Substantiating arched support made of composite materials (carbon fiber-reinforced plastic) for mine workings in coal mines

V I Bondarenko¹, I A Kovalevska¹, S V Podkopaiev², I V Sheka¹ and Y S Tsivka¹
¹ Dnipro University of Technology, 19 Dmytra Yavornytskogo Ave., Dnipro, 49005, Ukraine
² Donetsk National Technical University, 2 Shybankova Square, Pokrovsk, 85300, Ukraine
E-mail: v.domna@yahoo.com, kovalevska_i@yahoo.com, sci.vice_rect@donntu.edu.ua, vsheka1996@gmail.com, evgeniy.tsivka@ukr.net

Abstract. This paper studies a new composite materials based on carbon fiber-reinforced plastic, which is planned to be used for supporting the preparatory workings when mining the coal at depths of more than 1000 meters. The composite material made of carbon fiber-reinforced plastic has sufficient high physical-mechanical properties, which are even higher than that of low-alloy steel used as the main material for supporting in coal mines. The purpose of the research is to substantiate the model of support (arched three-link) and determine its rational parameters. The calculation of the stress-strain state around mine working, using the support made of composite materials, has been performed based on the method of finished elements in the Solid Works software product. In addition, a model of the support for coal mines has been developed on a 3D-printer. This made it possible to conduct additional research on the interaction of the support with the rock mass. Using the Solid Works software, a detailed modeling of the composite supporting system has become possible. The stress-strain state of the rock mass has revealed that support can be used to improve the strength characteristics and prevent uneven pressure distribution around mine workings. A support made of composite materials contributes to the introduction of resource-saving technologies in the mining industry.

1. Introduction
In the 20th century, the coal-mining industry is still one of the most important sectors of the world economy in many countries. At present [1], [2], the importance of coal decreases, mainly due to its negative impact on the environment and the change over to alternative energy sources. However, its use in the energy sector is several times cheaper than natural gas. This allows coal companies to increase production during periods of rising oil prices and leads to an increase in the cost of coal. The implementation of new technologies in the field of processing and use of coal has made it a relatively eco-friendly source of energy.

Long-term macroeconomic indicators show that the world is ready to completely abandon the coal economy. While some countries are phasing out the use of the thermal coal, sales and production may decline in the future, but global demand [3] will remain stable. For example, the current coal share in global energy production is approximately 40 percent.

From the data in figure 1, it can be concluded that the coal-mining industry is a dynamically developing industry [4]. Stable demand is provided by high consumption at the world's energy
enterprises. According to experts, with the current of consumption, the world’s coal reserves will be enough for about 230 years (natural gas – for 60 years, oil – for 40 years). This indicates the prospects of coal as an energy resource.

In modern conditions of influence of decarbonization trends [5], [6], [7], [8], [9], significant attention is still paid to mining of minerals, especially in the context of deteriorating mining-geological conditions [10], [11], [12], which corresponds to the scientific needs of the world economy. There is also a gradual shift from metallic materials to composite plastics, which is conditioned by the greater lightness and plasicity of the latter.

Analyzing the trends in coal-mining industry development in Ukraine [13], it should be noted that rather difficult mining conditions, which are constantly becoming more complicated, are a serious problem in mining the reserves (figure 2). It is with an increase in the depth of mining operations that the mining-geological conditions worsen and the need to ensure the stability of mine workings increases. In Ukraine, the average depth of more than 600 meters and 15 percent – more than 1000 meters. The increase in the depth of mining over the past 30 years on average in Ukraine 505 meters, or 16.8 meters per year.

Figure 2. Deformation of fastening elements in the mine workings at deep mines.

