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CFD Simulations of the New Construction of Light Brattice Wall for Mine Shafts

Tomasz Rokita [1], Paweł Kamiński [2,*], Hubert Ruta [1] and Zbigniew Szkudlarek [3]

[1] Department of Machinery Engineering and Transport, Faculty of Mechanical Engineering and Robotics, AGH University of Science and Technology, Adama Mickiewicza Ave. 30, 30-059 Krakow, Poland; rokitom@agh.edu.pl (T.R.); hubert.ruta@agh.edu.pl (H.R.)
[2] Department of Mining Engineering, Faculty of Civil Engineering and Resource Management, AGH University of Science and Technology, 30-059 Krakow, Poland
[3] Division of Machines and Equipment, KOMAG Institute of Mining Technology, 44-101 Gliwice, Poland; zszkudlarek@komag.eu
* Correspondence: pkamin@agh.edu.pl

Abstract: Brattice walls in mine shafts are used for various purposes, for example, permanent brattice walls can be used to separate ventilation sections. They can be also used in the case of modernization of the hoisting system, as it is in Shaft no. 1 of the Szczygłowice department, part of the Knurów-Szczyłowice coal mine. To shorten the time and reduce costs of the hoist modernization, the shaft is to be partitioned into two sections—with the hoist operating in one of them and another one being modernized in the other section. The new construction of the light brattice wall was designed for this purpose. To prove its usefulness and safety it was tested in the laboratory and computer simulations. The following paper presents CFD simulations of the brattice—its methodology and results together with an overview of works to be conducted in the shaft.

Keywords: brattice wall; composites for mining industry; mine shaft; hoisting system modernization

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1. Introduction

The industrial revolution of the 19th century caused an increase in demand for coal, which was the main energy source at that time [1–4]. The effects of coal production and consumption are constantly growing distances between mining areas and mine shafts and a need for exploitation of deep-lying deposits. As a consequence of such situations, a necessity of mine shaft deepening for opening up deposits and shortening transport routes. Shaft deepening positively affects the level of employees safety, effective working time, and economic score of the mine [4–8].

In 2020, coking coal was introduced to the updated list of critical raw materials for the EU as a strategic raw material for the European steel industry. It might be an important issue for the Polish economy, as there are still many underground mines producing coking coal in Poland. However, this opportunity for the Polish mining industry requires taking action to ensure economically viable coking coal production.

Most of the Polish underground coal mines exploit deposits where geological and mining conditions are extremely hard, because of deep depths, high temperatures and high levels of natural hazards, such as methane or water. Such harsh conditions require deepening and regular maintenance of most of the mine shafts of JSW Group, which is a European leader in coking coal production, as well as other underground mines.

Different methods of shaft sinking and elongation are currently in use, of which the most popular is the drill and blast method and concrete shaft lining. The drill and blast method can be divided into four sub-methods [6,7,9,10]:

- Deepening from the ground level with haulage of excavated material to the surface,
- Deepening from the ground level with haulage of excavated material to a mid-level,

- Deepening from the sub-level with haulage of excavated material to the operating level,
- Deepening from the sub-level with haulage of excavated material with a large-diameter borehole.

All the work interfering elements of the shaft lining, equipment and hoisting system, including shaft deepening and elongation of the hoisting system, requires stoppage of the hoisting system, which is equivalent to putting the shaft out of service. In the case of two hoisting systems operating in the shaft, none of them can be used when one is being modernized. Putting hoisting systems out of service causes economical and practical issues because other mine workings and transport systems have to deal with a workload of the shaft excluded from the operation.

However, such a situation might be avoided by the partition of the shafts for two or more vertical sections using a brattice wall. In such a case, in one section elements of the hoisting system can be modernized and in another, the hoist can operate undisturbed. Brattices in mine shafts are used for various purposes, for example, permanent brattice walls can be used to separate ventilation sections for air split in the shaft, so it can be used as both downcast and upcast shaft. However, such a situation is mostly spotted in theory [6,11]. Brattices in mine shafts might be also used in the case of modernization of the mine shaft or hoisting system.

More popular than vertical partitions are horizontal ones, in the form of artificial shaft bottom (shaft safety platform). Application of such construction in the deepened shaft is required by Polish law. Its task is to protect people working below from falling objects, particularly the conveyance [5,6,12–16]. Similarly, the brattice wall is designed to protect people working in the shaft from unpredicted conveyance's behavior in another column.

The process of brattice installation is time-consuming and laborious. It can be assembled from a conveyance or working platform, which is much more easier and convenient, but more expensive and time-consuming. Moreover, the elements of the brattice wall are characterized by significant size and high mass, because they are usually made of steel. What is particularly important, the shaft operation has to be stopped for the time of brattice wall installation.

In response to issues raised, personnel of faculties of Mining and Geoengineering and Mechanical Engineering and Robotics of AGH UST in Krakow in cooperation with the department of design, innovations and development of PBSz SA (Shaft Sinking Company) designed the construction of light brattice wall for mine shafts, which allows for safe shaft lining or equipment modernization, while its assembly is much quicker than traditional steel constructions. The new construction of a light brattice wall was tested both in a laboratory and in real-life conditions in a mine shaft. Computer simulations were also conducted. These simulations are presented in the following sections.

The solution presented in this article is an innovative approach to a problem, so its application in mineshaft without any verification is prohibited by Polish mining authorities. Thus, the decision has been made to conduct CFD simulations because of experience in this area and the flow character of the issue. Moreover, data obtained in CFD analysis were used in strength (displacement) analysis, which allowed to determine the distance between the brattice wall and a moving cage, which is crucial in terms of the safety of this solution.

2. Modernization of Shaft No. I of Szczygłowice Department in the Knurów-Szczygłowice Coal Mine

Knurów-Szczygłowice coal mine is a part of JSW Group since 1 August 2014 [17]. Development of the colliery made modernization of the hoisting system of the southern section of the shaft no. I of Szczygłowice department necessary with elongation of its hauling depth from 450 to 850 m. The new hoisting system after the modernization has to operate on levels 450, 650, and 850 m with a possibility to transport mine carts, materials and people, and allow to transport people to the level 350 m. Moreover, operating parameters of the hoisting system (hoist, sheave wheels, headframe, shaft furniture, shaft signaling) should allow one to elongate the hauling depth to the level 1050 m without the need for their modifications.

Shaft no. I of Szczygłowice department in the Knurów-Szczygłowice colliery is equipped with two hoisting system. The hoist installed in the northern section operates to a level of 850 m. The hoisting system installed on the southern side operates to 450 m and will be modernized. Both hoists are equipped with four-compartment cages.

Table 1 presents the technical characteristics of the hoisting system operating in the southern column of the shaft.

Table 1. Technical characteristics of the hoisting system operating in the southern compartment of shaft no. 1 of the Szczygłowice department of the Knurów-Szczygłowice coal mine.

