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IMPACT OF LOAD ON THE CONTACT SURFACE OF COOPERATING CHAIN LINKS OF SCRAPER CONVEYORS

Summary. The article presents the impact of load on the contact surface of cooperating chain links in scraper conveyors. A finite element method (FEM) simulation was conducted for a chain operating on a sprocket, based on which stress and strain maps were determined for different load levels. The contact surface areas of the chain links and the reaction forces were also calculated depending on the load, which allowed the determination of surface pressures.
Keywords: transport, link chain, FEM, scraper conveyor

1. INTRODUCTION

Chain drives are one of the oldest and most widely used solutions in transport technology, which have been a reliable system for transmitting power between machine and equipment components. Their versatility, durability, and simplicity of design make them an integral

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component of many transport devices, from typical equipment such as bicycles or motorcycles to advanced conveyor units used in the mining, cement, and power industries.

The most commonly used conveyor solution based on a chain drive is the scraper conveyors. Mining scraper conveyors are classified as cable conveyors, where the cable is a chain/chains driven by a chain wheel and moving along the conveyor chute. Scrapers installed transversely to the direction of movement of the chain (installed at equal intervals - with a constant pitch) are the transporting components. Chains with scrapers create a closed loop (endless chain) consisting of two branches. A closed loop can be both horizontal and vertical (more often) [1, 2, 9-11] .

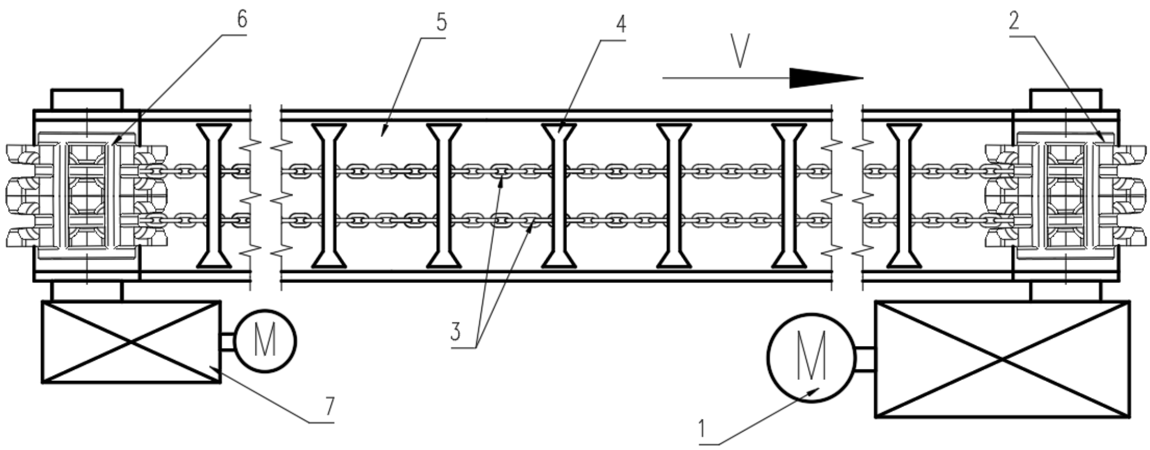

Fig. 1. Schematic design of the scraper conveyor – view on the upper part of a chain (V – direction of the material/run-of-mine transport)

The principle of operation of the scraper conveyor is to generate torque on the chain wheel (through the drive – a motor and a gear) and transmit it in the form of a pulling force to the chain links with the scrapers. Both the scraper chain and the scrapers are located inside the conveyor pan, which creates a transport channel shielded on three sides. Movement of the chain and sliding of the scrapers along the conveyor pans result in the removal of the excavated material and its transport along the chain movement to the end point of transport or the next means of transportation [1, 2, 9-11].

Cooperation of chain links with the drum, cooperation between the links in the joint area, and the extremely difficult and complex environmental conditions in hard coal mining plants result in the complexity of the wear processes of link chains in terms of friction, corrosion, and fatigue. The most important factors increasing the degradation of chains and scraper conveyor assemblies are the following:

- stone and coal dust in the cooperation zone of chain links (joints),
- corrosive effect of mine water from the spraying devices and from goafs,
- dynamic loads from conveyor drive starts and uneven loads,
- frequent overloading and blocking [3, 4, 6, 8].

