Modeling the rational parameters for innovative fastening systems in mine workings using composite materials

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ABSTRACT: The leading methodologies (mathematical modeling and computational experiment) for studying geomechanical models to represent the state of systems "rock mass - reinforced rocks - innovative support system" in complex mining and geological conditions are considered. Mathematical modeling of carbon fiber-reinforced plastic arch support (CFRP) was carried out. A comparative analysis of the stress and strain state of the system "rock mass - support made of composite materials" with the stress and strain state of the existing roof support system in the mine was carried out. A laboratory simulation was carried out to determine the carrying capacity of the new shoring structure by creating a model on a 3D-printer in accordance with the basic principles of geometric similarity theory. The reliability of the calculations carried out and the results obtained has been substantiated by comparing the data of the computational experiment and the laboratory simulation.

Keywords: carbon fiber-reinforced plastic, mine workings, composite material, support, stress-strain state, physical and mechanical properties.

1 INTRODUCTION

The energy sector of Ukraine directly depends on the coal industry as the basis for the country's industry development (e.g. Ivanova et al. 2021 and Mamaikin et al. 2017). It is based on the energy-saving principles and effective use of all available energy resource. Despite the latest global trends in decarbonization (Kermeli et al. 2022), the coal industry in Ukraine is the main, pivotal, city-forming one and, despite the decline in prestige, remains one of the main industrial sectors.

One of the main directions for implementing the task of increasing the reliable operation of coal mines is not only improvement of the coal mining technology, but also ensuring the proper stability of the extraction workings, including for their repeated use (Kovalevska et al. 2020).

The factors discussed above testify to the relevance of this research, but first it is necessary to review the main publications and trends on the issue of fastening the mined-out space, both with arched supports and roof-bolting supports (Table 1). This will determine the main directions in conducting the research.

Table 1. Studies dedicated to fastening the mined-out space with arched frames and roof-bolting supports.

Scholars	Year	Scientific novelty
Bondarenko et all	2022	Arched support made of composite materials (carbon fiber-reinforced plastic (CFRP) for mine workings of coal mines is substantiated
Krykovskyi et all	2021	The interaction of roof-bolting support with the rock mass during the strengthening of weak rocks with the help of roof-bolts, as well as the modification of the roof-bolting support technology in the conditions of increasing intensity of coal mining, has been determined.
Fomychov et all	2020	Optimal parameters for designing a reusable mine working have been found.
Rajwa et all	2019	The safety of supporting and driving longwall faces with caving ahead of the longwall face is substantiated.
Khalymendyk and Baryshnikov	2016	Substantiation of cable bolts parameters for supporting mine workings in conditions of laminated rocks.

From the data presented in the table, it can be concluded that at present there is a steady tendency towards the creation and implementation of new methods of mine working support to improve the work of miners and reduce the costs of fastening and constructing mine workings.

The use of any technology for maintaining and protecting mine workings requires conducting a series of experimental research, the purpose of which is to identify the peculiarities of the developed fastening system compatibility with the actual mining-geological characteristics of the rock mass (Snihur et al. 2022).

An effective way to increase the stability of mine workings is a support from composite materials which will improve the state of mine workings. Innovative support makes it possible to reduce the negative rock pressure manifestations and creates favorable conditions for uninterrupted and safe operation of mine workings.

The choice of carbon fiber-reinforced plastic as a fastening material is conditioned by its strength characteristics (Bondarenko et al. 2023), which are not inferior to the characteristics of alloy steels used for mine working supports.

However, the issues of implementing supports made of composite materials remain insufficiently studied, which requires the search for new technological solutions in this direction. Therefore, modeling the rational parameters for innovative fastening systems in mine workings using composite materials is an important and relevant scientific task.

2 RESEARCH METHODS

To achieve the purpose set, the research is conducted using mathematical modeling by the finite element method (FEM) in the Solid Works software product.

The supports are modeled of constant and variable section with circular cross-section made of carbon fiber-reinforced plastic and St.5 steel (SCP profile 27) in the appropriate mining-geological conditions. To obtain the correct distribution of the rock mass stress-strain state in the conditions of the Western Donbass mines (for example, Heroiiv Kosmosu mine), an elastic-plastic formulation of the problem is used. In addition, the physical-mechanical properties of materials and rock sare taken into account, as well as the mining conditions, such as mining depth, inclination angle, elasticity modulus, Poisson's ratio, shear modulus, bulk density, compressive strength and tensile strength.

Conducting a computational experiment involves a whole range of research on data collection, processing, preparation, as well as calculation and analysis of the obtained results. The problem solution using the FEM method is divided into several main stages, such as the substantiation and creation of a geometric model, substantiation of the physical-mechanical properties of materials, the

addition of boundary conditions, the construction of a finite element mesh, and the analysis of the results obtained.

To analyze the results of calculating the stress-strain state, the intensity σ curves are used, which give an ability to assess the qualitative and quantitative pattern of the stress distribution in the support.

During the research, a laboratory experiment is conducted on a hydraulic press. This experiment includes the following set of actions related to the creation and testing of supports made of composite materials.