Parameter	Value
Headframe	steel
Minecarts circuit	+14.2 m
Conveyances	two four-compartment cages with a capacity of 75 kN
Hoist tasks	transport of excavated material in mine carts transport of materials in three compartments transport of people in four compartments, max. 72 people
Operating levels	250 and 350 m—one conveyance 450 m—two conveyances
Hoist	K6000/1600 located on the bank level Ward Leonard motor control system
Hoisting speed	10 m/s—excavated material hauling 8 m/s—transport of materials 6 m/s—transport of people
Capacity	7.5 Mg—excavated material hauling 7.5 Mg—transport of materials 6.6 Mg—transport of people
Shaft furniture	steel buntons every 3 m stiff wooden guides
Hoist rope	steel Ø56 mm
Balance rope	flat 188 × 33 mm
Type of shaft	two sections downcast diameter of 7.2 m

Modernization of the hoisting system in the southern column of shaft no. 1 comprises of the following processes [18]:

1. Disassembly of:
    - ○ Conveyances, hoist and balance ropes with suspensions,
    - ○ Guide tower,
    - ○ Sheave wheels,
    - ○ Fall back arrestor lugs,
    - ○ Wooden guides,
    - ○ Balance rope redirecting station,
    - ○ Artificial shaft bottom below the 450 m level,
    - ○ Shaft devices in the shaft top building, on the zero level and the 350, 450, and 650 m levels,
    - ○ Shaft signaling devices;
2. Assembly of technological equipment for the modernization of the hoisting system:
    - ○ Hoist with a kibble,

- ○ Technological platforms near the zero level,
- ○ Brattice wall,
- ○ Technological platforms in the vicinity of the level 650 m;

3. Installation of the shaft sump equipment below the level 850 m in the southern section;
4. Installation of ventilation and dewatering devices in the shaft sump;
5. Modernization of the hoisting machine:
   - ○ Two-rope drive wheel with brake discs,
   - ○ Driveshaft,
   - ○ Engine,
   - ○ System of the brake disc,
   - ○ Motor control system,
   - ○ Digital speed regulator;
6. Hoisting machine power supply:
   - ○ Installation of new 6 kV, 500 V, and 400/230 V electrical rooms,
   - ○ Installation of supply line to the 6 kV cable room;
7. Modernization of the overhead crane in the hoisting machine room,
8. Shaft signaling modernization,
9. Headframe and guide tower reinforcement,
10. Installation of new shaft furniture between zero and 850 m levels,
11. Adaptation of the shaft devices for the support of loading and unloading of materials and people on the levels.

As the hoisting system installed in the northern section of the shaft is an important part of the mine's transport chain, the assumption was made that all of the listed works have to be conducted without putting the northern hoist out of service. Thus modernization of the hoisting system in the southern part of the shaft requires the application of a brattice wall to shorten the time of stoppage of the northern hoist. To minimize the time of stoppage, a light brattice wall made of synthetic materials was designed. It can help reduce the time of the brattice assembly as well as lower the cost [19].

3. The Light Brattice Wall Construction

As it was presented in Table 1, shaft no. 1 of the Szczygłowice department in the Knurów-Szczygłowice coal mine is a downcast shaft comprising of two sections (southern and northern) with a diameter of 7.2 m and depth of 873.80 m and concrete shaft lining. The shaft is equipped with two hoists—one on the northern side, operating to the level 850 m—and another on the southern side with the hauling depth of 450 m. Each of the hoists is equipped with two four-compartment cages. A cross-section of the shaft is presented in Figure 1.

Designed light brattice wall consists of:

- Steel buntons,
- Bunton consoles,
- Composite nets forming the actual brattice wall,
- Tensioning beams,
- Steel locking sheets,
- Tensioning belts with attachments.

Single brattice wall elements are installed between two buntons (top bunton no. I and bottom bunton no. II). Buntons are made of C300 steel profiles. They are assembled to the shaft lining with consoles, chemically anchored with M30 bolts.

The actual brattice wall construction is made of Grid Carbo type polyester fiber composite net of 15 × 15 mm mesh size. The length of a single net sheet is about 30 m. It is to be extended between the top and bottom buntons. The total width of the brattice wall is about 7.1 m, however, it is split into three sections of width consecutively 3755, 1765, and 1738 mm. Technological gaps for buntons and other elements of the shaft equipment are to be made in the net. Tensioning beams are to be assembled on both vertical ends of the net using steel locking sheets. Vertical sheets of the net section are to be end-to-end jointed with steel sheets. They are also to be assembled into a ladder compartment using tensioning belts with attachments. A view of the tensioning belt and the attachment is presented in Figure 2.