Analysis of contact between neighboring chain links that articulate with each other while rolling through the drive or return wheel is important regarding the chain degradation process. These links have a point elastic contact on the torus inside of each cell. Theoretical basis for the analysis of such zones includes, among others, the Hertz problem, which is the foundation of the state-of-the-art theory of elastic contact. Described by the German physicist Heinrich Hertz in 1882, this problem concerns the analysis of stresses and strains arising in elastic bodies at their points of contact. Hertz's theory is extremely important for understanding how materials behave under contact loads, which has wide applications in the design of mechanical components such as bearings, gears, shafts, and many other components exposed to point or linear contact [5].

The basic assumption of Hertz's theory is the analysis of contact between two elastic surfaces in a situation where they do not undergo plastic deformation. In practice, this means that materials behave according to Hooke's law, and deformations are proportional to the applied forces. The Hertz problem allows determining the distribution of stresses and strains in the contact area, which allows assessing the durability and strength of the analyzed components. Precise calculations enable predicting the extent to which surfaces will deform and determine the maximum stresses, which are crucial to avoid damage and premature wear.

Nowadays, Hertz's theory is the foundation for many advanced computational methods, such as the finite element method (FEM), which enables more complex and precise contact analyses. This article presents deformation analyzes and surface pressure analyzes of cooperating chain links using computer methods. The cooperating links have point contacts of the two internal parts of the tori, which is consistent with the described issues. The analysis required using the special software based on the finite element method. Hexagon software was used, i.e., Patran pre- and post-processor and Nastran computational solver. Nonlinear static analysis was performed. Nonlinearities resulted from simulating the contact and use of an elastic-plastic material model.

2. GEOMETRIC MODEL

The 3D geometric model (Fig. 2) making the basis for creating the computational model was designed using Autodesk Inventor software. It consists of a driving star and one pair of links 14x50. The size of the actual conveyor chain was selected according to PN-G-46701:1997 Standard - Mine link chains [7].

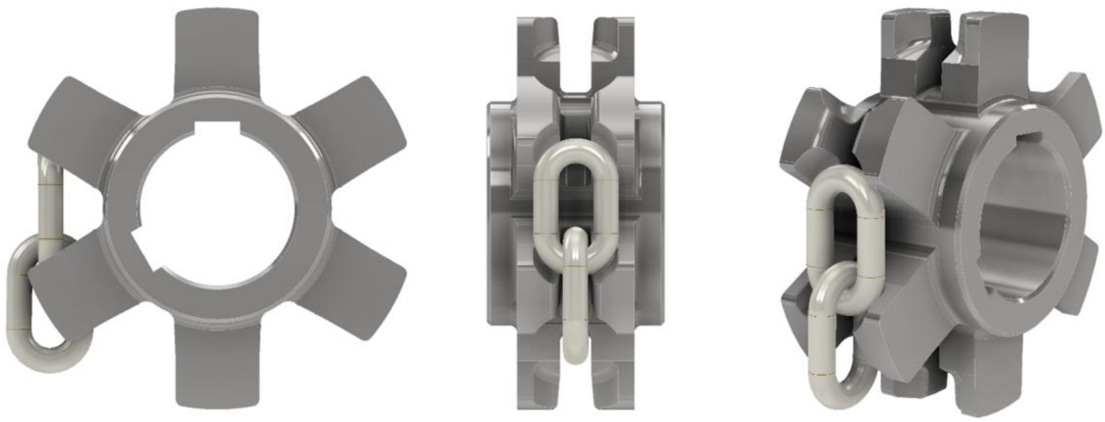

Fig. 2. 3D geometric model of the driving star with a pair of cooperating links

3. COMPUTATIONAL MODEL

3.1. Finite elements mesh

The geometric model was moved to the Patran preprocessor environment. This model was then discretized and a finite element mesh was created, consisting of the following:

