Continuous Support for Roadways

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Abstract: Opening deeper coal seams requires constructing underground mine roadways in difficult geological conditions. Supporting of such roadways is subjected to a very high load from the rock mass. The types of roof supports used so far do not provide immediate support for the rock mass, which tends to converge the roadway, allowing for a rapid build-up of stresses in the surrounding rock mass. The article presents a new type of frame roadway support. This is a yielding support (consecutive arches are connected in a helical pattern), enabling the successive arches to be provided with initial load-bearing capacity already at the construction stage. The so-called unscrewing of the helix enables the arches to be pressed against the surface of the developed roadway with a controlled force. The introduction discusses the types of yielding roof supports used in the Polish mining industry and indicates their characteristic features. Further along in the article, the assumptions adopted for the construction of models to be tested and assumptions for the static and dynamic load to the models are defined, and the results of the model numerical tests are presented. The tests were aimed at comparing the qualitative behavior of the new roof support and the closed, circular support which is closest to it. The results of numerical tests confirmed the strength of the new solution not lower than the closed (circular) frame support, previously used in the most difficult geological conditions.

Keywords: mining industry; roadway systems; roadway closed support; arch support; numerical tests

1. Introduction

Mining the deeper coal seams in Poland means that the load to mine workings from the rock mass and the risk of rock bursts are systematically increasing. In these conditions, the key issue is to ensure adequate stability of mine workings. It seems that it is much easier to secure stability of a longwall panel than the roadway. Following the certain rules in the longwall, we are able to effectively adapt the powered roof supports to absorb dynamic loads resulting from the rock mass burst [1,2]. The longwall panel stability is more complex and depends on many factors [3–5], but undoubtedly the initial and working load bearing capacity of the roof support are the most important factors [6–8].

We are dealing with slightly different problems in ensuring the stability of roadways, especially those exposed to action of the longwall front. In the literature, the roadway convergence is the most frequently mentioned reason for the loss of roadway functionality [6,7,9], which in the case of an open frame support is mainly caused by the floor heave [10,11]. On the other hand, in the case of a closed (not circular) support, uneven strain of each component of the frame arches is a reason for roadway heave. The unfavorable concentration of stresses in side walls is another threat to roadway functionality. After opening the roof rocks, support should enable the quickest possible cooperation with the rock mass; however, in the case of a typical support frame, support frames gain load bearing capacity with a delay, after a significant roof convergence [9–12]. Moreover, as a result of exceeding the strength of rock layers, the floor is destroyed and heaved to the
roadway [13–15]. Therefore, there is a need to develop a new roof support of a design that allows initial set to load, favorably affecting the cooperation of the roof support with the rock mass [16,17].

In connection with the above, tests on adaptation of roadways to take the increased dynamic load is justified in this situation.

Due to the variety of tasks, different transverse dimensions of the roadway and variability of geological and mining conditions, many design solutions are used to support roadways. Currently, in underground mining plants, in the roadways and the areas of increased operating pressure, a yielding, steel frame support is used. According to the standard [18], the yielding support is composed of sets or components which, under the action of the rock mass pressure, slide down to the structurally assumed length.

Open, yielding, LP type frame support is mostly used to protect preparatory, newly developed or rebuilt roadways. The arches of the LP support, shown in Figure 1, consist of side arches and roof arches (one, two or more), connected with each other by clevises, friction locks or articulating joints.

![Figure 1. Frames of yielding arch support type LP (a) three-elements, (b) four-elements.](image)

The gained experience shows that the open roof supports do not ensure full stability of the roadway, and the additional method of reinforcing the roof supports often result in narrowing the dimensions of the roadway cross-section [19]. Another disadvantage of the open roof support is the fact that the widest exposed surface (floor) is not protected, which, in the case of high pressure of the rock mass, may lead to heaving the rock layers of the floor to the roadway. Heave, as relaxation of the floor rock, is described in the literature as pressing and lifting the floor [13–15]. Pressing the floor is a continuous, inertial relaxation and displacement of small rock fragments (Figure 2a), while lifting the floor involves slowly or rapidly lifting a cracked layer of rock as a plate (Figure 2b).

Analysis of damage to the open roadway support, including 63 cases of rock bursts in hard coal mines, indicates the floor heave as the most common cause of damage [19]. The intensive process of the floor heave requires searching for new support solutions that will protect the roadway floor with sufficiently high load bearing capacity. As a result of experimental work, closed roof support designs have been developed, which consist of side wall, canopy and floor arched components. Examples of closed roof support designs are shown in Figure 3.
Figure 2. Floor heave: (a) pressing the floor, (b) lifting the floor.

Figure 3. Frames of closed yielding frame support: (a) ŁZP type, (b) ŁPZS type, (c) oblate yielding arch support, (d) circular.
From a number of design solutions [9,20–25], the closed reinforced support of the ŁPZS type is used, including the Polish mining industry (Figure 3b), where, in the Bogdanka mine, it allowed for supporting the roadway without rebuilding for a longer period of time [9]. The oblate closed support is also used (Figure 3c), but as shown in results from the GIG tests, cited in [26], the load-bearing capacity of this support is significantly lower compared to the arc-shaped support (Figure 3a) and requires additional reinforcements (e.g., bolting, installation of girders, support with individual stands). In the Bogdanka mine, it was observed that in the case of a closed support, used in a roadway with a strong upward floor inclination, the load to the side arches increases, which most often leads to damage to the support arches [27]. The uneven load to the arch components of the closed support arches is caused by the variety of shapes of these components, and thus their different resistance to rock mass pressure.