Proceeding from this, a scientific-technical problem immediately arises – the development of support from composite materials for mine working of coal mines located on ultra deep horizons, especially where a sharp deterioration in mining geological conditions is observed. The support structure should not only be light weight due to the use of composite materials, but also meet
all the requirements of strength and stability. The implementation of innovative materials is not only actively developing, but also meets certain goals and objectives. These include: strength, elasticity, resource saving, environmental friendliness and durability. Innovative materials have a number of properties suitable for fastening of mine workings. However, as indicated by research on the physical-mechanical properties [14], [15], it is better to use carbon fiber-reinforced plastic (CFRP) as a fastening material for the coal-mining industry, since it has high bending strength (1190 MPa) and a low density (1500 kg/m$^3$), as well as ultimate tensile strength (1400 MPa), etc. An analysis of the physical-mechanical properties of composite materials [16] confirms that CFRP is light weight (5 times lighter than metal), resistant to mechanical stresses, flexible, and can be made of any geometric shape. One of the problems for using the carbon fiber-reinforced plastic [17], [18] is its high cost. Having analyzed the global trend in the market of composite materials, dependence has been constructed (figure 3) that shows that in about 5 – 10 years the material cost will be equal to that of metal.

![Figure 3. Dynamics of changes in the cost of steel and CFRP for the next years.](image)

The only way to reduce the cost of CFRP is to improve the process of automating the CFRP production, which will reduce the material cost and help to be competitive in the market for innovative and metallic materials.

Horizons with increased nonuniform pressure, developed by coal mines, are an integral part of mining operations. With an increase in the depth of mining, the costs of conducting and maintaining preparatory mine workings, the share of which in the cost of coal reaches 30 – 45 percent, increase significantly. For the fastening of mine workings, mainly arch supports from a special SCP profile (90 – 95 percent) are used, the specific metal consumption of which has doubled and amounts to 600 – 1000 kg per meter run. However, annually, the average length of repaired mine workings reaches 43 – 57 percent, and fully refastened mine workings – 12 – 25 percent of the volume of maintained mine workings [19].

The process of developing a technology for fastening a mining area [20], [21], [22], [23] is a very difficult task, which is aimed not only at preventing the rock mass deformation, but also at controlling the negative phenomena: water inflows, heaving of bottom rocks and others.

The purpose of our research is mathematical modeling of a rock mass with a support from CFRP in real mining-geological conditions, analysis of the obtained stress-strain state and substantiation of recommendations for the possible use of innovative fastening elements.
2. Problem statement and solution
The development is based on the task of improving the arch support, in which, by implementing new structural elements and their interconnection, the possibility of damping is achieved by changing the interaction of the cap board with the frame prop stays, thereby making the structure lightweight, reducing stresses around the fastening contour, especially in difficult mining-geological conditions. Due to this technical solution, the labor intensity of the work performed is reduced, which accelerates the time of technological work, as well as the safety of miners. The model of an arch yielding support (figure 4) made of composite materials for coal mines on ultra-deep horizons (developed Tsivka, Bondarenko, Kovalevska, and Sheka, 2021) includes cap board connected by yielding nodes with prop stays of the same profile. The yielding nodes are made in the form of a rod-shaped cylinder filled with a plastic material, with the possibility of moving frame cap board in the vertical plane, as well as damping the support.

Figure 4. Model of an arch yielding support of replaceable profile from CFRP: 1 – metal, 2 – carbon fiber-reinforced plastic (CFRP), 3 – plastic material, 4 – replaceable profile capboard, 5 – metal rod-shaped piston, 6 – replaceable profile prop stay, 7 – orifice hole, 8 – yielding node.

The yielding property of a structure begins to occur in difficult mining-geological conditions. The frame cap board with a built-in metal rod subsides, after which the plastic material flows and exits through the orifice hole. The arch support begins to work in a yielding mode under conditions of significantly high stresses. There is a possibility of a plastic material leaking through the orifice opening, when the structure begins to dampen, and the metal rod is lowered along the frame prop stay. This is accompanied by a more uniform distribution of stresses along the entire support contour, which, together with the replaceable profile factor, helps to reduce the negative phenomena of rock pressure manifestations.

The presented model can ensure the stability of mine workings by means of more uniform stress distribution around the support contour, as well as to increase the load-bearing capacity of structure due to variable section with a significant reduction in the special profile weight by 5-6 times. At the same time, the labor intensity of performed work is reduced and the miners work safety is increased.

