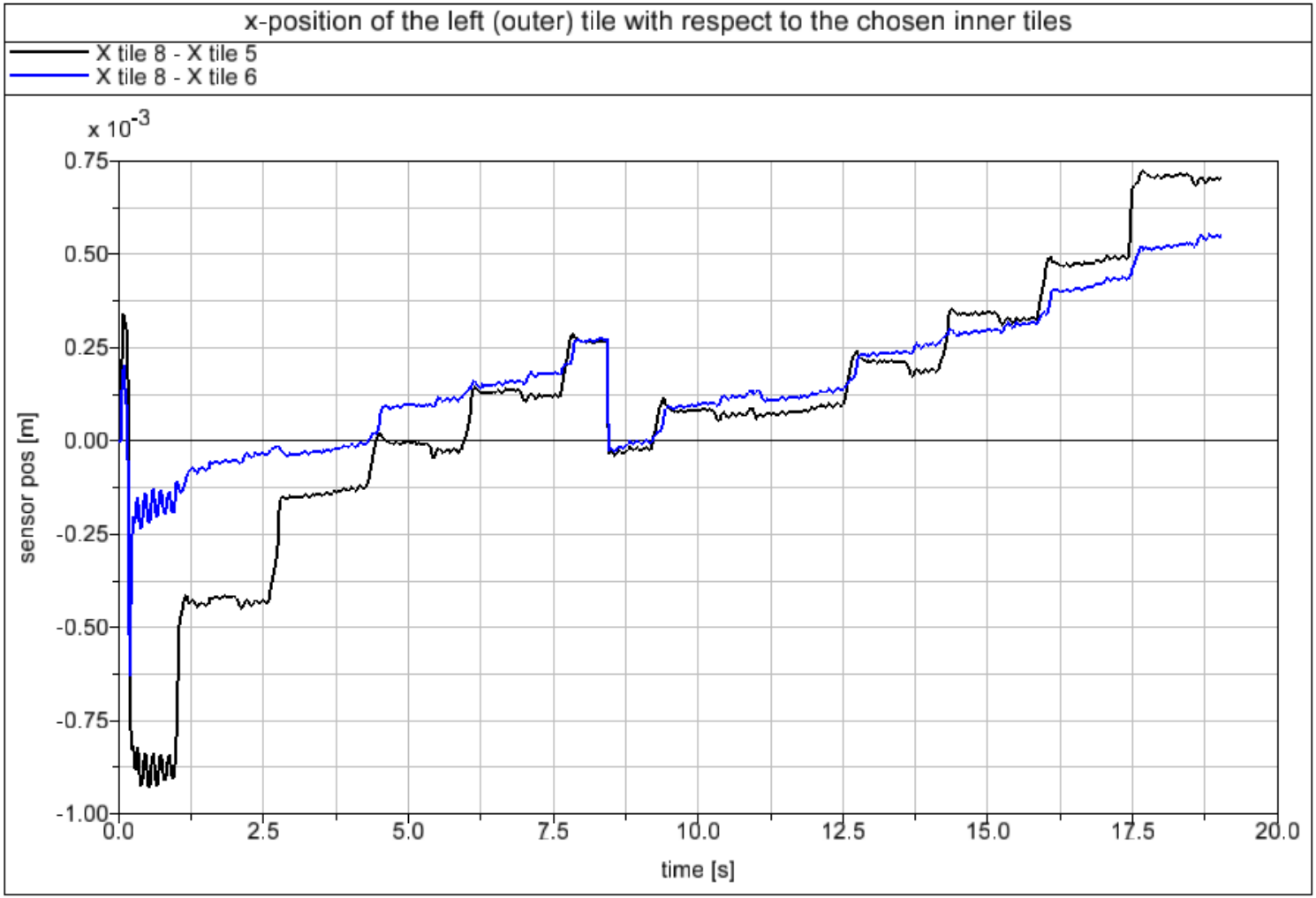


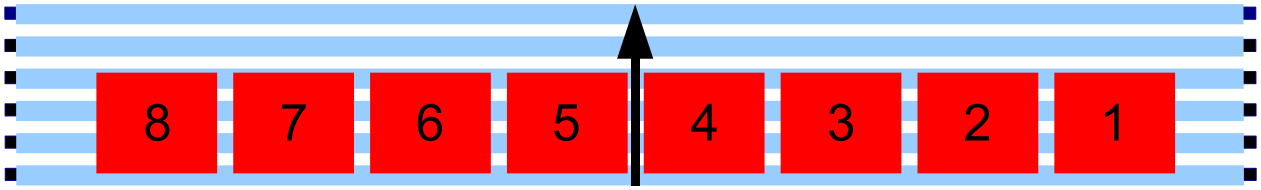


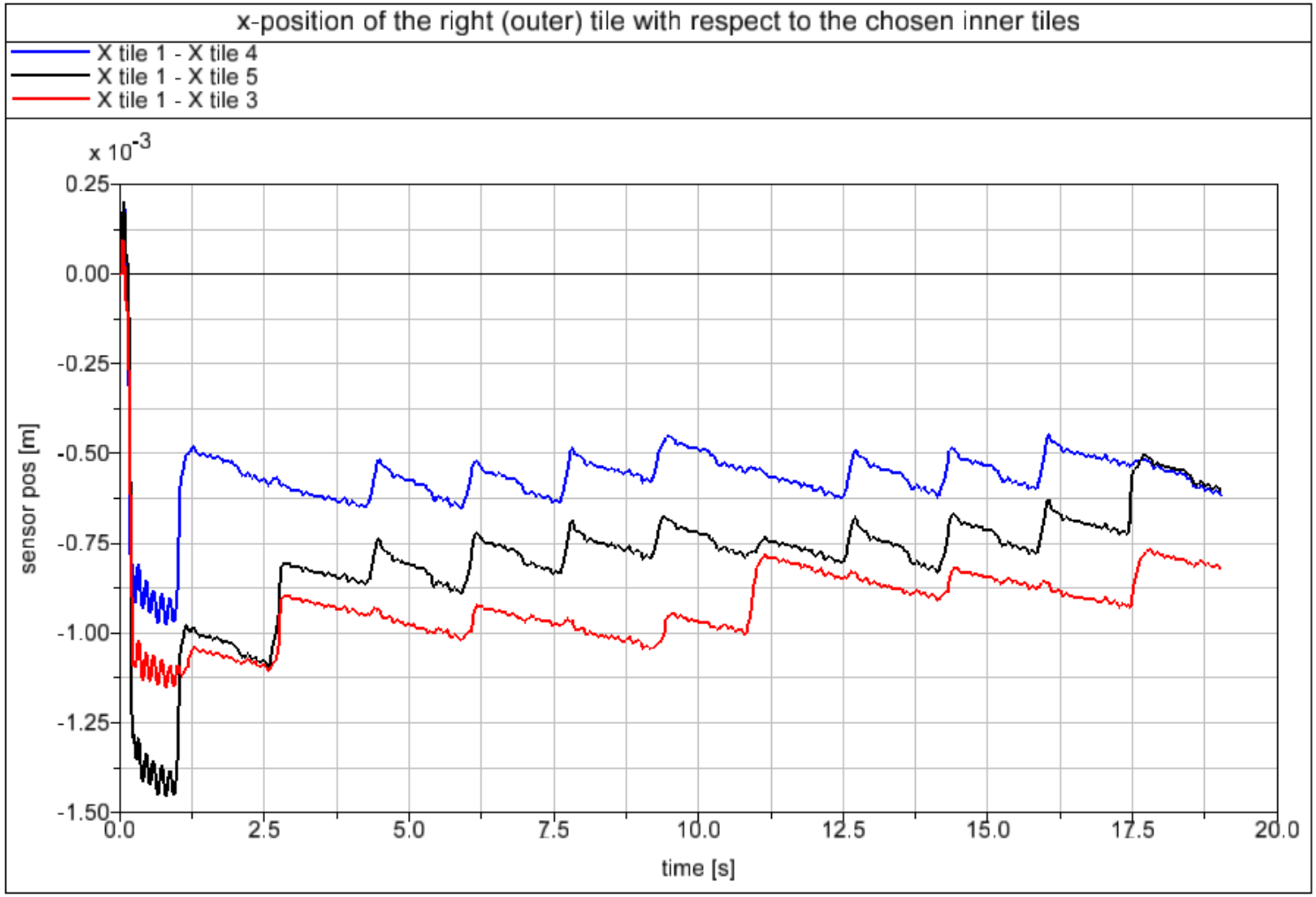


- The problem of "faster outer" tiles with respect to "inner" tiles was verified ...