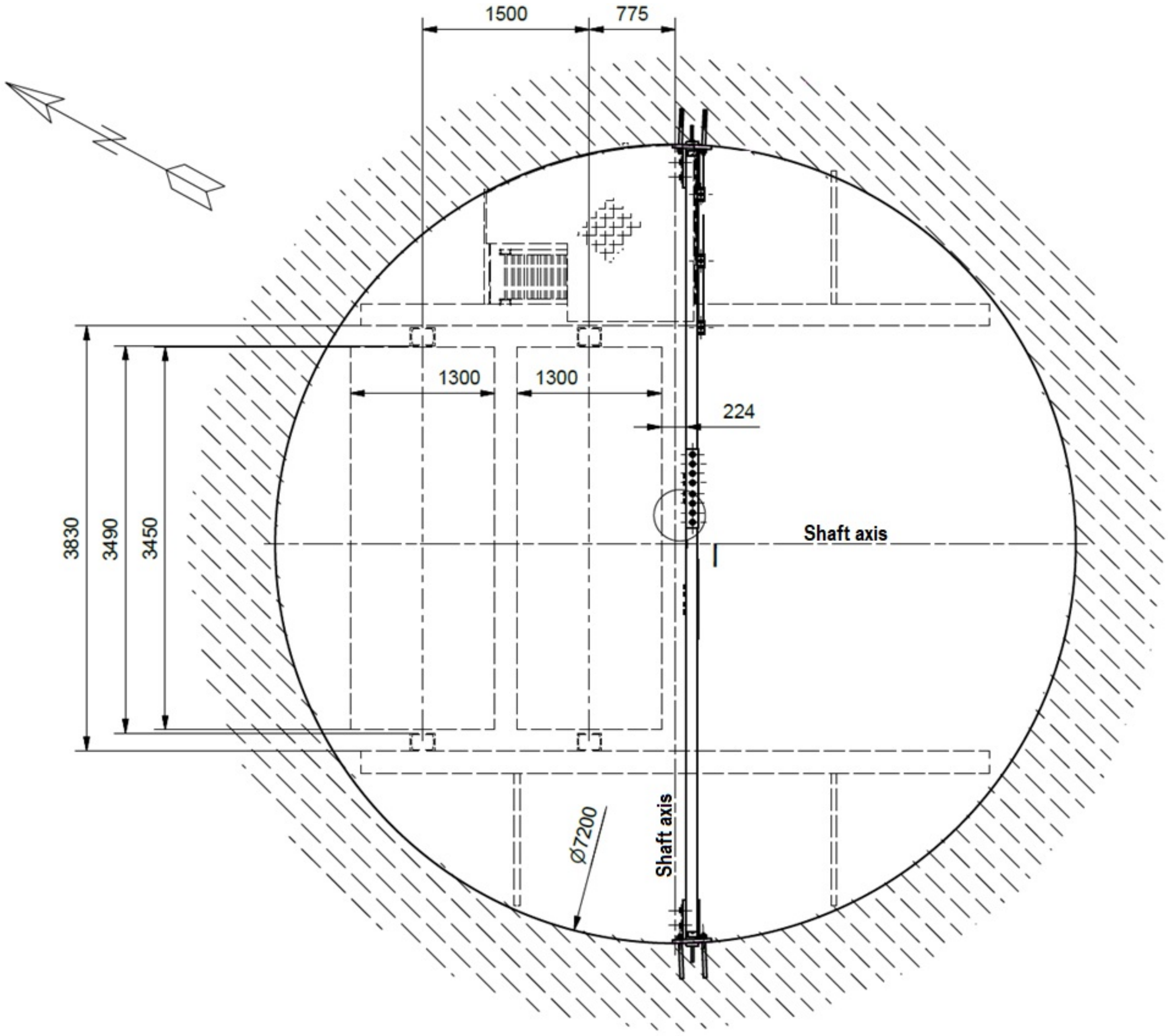

Figure 1. Cross-section of shaft no. 1 of the Szczygłowice department in the Knurów-Szczygłowice coal mine.

Elements of the brattice wall are to be jointed using fasteners, such as screws, nuts and washers. All fasteners have to meet the requirements of appropriate Standards [20–22]. They also have to be corrosion protected by electro-galvanizing. Welded joints have to be made according to welding procedure specifications (WPS). Steel elements can be corrosion protected by hot-dip galvanizing, while screws, nuts and washers have to be electro-galvanized. The surface of the elements before the galvanizing has to be prepared according to the Standard PN-EN-ISO 1461. Figure 3 presents the assembly of the net to the top shaft bunton.

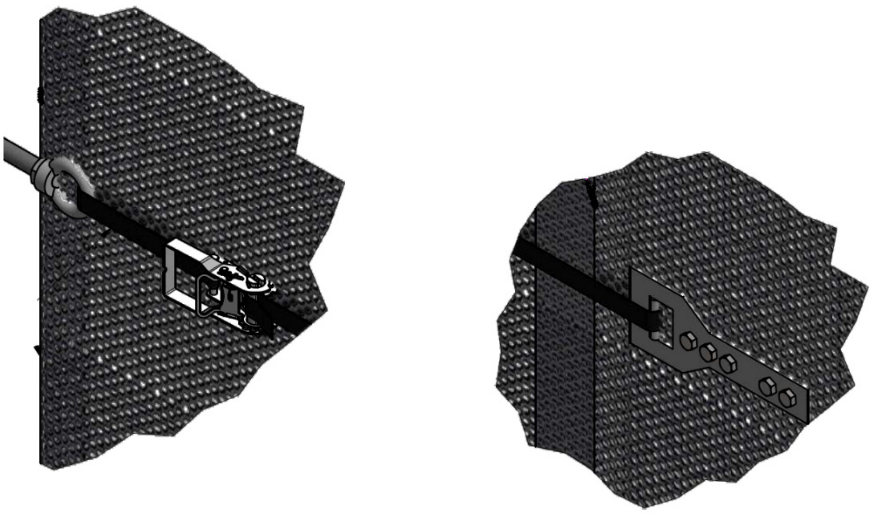

Figure 2. A view of the tensioning belt and the attachment.

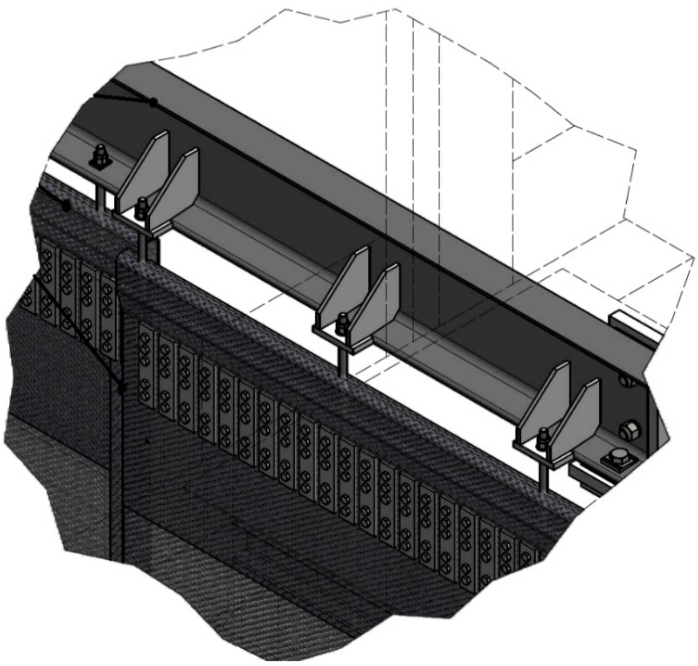

Figure 3. Assembly of the net to the top bunton.

4. Simulations

Simulations were conducted using the finite elements method (FVM) in Ansys CFX. The simulations aimed to verify the conceptual design of the brattice wall before the installation of its test section in the shaft. For the FVM analysis, a 3D CAD model of a 60 m long shaft section was prepared, comprising.

- Shaft lining of 7.2 m diameter,
- Artificial shaft bottom,
- 30 m long brattice wall section,
- Mine cage.

Described model is presented in Figure 4.