- 533 thousand nodes,
- 69 thousand finite elements TET10 – driving star represented by a section that is 1/3 of the geometric model (Fig. 3). The TET10 element is a ten-node tetrahedral element used in numerical simulations. It consists of 10 nodes: 4 at the vertices and 6 at the midpoints of the tetrahedron's edges. It enables modeling of complex geometries and stress fields with greater accuracy than simpler elements due to quadratic shape functions. It is applied in analyses of mechanics, thermodynamics, or fluid flow.
- 40.4 thousand finite elements HEX8 – two chain links. The HEX8 element is an eight-node hexahedral element used in numerical simulations. It consists of 8 nodes located at the vertices of a cube. It enables modeling of regular geometries and physical fields with good accuracy, using linear shape functions. It is applied in analyses of mechanics, thermodynamics, or fluid flow, particularly in regular structures. HEX8 elements are more efficient because with a smaller number of nodes, they enable obtaining results of higher quality than TET10 elements, especially in non-linear tasks, i.e. contacts and large deformations, (Fig. 4),
- number of HEX8 elements has been increased in the contact zone (Fig. 5).

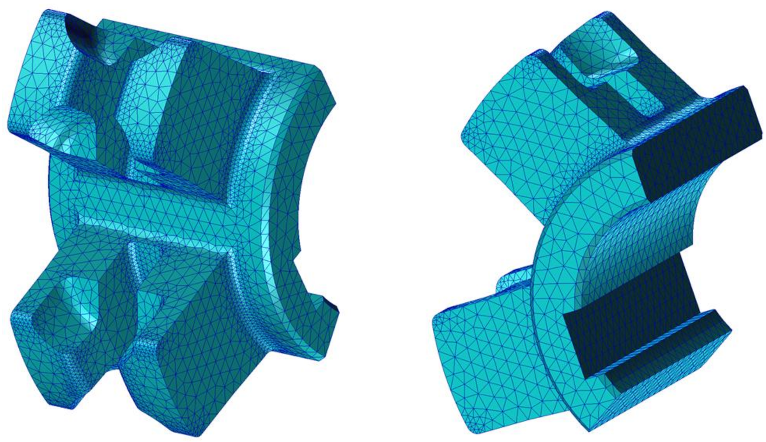

Fig. 3. Finite elements mesh of a driving star (TET10 solid elements)

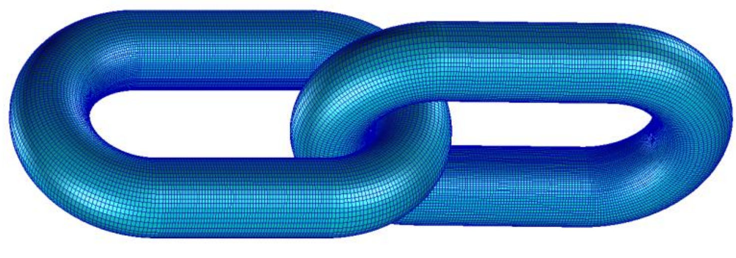

Fig. 4. Finite elements mesh of collaborating links (HEX8 solid elements)

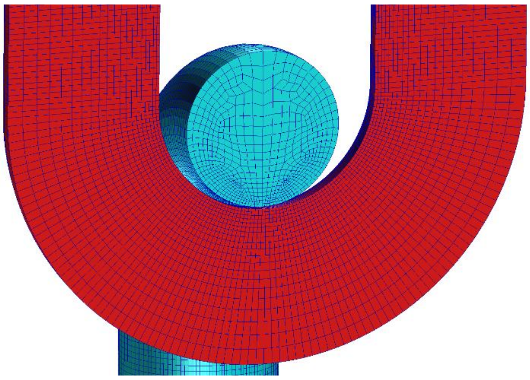

Fig. 5. Increased number of finite elements in the contact zone between chain links

3.2. Finite elements mesh

There are the following assumptions and material parameters for numerical analysis:

- driving star – linear-elastic material:
  - Young's modulus – 205 GPa,
  - Poisson's number – 0.3,
- chain links – linear-elastic material with reinforcement C grade steel:
  - Young's modulus – 205 GPa,
  - Poisson's number – 0.3,
  - conventional yield strength – 700 MPa,
  - tensile strength – 850 MPa,
  - relative elongation at a breaking load – 14%.