8
7
6
5
4
3
2
1

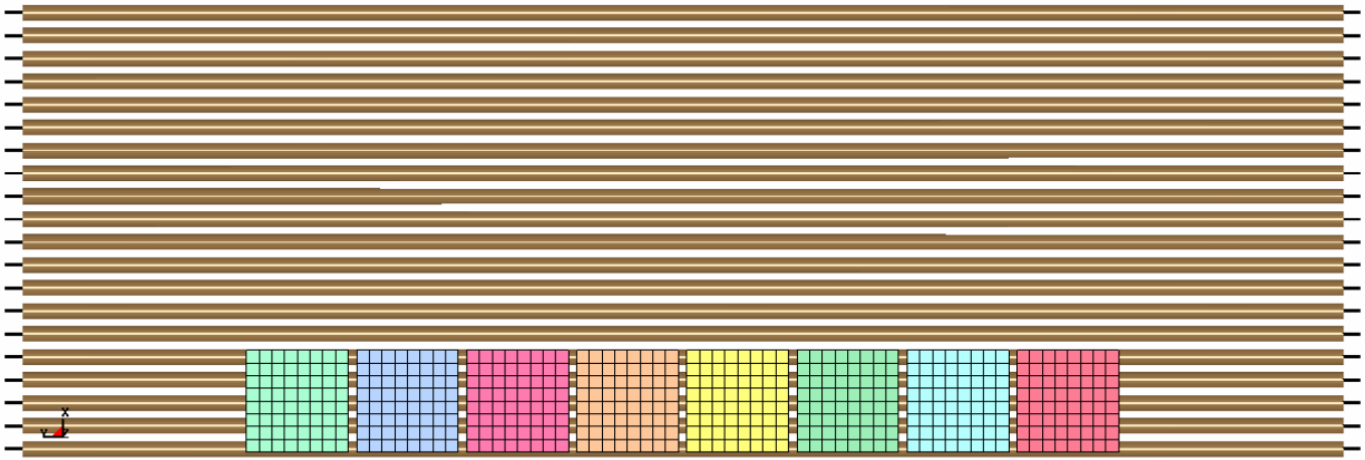

x-position of the left (outer) tile with respect to the chosen inner tiles
X tile 8 - X tile 5
X tile 8 - X tile 6
x 10-3
0.75
0.50
0.25
0.00
-0.25
-0.50
-0.75
-1.00
sensor pos [m]
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
time [s]