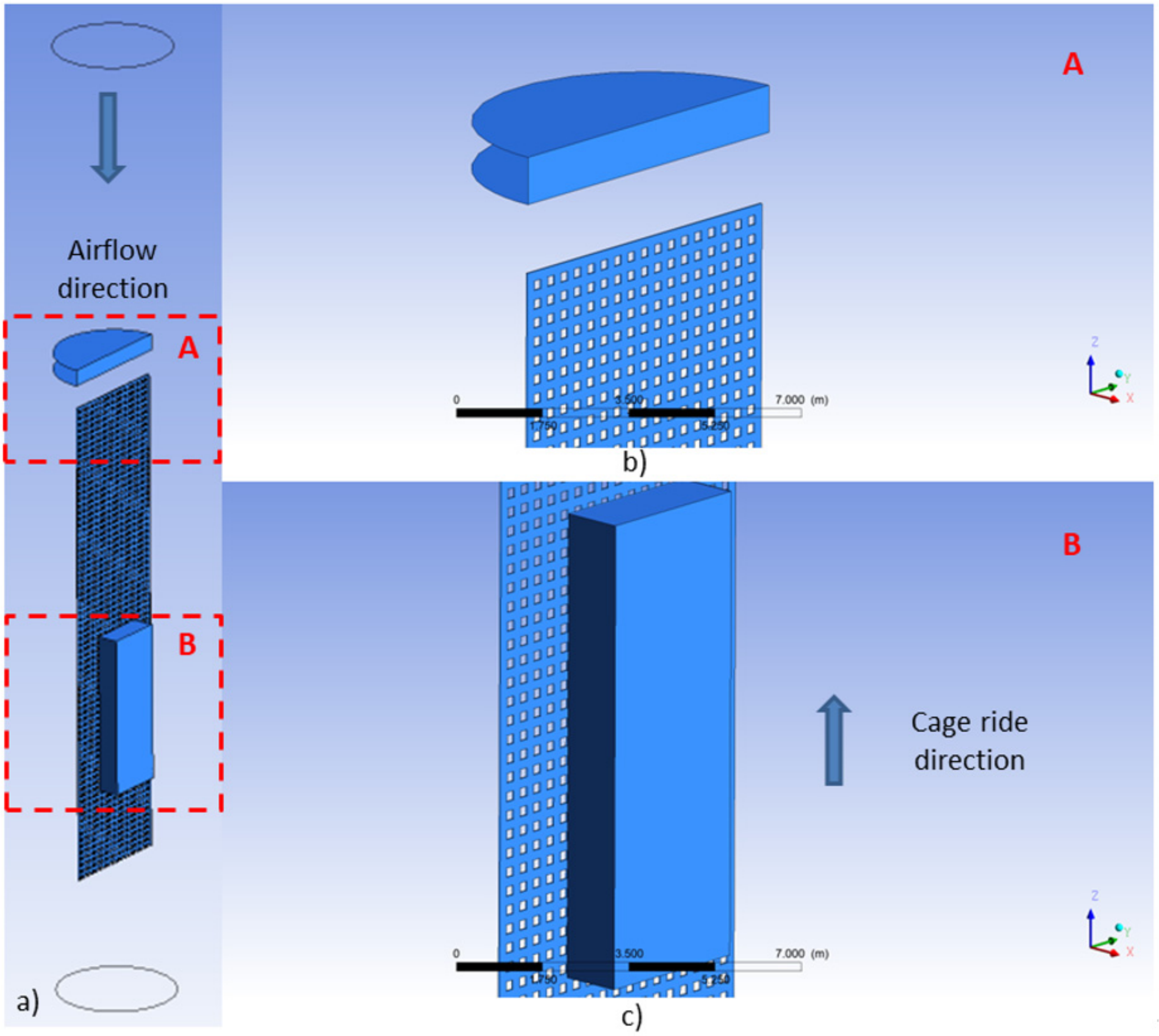

Figure 4. (**a**) Model for CFD analysis; (**b**) Close up for the vicinity of the artificial shaft bottom; (**c**) Close up for the vicinity of the cage.

The research was divided into two stages. The first of them consists of Computational Fluid Dynamics (CFD) analysis comprising forced airflow of speed about 6–8 m/s and movement of the conveyance with a speed of 10 m/s, which was selected as the most adverse case of the airflow. The assumed speed of the conveyance is in fact its maximum speed in the shaft. The model is characterized with huge dimensional disproportion, as the maximum dimension is the length of the shaft section, which is equal to 60 m (60,000 mm), while minimum dimensions are the net thickness, which is 3 mm and mesh sizing of 15 × 15 mm, so the ratio of extreme dimensions is about 20,000. Taking into account the need for the discretization of the model with a huge disproportion of dimensions together with the requirement for generating so-called boundary layers (inflationary layers) for purpose of determination of air particles flow and influence of the local pressure, a fully realistic model is impossible to discretize. Therefore the net was scaled to the smallest possible dimensions. After 13 times scaling, 40 mm thick net of 200 × 200 mm mesh sizing was obtained, which allowed to discretize the whole model. Modelled airflow between two sections divided with the brattice wall is similar to the real one. Discretized model is presented in Figures 5 and 6. Discretization allowed one to obtain over 12 million finite elements and about 3.5 million nodes.