3.3. Boundary conditions

For the purposes of the calculations, the following boundary conditions were assumed:

- rotation of the driving star around the axis of rotation, Fig. 6 - the rotation was forced by a displacement corresponding to the relative elongation of the pair of links at breaking load and was equal to 0.17 rad - a relative elongation of 14% corresponds to the elongation of the pair of links by 14 mm,
- connection of the drive star to the chain link - to force movement of the chain link (upper link), in line with the moving drive star, MPC RBE2 type replacement elements were used. MPC RBE2 (Multi-Point Constraint Rigid Body Element 2) elements are a type of element used in numerical simulations, particularly in finite element analysis (FEA). They are rigid elements that define a kinematic relationship between one independent (master) node and one or more dependent (slave) nodes. The motion of the independent node fully determines the motion of the dependent nodes, with no relative displacement between them, imparting infinite stiffness to the modeled region. RBE2 is used to represent rigid connections, such as in modeling rigid structural components like beams or welded joints, where deformation between nodes is negligible. Star nodes and links are connected using these elements, Fig. 7,
- contact between the combined elements - spatial contact was used on the surface of the links and the driving star, Fig. 8. Friction coefficient $\mu = 0.1$ was introduced,
- fixation of the lower link - to recreate cooperation of the link with subsequent links, the MPC RBE2 substitute element was used to obtain support while simultaneously monitoring the reaction value in one node, Fig. 8.

4. DISPLACEMENT AND REDUCED STRESSES

The simulation was carried out by generating the rotation of the driving star until the chain links were extended by 14% - that is, until the moment that, according to the catalogue, is the minimum at which the link breaks. All published results of strength calculations use the SI system of units. Maps of displacements and reduced stresses at 14% elongation are shown in Fig. 9-10. Fig. 11 shows the change in the stress map for elongation of 0.7%, 1.4%, 3.5%, 7%, 10.5% and 14% (corresponding to 5, 10, 25, 50, 75 and 100% of maximum elongation, respectively).

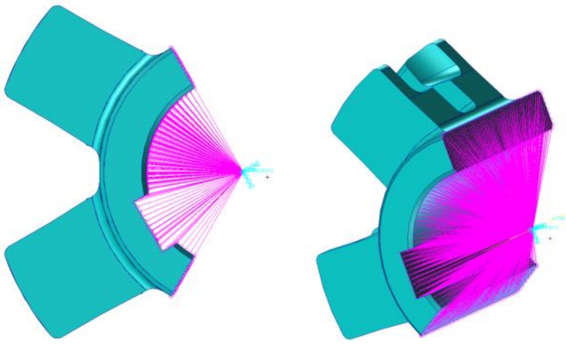

Fig. 6. Rotation of the driving star around its axis of rotation. MPC RBE2 special numerical component is used (purple color)

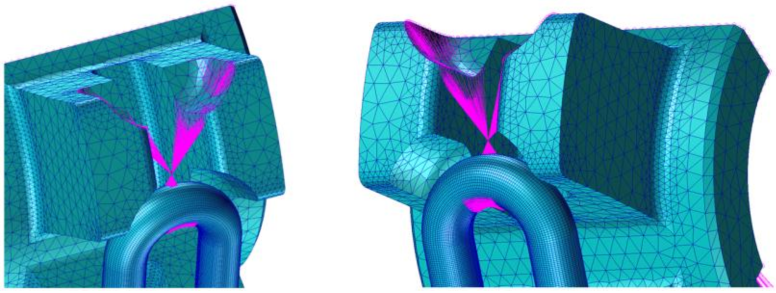

Fig. 7. Connection of the link with a driving star. MPC RBE2 special numerical component is used to connect two separate components

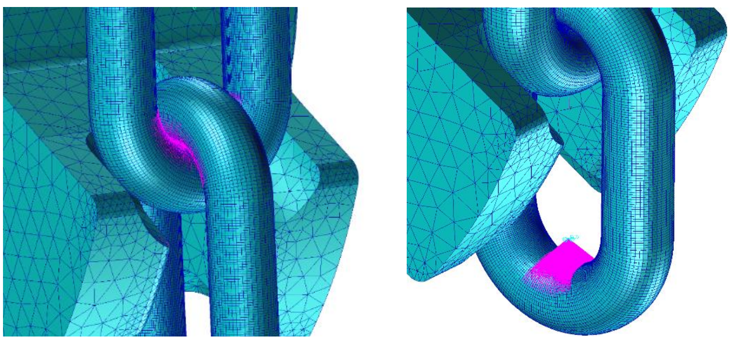

Fig. 8. Definition of contact on the surface of the links and the driving star (left), fixation of the lower part of the link with the MPC RBE2 element (right)