Stage №1. Creating a support model for its printing. In the Solid Works software, based on the similarity criteria, a support model is created that is 10 times smaller than the real model.

Stage №2. 3D-model printing. At this stage, a support model is printed using 3D-technologies. The material for manufacture is carbon fiber-reinforced plastic.

Stage №3. Conducting a laboratory experiment. The printed support is loaded on a Torin 20 T hydraulic press. To achieve high accuracy of the experimental results, optimal loads are chosen.

Using this method, it is possible to solve the specified scientific task.

3 RESULTS

The assumed height and width of the model make it possible to accurately and reliably calculate the stress-strain state of astratified mass under difficult mining-geological conditions using the Solid Works software product.

One of the research stages is the analysis of the mass stress-strain state according to vertical and horizontal stresses, as well as its intensity.

The loads applied to the mass are 11.75 MPa, calculated by the formula:

$$\sigma = \gamma \cdot H,$$

where γ – rock density (2500 kg/m^3), H – mining depth.

The modeling results are generalized, revealing the problem of non uniform rock pressure distribution around the mine working under specified conditions. Therefore, in Figure 5, a stratified mass of arched support made of St.5 steel (SCP profile 27) in terms of intensity has been modeled.

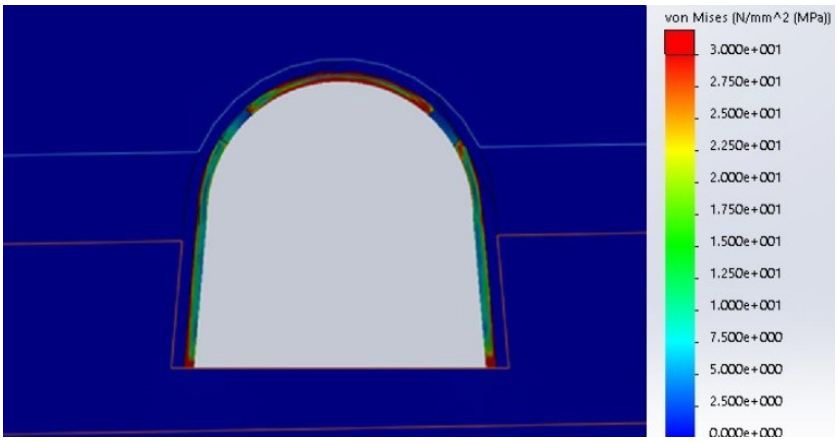

Figure 1. SSS analysis of support made of SCP profile 27in terms of intensity.

When the mass load is approximately 300 MPa, the localized tensile stress zones in the joists and prop stays of the frame can be seen, marked in red. The frame cap board is exposed to local tensile stresses and, to a lesser extent, compressive stresses. Significant compressive stresses can be seen as the frame prop staysabsorb all vertical loads. Horizontal stress is a strong compression in the lower part of the frame due to increased pressure on the walls.

Analyzing this method of supporting, it can be seen that the stress intensity during frame fastening is very high. As a result, such supports made of metal are not sufficiently reliable and do not perform the function of uniform pressure distribution along the mine working contour.

The next modeling step is the use of an arched support made of carbon fiber-reinforced plastic of constant section with circular cross-section.

When analyzing the interaction between the stratified mass state and the CFRP support, a range has been determined from compressive stresses of -30 MPa to tensile stresses of +30 MPa. Taking into account the stress intensity, when analyzing the CFRP arched support SSS, the stress from 0 to +300 MPa is set (Figure 2).

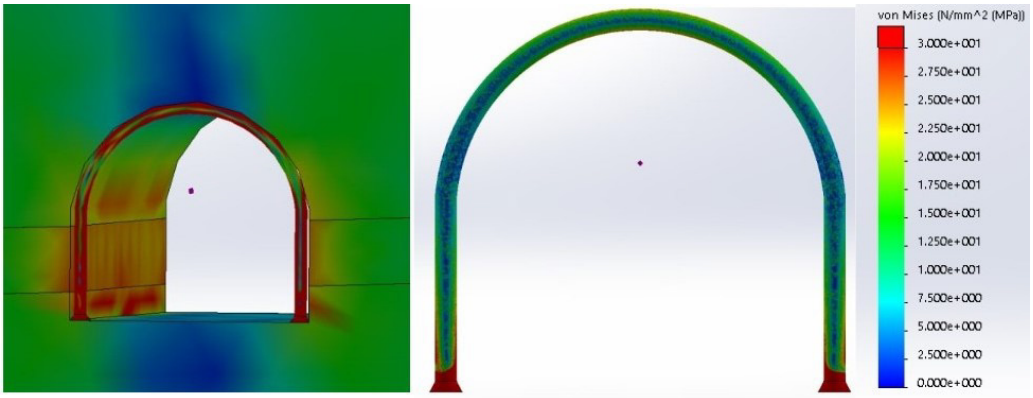

Figure 2. SSS analysis of the CFRP arched support of constant section.

Stresses from 20 to 50 MPa are observed in the upper part of the frame, while the highest stresses are observed in the heel of the prop stay, which is a normal operating condition for this type of support. The stress range of yielding joists is from 5 to 15 MPa due to the new technology of using carbon fiber-reinforced plastic for support.