With the help of computer modeling in the Solid Works software product, a support made of composite materials and a laminal isotropis mass have been modeled in detail for the conditions of PFSC Mine Administration “Pokrovskie” (figure 5). In addition, to substantiate it, the intensity of stresses in the “mss-composite support” system has been studied. The model has a number of limitations, such as: the depth of mining the extraction working, as well as its orientation relative to the coal seam; structure of rock layers and their
physical-mechanical characteristics; typical section of mine working, as well as structural and technological characteristics of the composite support.

Despite the limited size of the border rock zone, it is in it that the main geomechanical processes occur, which ultimately affect the stability of mine working. These include the formation of de-stress zones in the rocks of the roof and bottom of mine working, as well as zones of increased rock pressure (IRP) in the sides. In these areas, zones of the limiting state of the rock are formed (stages of weakening and loosening in the complete deformation diagram), which make a decisive contribution to the formation of loads on the support.

Figure 5. Composite support in a laminal isotropic rock mass according to the conditions of PJSC Mine Administration “Pokrovskoe”

The analysis of the strain-stress state of the rock mass under the action of horizontal and vertical stresses depends on the Poisson’s ratio of each rock layer, set in the Solid Works program when determining the number of parameters and mechanical characteristics of rocks. The loads of 27.5 MPa are applied, calculated by the formula:

\[ \sigma = \gamma H \]  

(1)

where \( H \) – the depth of mining (1100 m).

One of the most important characteristics that determine the stress distribution in the rock mass is the lateral pressure coefficient. With changing the load, the values of the coefficients also change. As the load increases, the coefficient also increases, and only in a certain load interval it remains constant. The lateral pressure coefficient is calculated by the Dinnik formula for the model:

\[ \lambda_{el} = \frac{v}{1 - v} \]  

(2)

where \( v \) – is the Poisson’s ratio of the required rock.

The vertical component (vertical intensity) at a specified depth is determined by the weighted average rock density, while the horizontal component (horizontal intensity) is proportional to geostatic pressure and is determined by the formula:

\[ \sigma_x = \lambda_{el} \gamma H \]  

(3)

Analysis of horizontal stress (figure 6) for the border mass presents the following information. To begin with, such a range of stress values has been set from -18 MPa for compressive stresses and up to +7 MPa for tensile stresses.
According to the research results, it can be seen that compressive stresses arise in the mine working side rocks within the range of -3 – 0.5 MPa. When examining the upper and lower layers of the coal seam with a Poisson’s ratio of 0.21, it can also be concluded that there are compressive stresses in the side rocks.

Analyzing the mine working immediate roof, represented by siltstone, it is possible to observe tensile stresses. In the central part, tensile stresses act in the range from 2.0 to 3.5 MPa. The immediate roof destruction in the mine working can occur in an area that is approximately 2.1 m wide and about 1 m high.

Taking into account the entire roof area, tensile stresses from +1 to +3.5 MPa act there. When examining the mine working bottom, the tensile zone has a smaller width than the width of the mine working and is approximately 3 m and a depth of 1.5 m. Tensile stresses in this area range from 2.5 to 4 MPa. There is also a zone of de-stressing in the lower part of the mine working, taking into account the coefficient of destruction and water-cut of the coal seam. Stronger tensile loads are observed in the right corner of the mine working than in the left corner, and this part of the right corner is about 3 m wide and 2 m deep. There are also de-stressing zones in both sides of the mine working bottom. This area is about 5 m wide and 3 m deep with a stress range from +1 to +2 MPa. Due to tensile stresses, heaving of rocks is expected in the mine working bottom.

The zone of two tensile stresses occurs above the coal seam 4 m wide and 4 m high, and below the coal seam there is a zone 5 m wide and 3 m deep. As far as the side rocks have a high degree of destruction and water saturation, but the coal seam has a high strength, according to the action of compressive stresses, destruction does not occur.