8
7
6
5
4
3
2
1

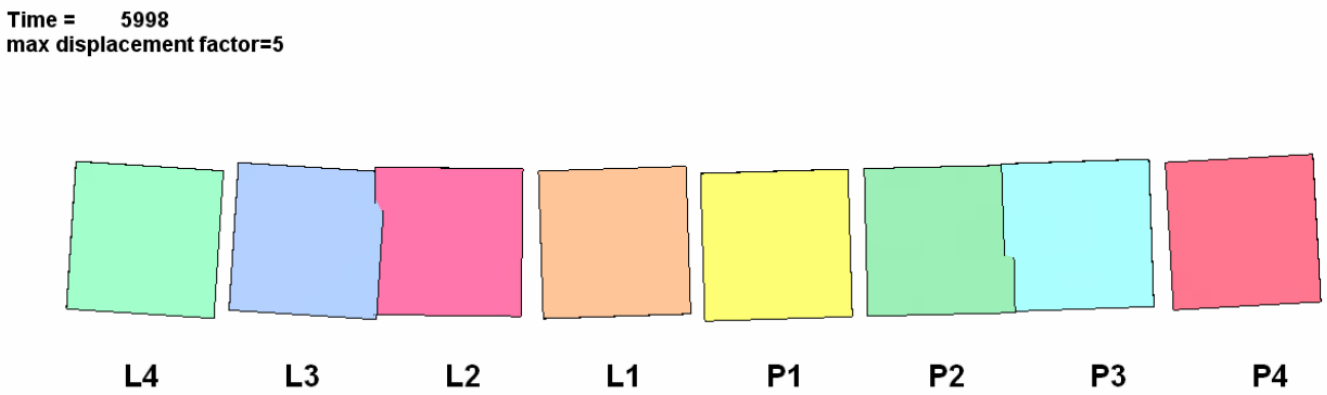

x-position of the right (outer) tile with respect to the chosen inner tiles
X tile 1 - X tile 4
X tile 1 - X tile 5
X tile 1 - X tile 3
x 10-3
0.25
0.00
-0.25
-0.50
-0.75
-1.00
-1.25
-1.50
sensor pos [m]
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
time [s]

Comparison of results obtained by LS-Dyna

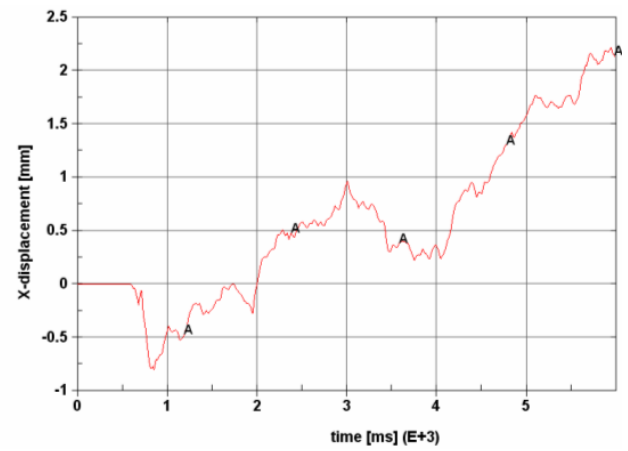
- The same problem was verified also in LS-Dyna (explicit solver, FEM)
- LS-Dyna deals with short duration events $\longrightarrow$ not so suitable for moving tiles (some improvements were necessary)

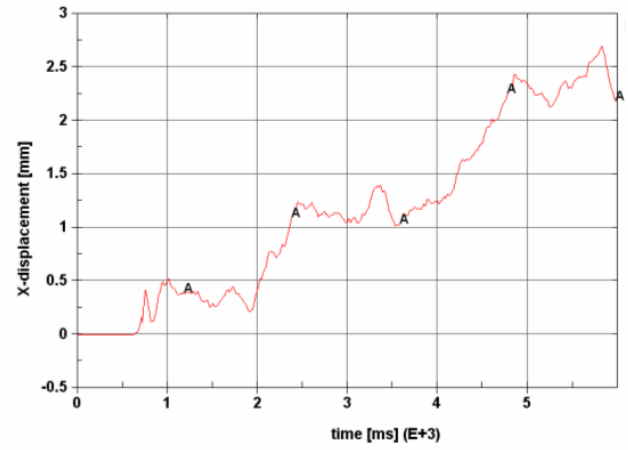


Comparison of results obtained by LS-Dyna . . .



Final displacement of tiles after moving through 20 rollers (scaling factor 5)





Differences $x_{L4} - x_{L1}$ and $x_{P4} - x_{P1}$ of x-coordinates of the tiles

Conclusion

- Tiles transferred on ceramic rollers ⟶ unusual multibody system
  - Problem characterized by multiple complex contacts and flexibility of the rollers
- SIMPACK software were chosen for the solution
  - Standard contact elements (not so efficient)
  - Very robust polygonal contact model (acceptable results)
- The problem of "curved row of tiles" after moving through a kiln was found even for perfect rollers
- The model was prepared for other simulations (sensitivity analysis, . . .)
- *This work was supported by the research plan MSM 4771868401 of the Ministry of Education, Youth and Sports of the Czech Republic*