The last step of our research is the stress-strain state modeling of the CFRP arched support of variable section.

Despite the reduction in the support section in those places where there is a thinning, the support works and meets the conditions of the Western Donbass mines.

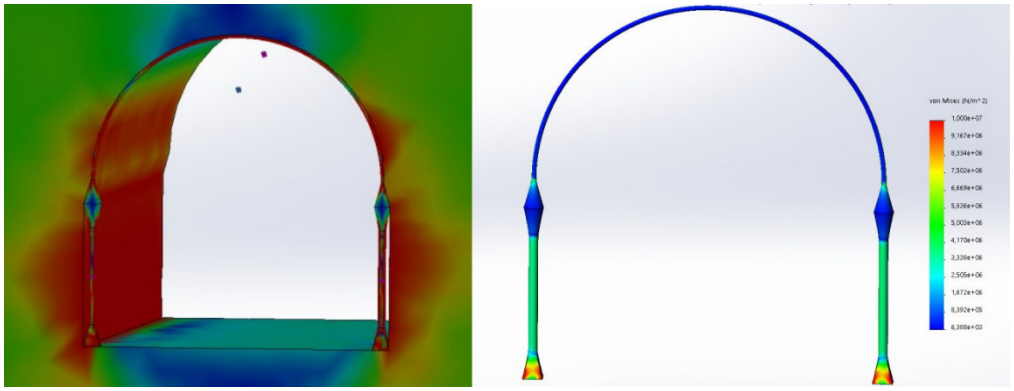

Figure 3. The SSS analysis of the CFRP arched support of variable section.

The stress intensity for this type of support was set from 0 to +300 MPa (Figure 3). Stresses from 25 to 63 MPa are observed along the entire cap board contour with variable section. With regard to the prop stays of variable section, the highest stresses from 58 to 97 MPa are concentrated in the heels, and this corresponds to preliminary research on this type of support. Paying attention to the yielding joists (from 16 to 25 MPa), they are not destroyed and completely perform operation, despite the highest stresses acting on them.

Having compared the results of the research on the stress-strain state of as tratified rock mass with a typical SCP 27 profile support and new CFRP support of constant and variable section with circular cross-section, the following conclusions can be confidently drawn. It is at the mining depths inherent in the Western Donbass mines and difficult mining-geological conditions with unstable rocks that it is necessary to pay urgent attention to the modernization of typical supports for mine workings, by introducing new types of supports with high rates of physical-mechanical properties, flexibility and low specific weight.

The stress distribution is fully consistent with the existing idea of the deformation processes around the mine working (e.g. Babets et al. 2022 and Fomychov et al. 2018). The results obtained do not contradict numerous geomechanical studies in this area (e.g. Bazaluk et al. 2022 and Bondarenko et al. 2019).

The next step of the research is the manufacture of a CFRP support model ona3D-printer, because 3D-printing technologies have become widespread in the last decade. The material for printing is a special carbon filament. This provides an opportunity to test and study composite support in the laboratory for compressive and tensile stresses, as well as to conduct additional research on the support resistance.

Figure 4. Research on a hydraulic press of a CFRP support and a composite sample.

In laboratory conditions, a CFRP support and a composite sample (Fig. 4) are separately tested. An equivalent stress of 8 KPa is set on the press, which shows the following results. In the prop stays of the frame, tensile stresses of approximately $\sigma = 0.3 – 0.5$ kPa act, and in the cap board of the frame, on the contrary, compressive stresses of $\sigma = 0.1 – 0.4$ k Pa act. Moreover, the frame prop stays begin to deform, but in general, the composite support withstands, as can be seen in Fig. 4. The prop stays and cap board are deformed in the same way as in the computer modeling. Testing of the composite sample shows that the material can with stand a load equivalent to the load on a metal support.

Laboratory research makes it possible to compare the results with computer modeling, the convergence of which is quite high and ranges within 85 – 90%, and to further recommend an innovative CFRP support for conducting a mine experiment.

CONCLUSIONS

Having analyzed the results of the mass stress-strain state and taking into account the characteristics of the supports, an arched support made of carbon fiber- reinforced plastic of variable section with circular cross-section has little advantage over a constant section in the distribution of stresses around the mine working. The only thing that significantly dominates is the amount of CFRP used, which makes this support less cheap and lighter. New supports made of carbon fiber-reinforced plastic have significant advantages over the typical ones due to their physical- mechanical properties. Our research has shown that innovative supports are 5 times lighter than metal supports and are more resistant to

mechanical stresses and can be manufactured in any geometric shape. Thus, this support will help to ensure high performance, be safe during its setting for miners and is already more appropriate for use at Ukrainian coal enterprises. A composite support model has also been created on a 3D-printer, which gives an opportunity to study the design in the laboratory on a press. This has confirmed the convergence of the results with computer modeling. The introduction of composite supports in the preparatory workings will provide an opportunity not only to improve the state of tunneling operations, but also strengthen the rock mass, as well as improve the working conditions of miners.

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