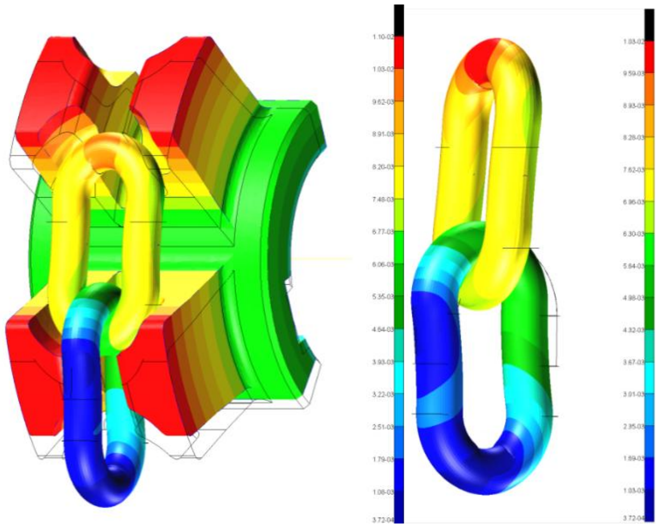

Fig. 9. Map of displacements (real deformation) on a dimensionless scale

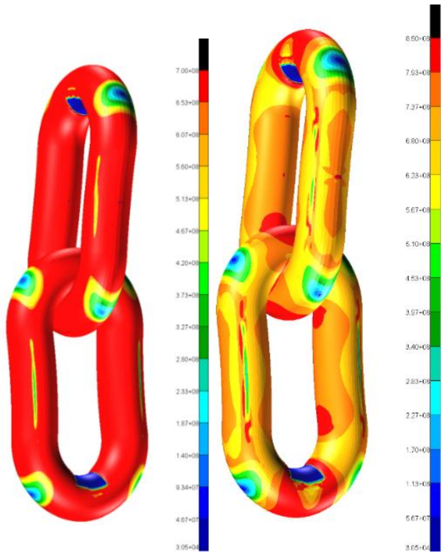

Fig. 10. Map of reduced stresses – on the left where red means a stress >700MPa, and on the right >850MPa

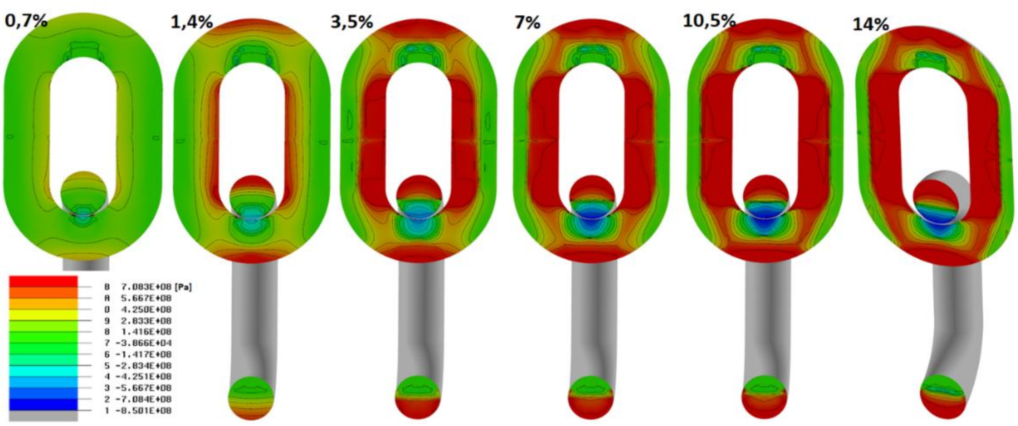

Fig. 11. Map of reduced stresses on the longitudinal cross-section of links pair – tension zones are marked with yellow and red and compression zones with green and blue – displacement 0.7-14%

5. CONTACT BETWEEN THE LINKS

Fig. 12 and 13 present the contact surfaces between the links for each degree of their elongation (according to Fig. 11).