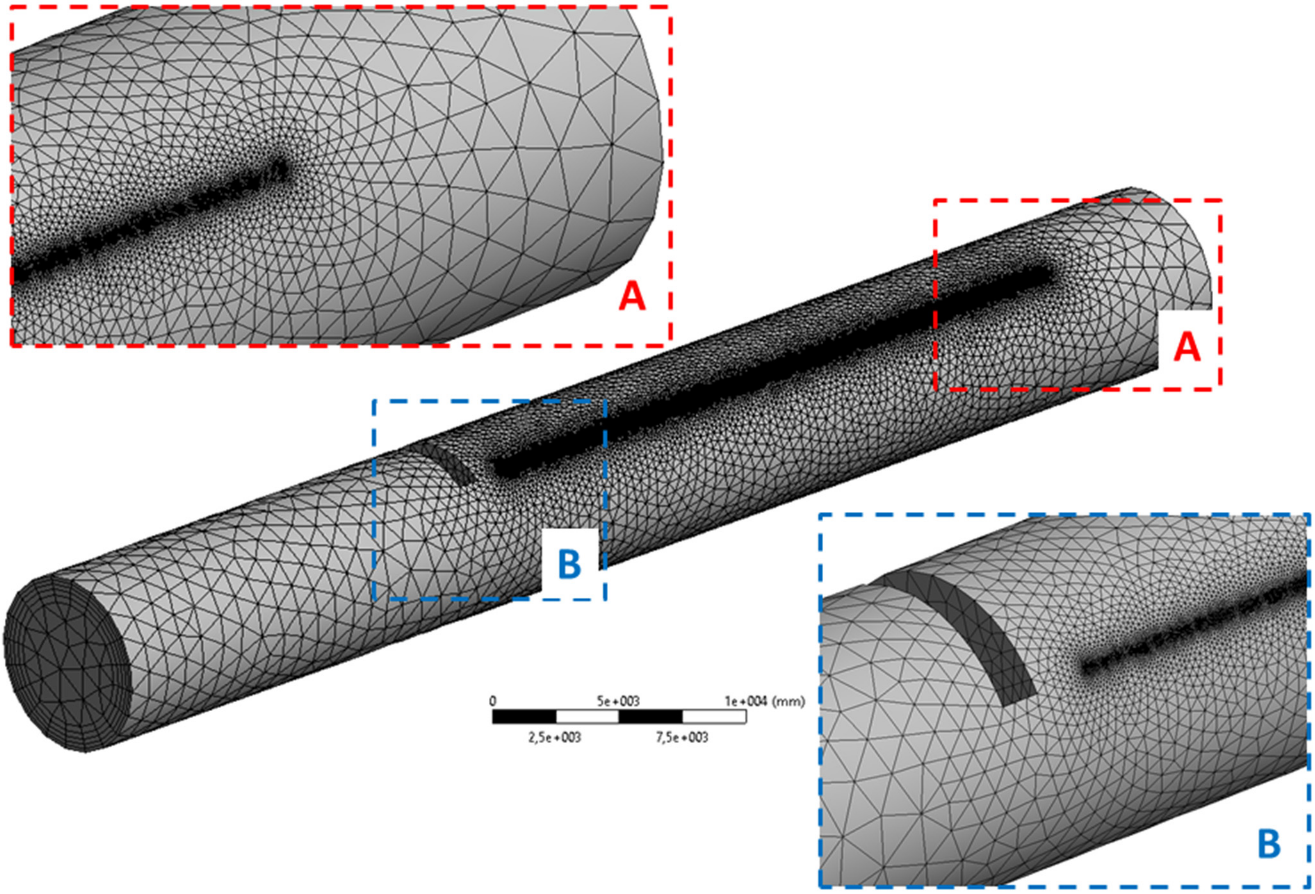

Figure 5. Discretized model for purpose of CFD analysis.

Boundary conditions were:

- Pressure equal zero at the entry to the shaft (to include the influence of turbulence on the net),
- Airflow with -Z direction (horizontal downcast movement) with the resultant value of forced airflow (6 m/s) and cage speed (10 m/s),
- No boundary conditions were specified for the brattice wall in the first stage of the CFD analysis. Only the presence of the brattice and indirect influence of the airflow boundary conditions on it were included.

The air domain model was determined in 50 iterations to obtain good results relevance. After the iterations values of the analyzed quantity were stable. Moreover, quality parameters, as skewness and orthogonal quality, were checked. Disturbances of the airflow caused by the artificial shaft bottom are visible in Figure 7, as well as local increases of airflow velocity. The simulation revealed that during the movement of the surface of the upper transom of the cage through the vicinity of the middle section of the brattice, the net is pushed away by overpressure caused by airflow. Despite the consideration of the moving conveyance case, the simulation was a static analysis, comprising the time and position of the cage.

Local airflow disturbances below the cage were also spotted. Together with overpressure, they pull the brattice towards the conveyance. In Figure 8, local distribution of pressure was presented, both on the active side of the brattice (southern side, where measurement was conducted) and the passive side. It is clear that in the areas of airflow disturbance occurrence, which are caused by artificial shaft bottom and conveyance (both top and bottom transom), a significant pressure gradient occurs. Analysis of their values allows one to notice that they are both positive and negative. Thus they form a system of under- and overpressures acting on the brattice in the direction by the x-axis (perpendicular to the surface of the brattice wall).

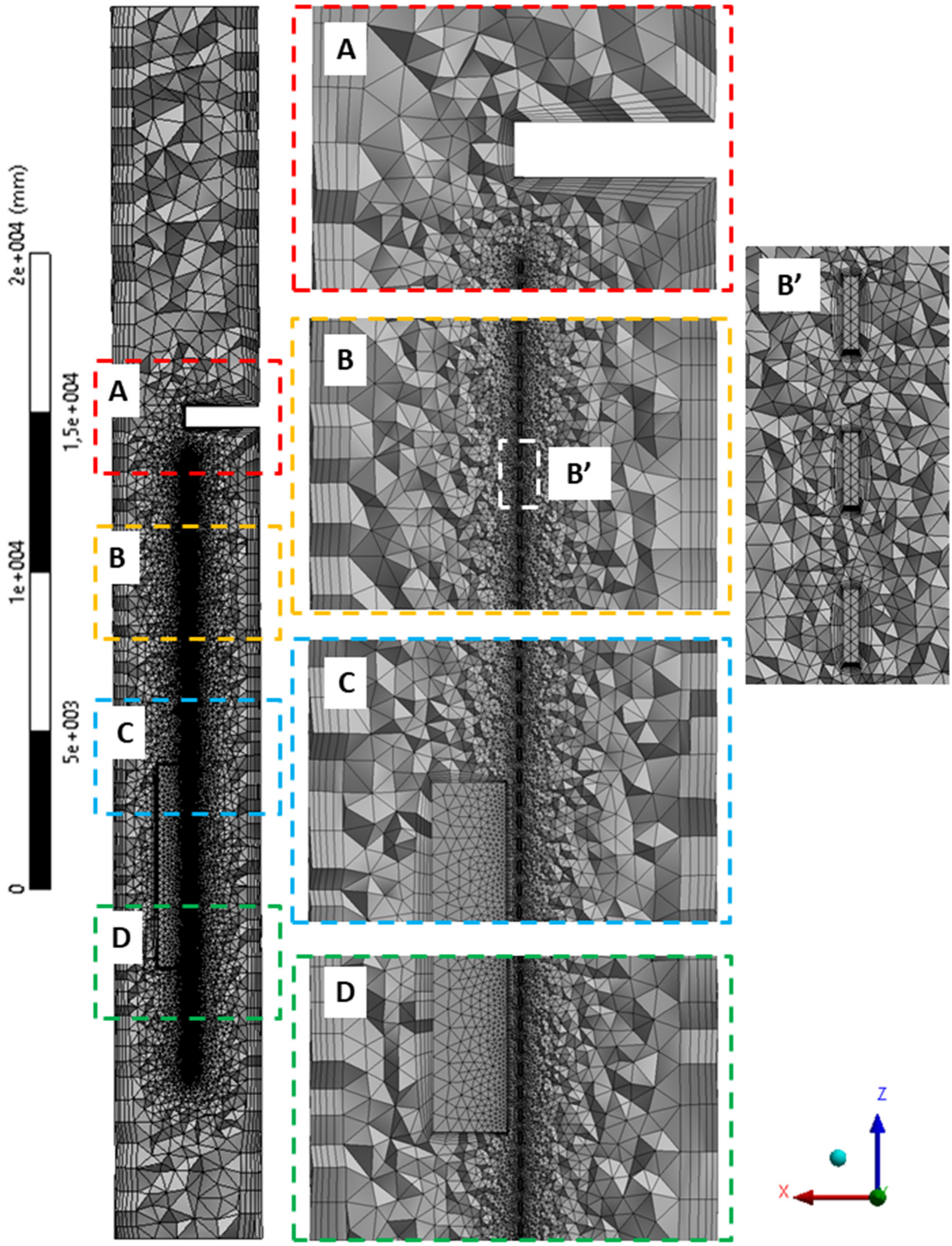

Figure 6. A discretized model with cross-sections and increased number of nodes in the vicinity of the cage and brattice wall for purpose of CFD analysis.