The analysis of the reduced stresses for the border rocks of the in-seam working in block №11, PJSC Mine Administration “Pokrovskie”, shows the following results. Under the coal seam, there is a significant area of rocks that are exposed to compression (figure 7). This area is approximately 3.5 m wide and 4 m deep. Stress range is 6.5 – 9.5 MPa. Rock heaving and increased stresses in the mine working bottom are possible, caused by rock dinting. Increased stresses occur in the corners of mine working, ranging from 27 MPa to 30 MPa. In these places, compression of rocks is possible.

Analysis of the distribution field of horizontal stresses in the frame support (figure 8) shows the following results. A range of -50 MPa for compressive stresses and up to +50 MPa for tensile stresses has been set for the frame support.

The peculiarities of the stress field in the composite support are as follows. Quite large
compressive stresses 34 – 40 MPa act in the cap board, the most destressed is the yielding joist, where compressive stresses 5 – 10 MPa act, as it should be when it comes into action. Tensile stresses practically do not act in the lower parts of the prop stays, while relatively large tensile stresses act in the middle part of the prop stays, approximately 45 – 50 MPa.

Taking into account the stress intensity, it has been determined in the SSS analysis of the composite support that the stress ranges from 0 MPa to +300 MPa (figure 9). Stresses 50 – 70 MPa act in the central part of the composite support cap board, and the other part is almost destressed. This indicates a relatively uniformly low-loaded cap board. Quite small loads 5 – 15 MPa act in the yielding nodes, which is caused by a completely new technology of the yielding mode. The frame prop stays are the most loaded, where the strongest stresses 80 – 110 MPa act.

The development of large depths of mining, especially in difficult mining-geological conditions with unstable rocks, requires a reassessment of the requirements for the role of support
characteristic. It should be noted that in the studies [24], [25], [26], the maximum permissible stresses are considered to be 100 – 150 MPa, which generally corresponds to typical mining-geological conditions and the existing development of means for fastening the mine workings. Under these conditions, the structure is stable, slightly deformed, operates in a yielding mode, and the mine working is able to perform its operational functions. Moreover, at great depths, the stress intensity can increase up to 200 – 250 MPa, and more will be inexpedient.

According to the quality factor, the parameters of the distribution components of stress deformations correspond to the existing representation of the rock mass deformation processes around the mine working [27], [28], [29]. The results obtained do not contradict numerous geomechanical studies in this area [30], [31], [32], [33], [34], [35]. This confirms the correspondence of the model to the real conditions of mining operations in coal mines.

What is more, in the last decade, 3D-printing technologies [36], [37], [38] have become widespread, with the help of which it is possible to create different models. In the studies [39], [40], [41] the three-dimensional printing process is called Rapid Prototyping. Thus, 3D-printing is a method that makes possible to obtain a layer-by-layer physical object from a mathematical model developed in a special CAD system. Technologies of 3D-printing are widely used in many fields, such as medicine (creation of artificial implants, etc.), in machine-building industry, in instrument-making industry, in energy, motor vehicle industry, etc. [42], [43], [44], [45].

Based on this, the following rather relevant scientific and technical task arises – the development of a model for coal mine support made of CFRP using a 3D printer. This makes it possible to conduct additional research on the support resistance. The manufacturing material is a special carbon thread for 3D printers, and the process of creating a support structure is shown in figure 10. This makes it possible to test and study the composite support for compressive and tensile stresses in the laboratory (figure 11).

Under laboratory conditions, an equivalent stress of 8 KPa is set on the press, which indicates the following results. In the frame prop stays, the tensile stresses of approximately 0.3 – 0.5 KPa act, and in the frame cap board, on the contrary, compressive stresses 0.1 – 0.4 KPa act.
Moreover, the frame prop stays begin to deform, but in general, the composite support remains stable, as can be seen from figure 11. This makes it possible to compare the results of computer modeling and laboratory tests.