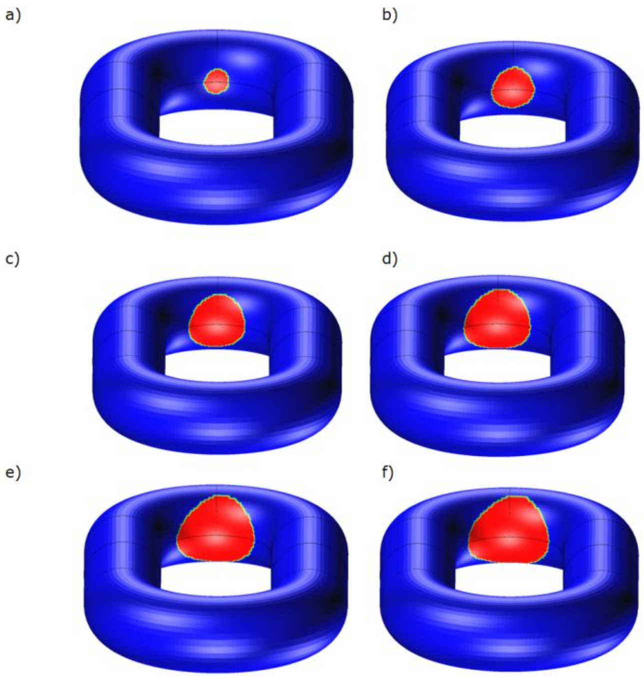

Fig. 12. Contact surfaces between the links for each degree of their elongation: 0,7% (a), 1,4% (b), 3,5% (c), 7% (d), 10,5% (e) and 14% (f)

The surface areas of each contact for each degree of elongation are shown in Fig. 13 below.

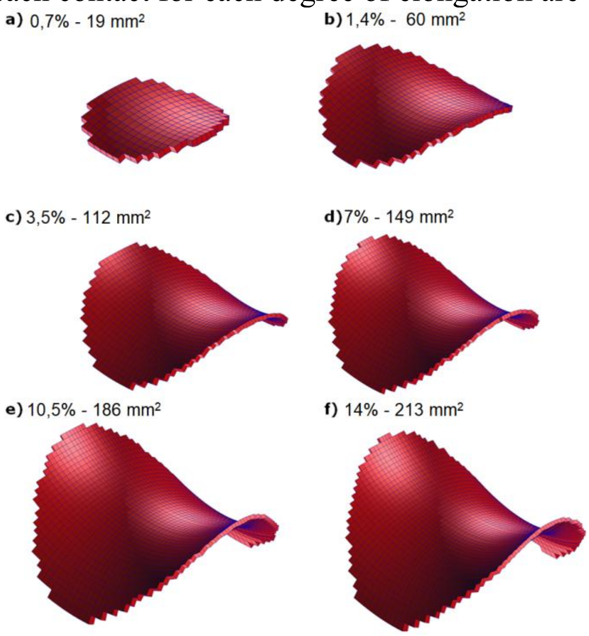

Fig. 13. Area of contact surfaces between the links for different levels of link elongation

The form of the deformation of the pair of links in the area of the contact zone and the reaction value are shown in Fig. 14.

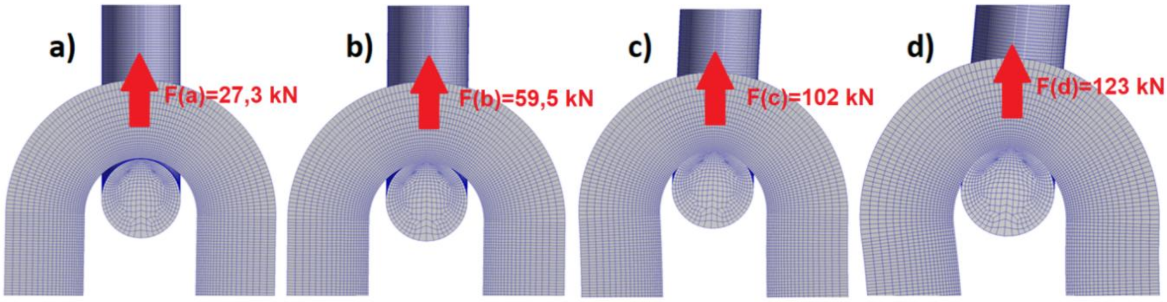

Fig. 14. Deformation in the zone of links cooperation at the following links elongations: 0.7% (a), 1,4% (b), 7% (c), and 14% (d)