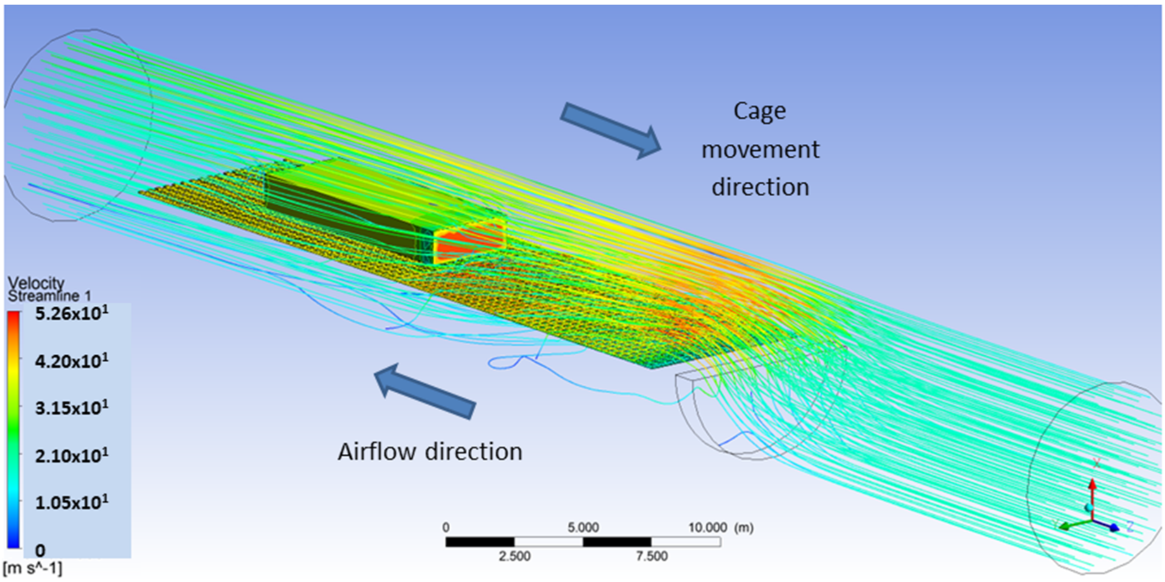

Figure 7. The trajectory of the air particles movement and their speed. Distribution of pressure on the brattice and cage with cage moving up (in Z+ direction).

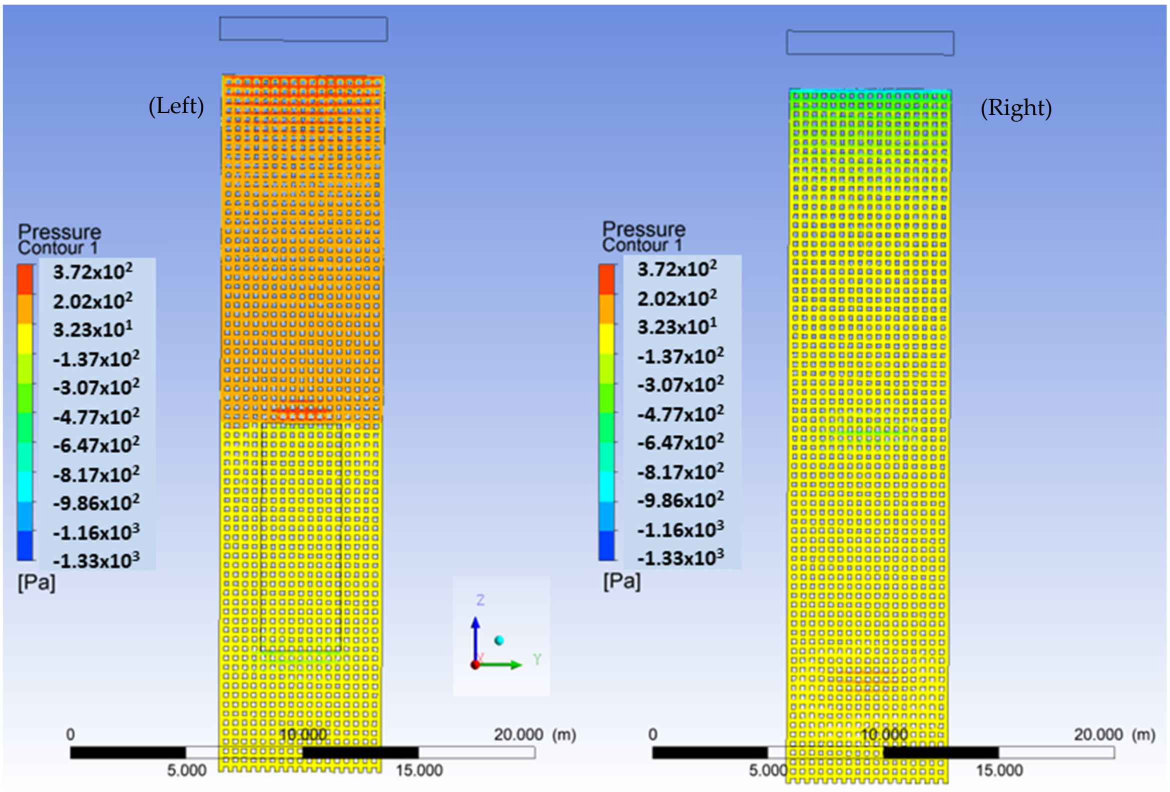

Figure 8. Distribution of pressure—active side of the brattice (**Left**), passive side (**Right**).

An increase in the pressure caused by the artificial shaft bottom and airflow disturbances are noticeable. Figure 9 presents a phenomenon of overpressure created just over the top transom of the cage moving upwards. It is induced by the airflow in the vicinity of the cage and so-called "apparent wind". Figure 10 presents the opposite situation. In the vicinity of the bottom transom of the cage, underpressure is created as an effect of disturbances and increase in air particles freedom of movement. Underpressure acting on the net causes pulling it towards the active side of the brattice.