3. Conclusions
The new structure is called a “composite support”. The innovative development idea is to move from the traditional SCP profile to a round section, as well as to move from a yielding joist to
a yielding node. With the help of computer modeling, a laminal rock mass has been developed, as well as a computational experiment has been performed. The study of SSS analysis of the composite support has revealed that the stress intensity in the frame structure of the support is not more than 110 MPa. Insignificant compressive stresses act in the frame cap board, and tensile stresses act in the prop stays. This indicates the support operation in a yielding mode even in difficult mining-geological conditions with significant manifestations of nonuniform rock pressure.

A composite support model, developed on a 3D-printer, makes it possible to study the structure using a press in the laboratory. The convergence of the results has been confirmed during computer modeling. The implementation of composite support in the mine workings will not only improve the state of drifting workings, but also strengthen the rock mass and improve the working conditions of miners.

ORCID iDs
V I Bondarenko https://orcid.org/0000-0001-7552-0236
I A Kovalevska https://orcid.org/0000-0002-0841-7316
S V Podkopaiev https://orcid.org/0000-0002-3258-9601
I V Sheka https://orcid.org/0000-0001-6818-2902
Y S Tsivka https://orcid.org/0000-0003-1325-8580

References
[1] Tkach S and Gavrilov V 2019 Problemy nedopol’zovani 3 71–82
[2] Bazaluk O, Ashcheulova O, Mamaikin O, Khorolskyi A, Lozynskyi V and Saik P 2022 Frontiers in Environmental Science 10 1–12
[3] Jewell J, Vinichenko V, Nache L and Cherpa A 2019 Nature Climate Change 9 592–599
[4] Timofeev O, Sharipov F, and Petrenko B 2021 Journal coal 1 63–67
[5] Immink H, Louw R T and Brent A C 2018 Journal of Energy in Southern Africa 29 14–23
[6] Kalantari H, Sasmico A P and Ghoreishi-Madiseh S A 2021 Renewable and Sustainable Energy Reviews 1 2–33
[7] Cheema-Fox A, LaPerla B R, Serafeim G, Turkington D and Wang H 2021 Financial Analysts Journal 77 93–108
[8] Glassmire J, Bitaraf H, Padapak S and Oudalov A 2021 Accelerating data center decarbonization and maximizing renewable usage with grid edge solutions Proceedings - Design, Automation and Test in Europe, DATE vol 2021-February pp 288–293
[9] Höning D, Baumeister P, Grenfell J L, Tosi N and Way M J 2021 Journal of Geophysical Research: Planets 126
[10] Khorolskyi A, Mamaikin O, Medianyk V, Lapko V and Sushkova V 2021 ARPN Journal of Engineering and Applied Sciences 16 1890–1899
[11] Shashenko O and Cherednyk V 2020 Tidings of Donetsk Mining Institute 2 176–183
[12] Solodyanyk O V, Hryhoriev O Y, Dudka I V and Mashurka S V 2017 Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu 14 19–27
[13] Symanovych G, Demyov M and Chervatuk V 2013 Influence mechanism of rock mass structure forming a stress on a face support Annual Scientific-Technical Colletion - Mining of Mineral Deposits 2013 pp 77–81
[14] Saravanan M, Prakash S, GnanaPrakash S, Akshaykrishna M and Aswin Subhash S 2020 Investigation of mechanical properties and characterization of hybrid natural fibre polymer matrix composites IOP Conference Series: Materials Science and Engineering vol 993 pp 1–7
[15] Goncharov A A, Dub S N, Agulov A V and Petukhov V V 2015 Journal of Superhard Materials 37 422–428
[16] Sheka I and Tsivka Y 2021 Collection of research papers of the national mining university 112–121