Determining the contact areas and the magnitude of the reaction allows for the estimation of the surface pressures in the contact zone. These values are presented in the Table 1 below.

Tab. 1

Determination of surface pressures

Link elongation	**Reaction [kN]**	**Contact surface area [mm^2]**	**Surface pressure [MPa]**
0.7%	27.3	19	1436
1.4%	59.5	60	991
3.5%	91.3	115	793
7%	102	149	685
10.5%	111	186	597
14%	123	213	577

The results regarding displacement maps, reduced stresses, main stresses, identification of compression and tension zone,s and the shape of the contact surface are presented for a chain link of real dimensions and strength parameters in accordance with the PN-G-46701:1997 Standard.

Reaction of 123 kN corresponds to the maximum link elongation (14%) declared by the manufacturer for class C chain steel.

After achieving the assumed elongation, the numerical simulation was stopped because its further elongation may be a source of the following:

- numerical instabilities (increasing the error in the obtained results),
- discrepancies in the results obtained on the test stand (by the manufacturer), which are related to the possibility of a random crack propagation (loss of material continuity). This randomness is related to the manufacturing process of each batch of links (e.g. the possibility of inclusions of contaminants inside the material or its inhomogeneity).

6. CONCLUSIONS

The results of the analysis described in this article, especially the determination of the contact area of two links depending on the applied load (Fig. 12-13) and the resulting surface pressures, allow forecasting the progress in chain wear.

As expected, the contact area of chain links increases with elongation increase, thus changing the point contact in the unloaded state with surface contact of the loaded links. The growth rate of the links contact area decreases and is the highest at the first stage of elongation and decreases with its increase.

Surface pressure is the highest at the first stage of elongation and decreases as the reaction increases below the yield stress value. Therefore, it can be concluded that the cooperating loaded links adapt to each other at the first stage of cooperation, creating the surface contact zone. Due to exceeding the yield point, this zone does not return to the point contact state after the load is removed.

This analysis is part of broader research work related to the synergistic impact of environmental factors on the wear of chain links depending on the combined operating factors. In the presented work, the contact parameters of the cooperating cells were determined for the needs of the mentioned research work carried out using a dedicated test stand (description in [12]). These guidelines enable determining the nominal parameters of the mentioned test stand in terms of load and strength, in particular in the aspect of determining the nominal force loading the chain links during tests, which will generate degradation of the chain joint with the dominant tribological factor and not as a result of decohesion or plastic deformations.

It should be noted that there is a trend in which the frictional wear process in cooperating parts is increasingly simulated using a coupling of two different computational methods. As coal or rock are not continuous materials, they are simulated in a software environment based on the Discrete Element Method (DEM), in which it is possible to map the behavior of these materials including simulating the wear process on the surfaces of the wearing parts that are most exposed to loads. The deformations and stresses that occur in metallic components, on the other hand, are calculated using the finite element method [13, 14, 15]. This should be considered as a potential direction for further research work.

The obtained analysis results are of significant importance from the perspective of broadly defined transport, particularly in the context of the operation and design of scraper conveyor systems used in the mining, extraction, or energy industries. Determining the contact parameters of interacting chain links and understanding the relationship between load, contact area, and surface pressures enables the optimization of chain design, enhancing their durability and reliability. Precisely identifying the conditions under which the transition from point contact to surface contact occurs facilitates better prediction of tribological wear, which translates into reduced maintenance costs and downtime for conveyors. Furthermore, these results support the design of test rigs that reflect real operational conditions, which is crucial for ensuring the safety and efficiency of bulk material transport in challenging environmental conditions, such as mines or raw material processing plants.

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