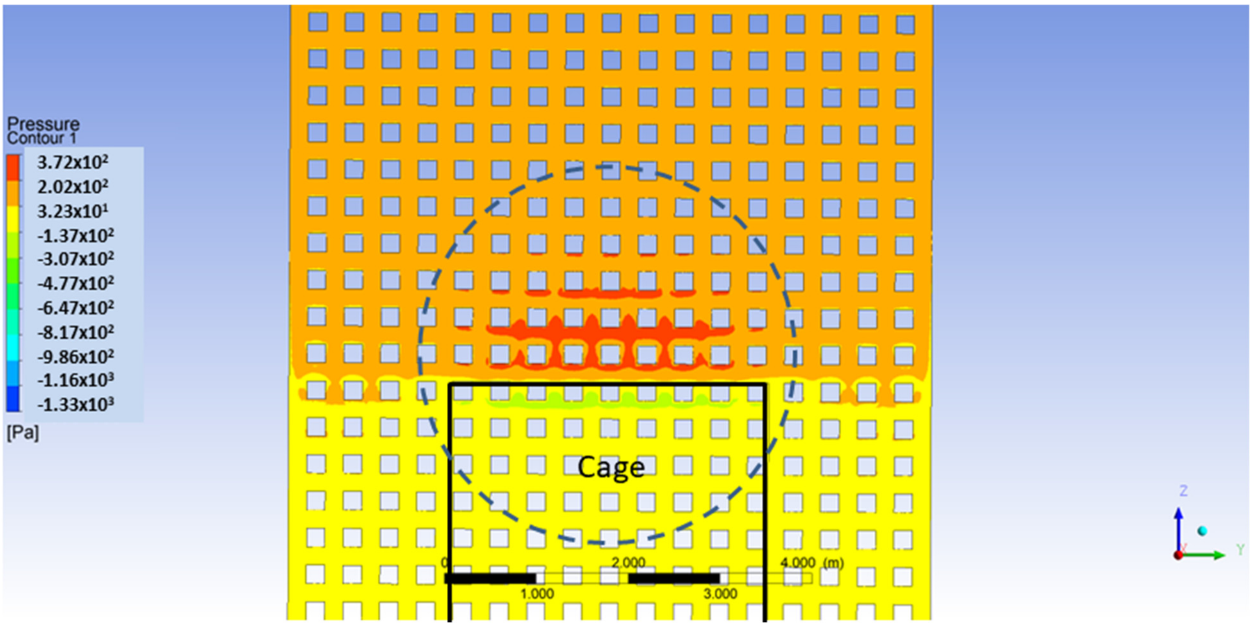

Figure 9. Local distribution of pressure on the active side of the brattice in the vicinity of the top transom of the cage.

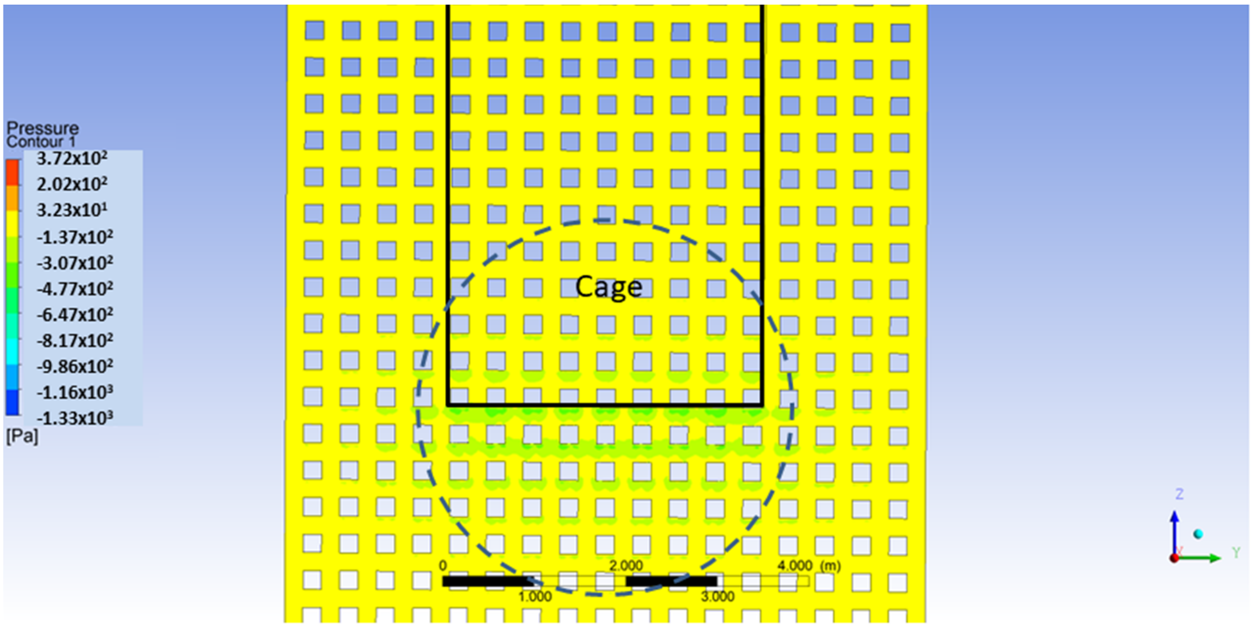

Figure 10. Local distribution of pressure on the active side of the brattice in the vicinity of the bottom transom of the cage.

The first stage of CFD simulations, described above allowed one to identify different areas of pressures and their values, which are induced by the movement of the cage and forced airflow in the shaft.

The second stage of simulation comprises strength analysis, identified areas and values of pressure were mapped and interpolated on the net model in strength analysis. The aim of the strength analysis was the determination of the brattice wall deformation induced by the moving cage. As the net is loaded only by its own weight and preloading, determination of stress state was not necessary. Displacement analysis required accurate parameters of the net's material. Laboratory tests with a testing machine allowed one to estimate the value of Young's modulus of the net's material. In turn, it allowed one to conduct strength numerical analysis, reflecting the laboratory experiment using a square fragment of the net with dimensions of 1 × 1 m (Figure 11).

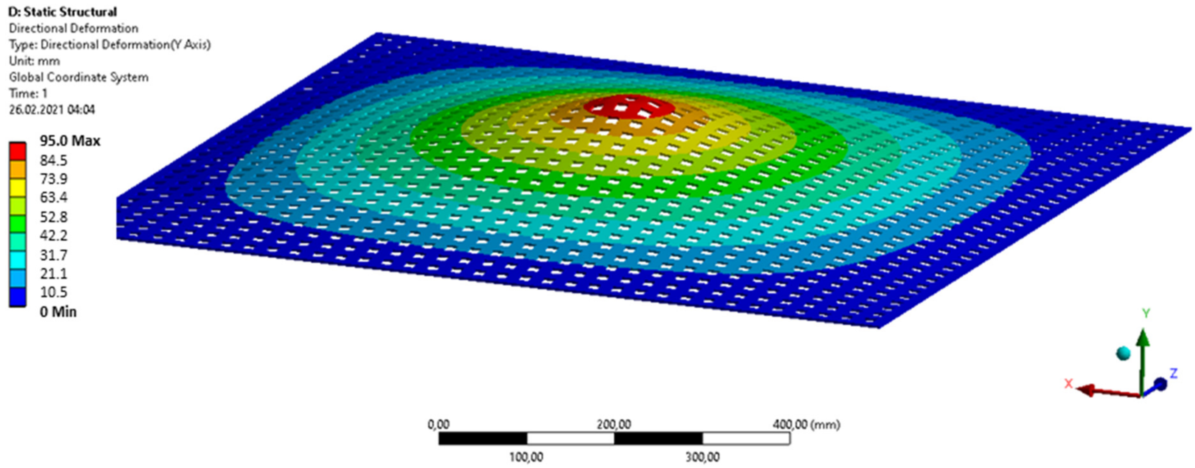

Figure 11. Displacement of the net in FEM analysis.