[17] Bakulin V 2020 Analysis of the effect of the physomechanical properties of composite materials of carrier layers on the stress state of sandwich shells with rectangular cutouts Journal of Physics: Conference Series vol 1705 pp 1–7
[18] Amir S M M, Sultan M, Jawaid M, Ariffin A H, Mohd S, Salleh K A M, Ishak M R and Shah A U M 2019 16 - nondestructive testing method for kevlzar and natural fiber and their hybrid composites Durability and Life Prediction in Biocomposites, Fibre-Reinforced Composites and Hybrid Composites pp 367–388
[19] Kovalevska I, Zhuravkov M, Chervatiuk V, Husiev O and Snihur V 2019 Mining of Mineral Deposits 13 1–11
[20] Bondarenko V, Kovalevska I, Cawood F, Husiev O, Snihur V and Jimu D 2021 Mining of Mineral Deposits 15 1–10
[21] Bondarenko V, Kovalevs’ka I, Svystun R and Cherednichenko Y 2013 Optimal parameters of wall bolts computation in the united bearing system of extraction workings frame-bolt support Annual Scientific-Technical Collelion - Mining of Mineral Deposits 2013 pp 5–9
[22] Khorolskyi A, Hrinov V, Mamaikin O and Demchenko Y 2019 Mining of Mineral Deposits 13 53–62
[23] Fomychov V, Fomychova L, Khorolskyi A, Mamaikin O and Pochevov V 2020 ARPN Journal of Engineering and Applied Sciences 15 3039–3049
[24] Matayev A, Kainazarova A, Arystan I, Abuev Y, Kainazarov A, Baizbayev M, Demin V and Sultanov M 2021 Mining of Mineral Deposits 15 103–111
[25] Barabash M, Salieiev I and Symanovych H 2021 Mining of Mineral Deposits 15 7–15
[26] Pruske S, Rajwa S, Wrana A and Krzemien A 2017 International Journal of Mining, Reclamation and Environment 31 558–574
[27] Ruppeneyt K 1975 Deformability of fractured rock mass (Nedra)
[28] Protod’yakonov M and Chirkov S 1964 Fracturing and strength of rocks in massif (Nauka)
[29] Rats M and Chernyshov S 1970 Fracturing and properties of fractured rocks (Nedra)
[30] Malkowski P, Niedbalski Z, Majcherczyk T and Bednarek 2020 Mining of Mineral Deposits 14 1–14
[31] Malkowski P, Niedbalski Z and Balarabe T 2021 International Journal of Coal Science and Technology 8 312–323
[32] Begalinov A, Almenov T, Zhanakova R and Bektur B 2020 Mining of Mineral Deposits 14 28–36
[33] Babets D, Stvyzhkova O, Shashenko O, Kravchenko K and Cabana E C 2019 Mining of Mineral Deposits 13 72–83
[34] Bondarenko V, Kovalevska I, Symanovych G, Sotskov V and Barabash M 2018 Mining Science 25 219–235
[35] Lozynskyi V, Saik P, Petlovanyi M, Sai K and Malanchuk Y 2018 International Journal of Engineering Research in Africa 35 77–88
[36] Praveena B A, Lokes N, Buradi A, Santhosh N, Praveena B L and Vignesh R 2022 Materials Today: Proceedings 52 1309–1313
[37] Shahrubudin N, Lee T C and Ramlan R 2019 An overview on 3d printing technology: Technological, materials, and applications Procedia Manufacturing vol 35 pp 1286–1296
[38] Dudek P 2013 Archives of Metallurgy and Materials 58 1415–1418
[39] Pečar B, Vrtačnik D, Pavlin M and Možek M 2021 Sensors 21 1–20
[40] Blasiak S, Laski P A and Takosoglu J E 2021 Polymers 13 1–15
[41] Premarathna C, Kulasekera A, Chathuranga D and Lalitharatne T 2019 A novel fabrication method for rapid prototyping of soft structures with embedded pneumatic channels MERCon 2019 - Proceedings, 5th International Multidisciplinary Moratuwa Engineering Research Conference pp 430–435
[42] Jamróz W, Szafrianiec J, Kurek M and Jachowicz R 2018 Pharmaceutical research 35 1–22
[43] Shahbazi M, Jäger H and Ettelaie R 2021 Colloids and Surfaces A: Physicochemical and Engineering Aspects 622 1–15
[44] Andrzejewski J, Cheng J, Anstey A, Mohanty A K and Misra M 2020 ACS Sustainable Chemistry and Engineering 8 6576–6589
[45] Nadagouda M N, Ginn M and Rastogi V 2020 Current Opinion in Chemical Engineering 28 173–178