The experiment consists of a force acting perpendicularly to the central point of the net and an analysis of its correlation with displacements. Values obtained in numerical analysis are:

- Displacement equal 95 mm,
- Force equal 5100 N,

Which corresponds to the results obtained in the laboratory test. After the statement of results compliance, parameters of materials were scaled to respond to the scaled up geometry of the brattice. The analyzed case comprises a construction with length and height is significantly greater than its thickness. As the producer of the net provides only basic strength parameters, scaling was simplified, but it provided relevant results. Despite geometrical scaling, material scaling was conducted. Laboratory tests of point loading of the net sample with diameters of 1 m × 1 m were allowed to determine the correlation between lateral force and displacement. Numerical simulations use the same correlation as it was obtained in the laboratory tests. Results obtained in CFD analysis are matching values of net deformation in the mine shaft.

Results of the experiment confirmed the assumptions and forecasts of the brattice's behavior. As it was stated before, the determination of the stress state of the brattice wall was not analyzed. The subject of the analysis was the net deformations, as no stiff construction was designed to install it in the shaft. As it can be seen in Figures 12 and 13, the brattice is pushed away from the cage in the area of overpressure occurrence, which is a desirable effect, as the greater distance between the cage and the brattice increases safety level. On the other hand, in the area of the underpressure occurrence, the brattice is pulled towards the cage. However, it is not considered a problem, as it happens below the cage after it leaves this area. The presented case was selected as the most unfavorable one.

Numerical simulations were conducted to analyze the brattice wall's behavior in real life in the mine shaft during its exploitation in terms of its deformations and estimation of safe distance between the brattice and moving cage. Real-life industrial tests confirmed the forecasted nature of the net movements in the plane perpendicular to the shaft axis. Values obtained in the simulations also tend to match the results of the tests conducted in the shaft.

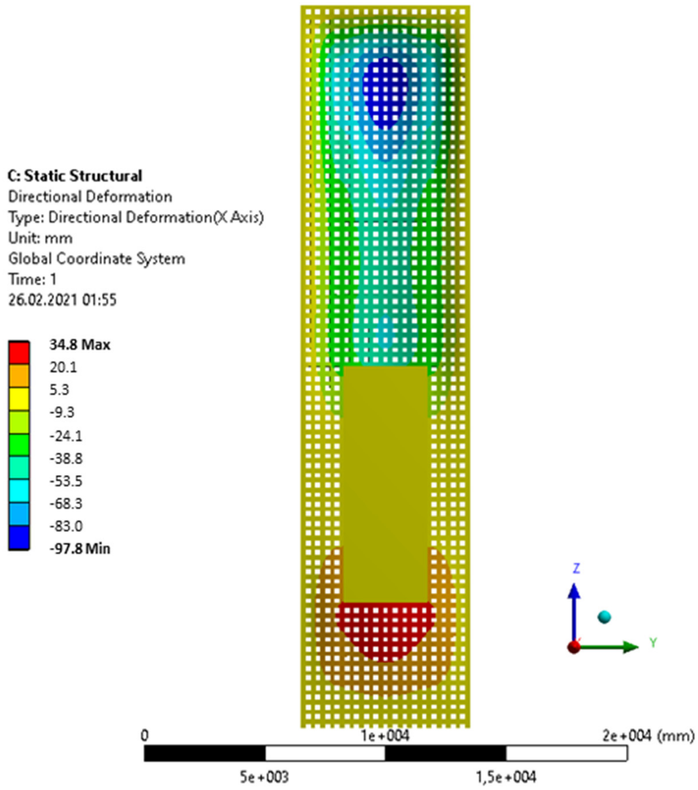

Figure 12. Map of displacement of the brattice caused by the movement of the cage.

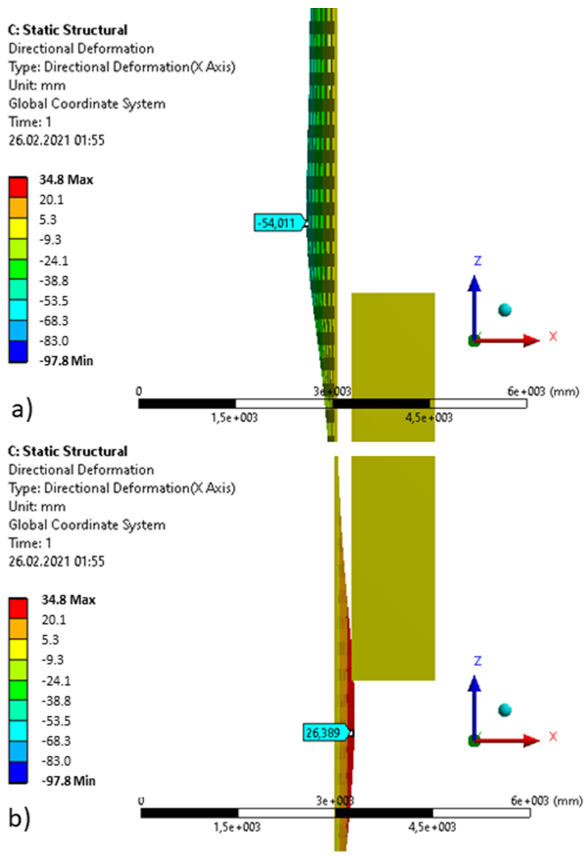

Figure 13. A character and values of displacement of the brattice, (**a**) over the conveyance and (**b**) under the conveyance.

5. Conclusions

Results of the numerical simulation confirmed that the assumptions were right and the behavior of the net was forecasted properly. Analysis of the results allows us to state that, following the forecast, in the area of overpressure over the moving conveyance, the brattice is pushed away from the cage, which positively affects the level of safety, as the distance between the cage and the brattice is increased. However, in the area of underpressure below the cage, the brattice is pulled towards the active side of the shaft, which however is not a real issue, as it happens after the cage leaves that place. If the net keeps its elastic properties after its displacement and it keeps getting back to the "equilibrium position", displacement are not an issue for the brattice use.

There is still room for improvement of the model of the brattice, tough. It can be done by specifying the model of the net's material, which can be done by conducting more laboratory tests with different boundary conditions or parameters of the acting force. It can become a starting point for further analysis or design of different brattice variants.

The new construction of the light brattice wall for mine shafts is a pioneering approach in the Polish mining industry. The low mass of the net and convenient technology of its assembly makes it an easy, cheap, and safe solution. It allows one to reduce the time of assembly of the brattice, which can help lower the cost and improve the economic score of the venture. Comparative analysis of different variants of the works on modernization of the hoisting system in the southern section of the shaft no. 1 of the Szczygłowice department in the Knurów-Szczygłowice coal mine revealed that the option comprising application of the light construction of the brattice wall allows one to reduce the time of the venture by 1.5 years in comparison to the option without the brattice wall, together with significant cost reduction.

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