In connection with the above, in difficult geological and mining conditions at great depths, it is advantageous to develop a roadway using the closed support with the frame of a circular shape (Figure 3d). The circular cross-section of the support results in even distribution of the rock mass pressure on each of the coils of the support’s frame is the main advantage of the continuous yielding support in the shape of a helical line (Figure 4). Even distribution of the rock mass pressure as the consecutive frames cooperate with each other. In addition, the spatial structure of the continuous support guarantees its high stability, minimizing the possibility of tilting, twisting and overturning of the arches, either as a result of blasting, rock bursts, and also as a result of uneven pressure.

Contrary to the description of continuous support known from the patent No. DE 3232448 (A1) [30], in the discussed solution the arched components do not require profiling.

Figure 4. Continuous support of a helical line shape: 1—arch components, 2—locks, 3—sprags [29].
in the shape of a helical line, because the distance of successive arches (coils) is determined by a hydraulic cylinder and the arches are bolted with steel sprags. The scheme of the continuous support frames setting to load is shown in Figure 5.

![Figure 5. Scheme of the continuous support frames setting to load 1—arch components, 2—clamps, 3—sprags, 4—cylinder.](image)

The hydraulic cylinder (4), shown in Figure 5, is equipped with special jaws that enable proper adjustment to the external surface of the arch components (1). After extending the cylinder (4), the appropriate distance between the arches for mounting the sprags is obtained (3), setting the support pitch. To connect the arches of the continuous support, known steel sprags or a new solution, as shown in Figure 6, can be used.

![Figure 6. Examples of locating the steel sprag 1—arch components, 2—clamps, 3—sprags.](image)

The steel clamps (2) shown in Figure 6 are connected with the arched components (1) of the support and are used to connect the adjacent arches with sprags (3). Clamps have a positive effect on the local increase in the stiffness of the arch components (in their sensitive places), which in turn strengthens the arches and ultimately increases the strength and stability of the entire support. Use of clamps causes the sprags to be evenly distributed around the entire circumference of the support, which in turn allows for precise setting the support pitch—the distance between the neighboring frames. It is also possible to
quickly and easily change the support’s pitch, using the telescopic sprags or the sprags of other lengths.

The main advantage of the discussed solution is the possibility of initial setting to load the support by “uncoiling” the helix formed of arched components, favorably affecting the co-operation of the support with the rock mass. In connection with the above, securing the roadway by a new continuous support would allow for maintaining the stress in the roadway being developed close to the condition of intact rock mass.

Due to the lack of information about testing or practical use of the continuous support, as well as taking into account its expected advantages, numerical analyses were carried out. The analyses aimed at comparing the strength of the continuous support arches of a helix shape with strength of the circular support arches. Finite elements method (FEM) was used as the most reliable numerical method for modelling the effect of static and dynamic loads to a mechanical system [31–33].

The results of numerical calculations should be treated as a qualitative description of the behavior of the frame roadway support under the action of external, static and dynamic loads.

2. Materials and Methods

2.1. Creation of Models for Numerical Tests

Geometric models of the frames of a closed continuous and circular support, made of arched components with a V25 cross-section of a diameter 5 m were created for numerical tests. In the case of a continuous support, the load is transferred to the adjacent frames, and so therefore the analyzed model consists of 5 arched components connected by locks. The model of the circular support consists of 4 arched components, connected with each other by locks.

At the same time, the necessary simplifications were made, enabling the discretization of models using HEX finite elements, which has high precision in reproducing the actual behaviour of the tested object [34]. For example, Figure 7 shows the following discrete models: frames of a continuous support and a single arched component. In Figure 7a, the red colour marks the side wall model with which the arched components of the support frame cooperate.

![Figure 7. Discrete models: (a) frames of the continuous support, (b) arched component.](image)

Model of elastic-plastic material of the following material properties was assigned to the homogeneous finite elements from which the FEM models of the support frames were created:
• Young modulus $E = 2.1 \cdot 10^{11} \text{[Pa]}$,
• density $\rho = 7850 \text{[kg m}^{-3}]\text{],}$
• Poisson’s ratio $\nu = 0.3$,
• yield point $R_e = 4.0 \cdot 10^8 \text{[Pa]}$.

Displacement of arch components, connected with locks, against each other is the principle of operation of the yielding support arches. Therefore, the frictional contact between the cooperating surfaces (Figure 8a) and the contact point between the side wall and the outer surface of the arched components of the support were defined (Figure 8b).

![Figure 8. Definition of contact between cooperating surfaces (a) frictional contact, (b) point contact.](image)

It was assumed that the coefficient of friction between cooperating surfaces of the steel arch components of the support is $\mu = 0.15$, while in the case of contact with the side wall it is $\mu = 0.3$.

In addition, the forces from the locks (clevises) connecting the arched components of the support frame were modelled (Figure 9). The forces generated from twisting moment of bolts in the joint were modelled in the form of a pair of compressive forces applied to the surfaces of the cooperating support arches.

![Figure 9. Points of applying the forces from locks (clevises).](image)

Several cases of external load acting on the frames, both of the continuous and circular support, were tested. The following load variants were modelled:
• the static load was modelled as a continuous load acting on a given section of the roof arch of the tested support frames.
• the dynamic load was modelled in the form of a rigid body (hammer) thrown freely onto the arch of the support from a height of 0.15 m.

2.2. Modelling of Static Load

The PN-G-15022: 18-11 standard [18] contains only guidelines for stand tests of open steel frames in the rigid and yielding state. Due to the above, the guidelines included in the standard were adopted to the installation and operation conditions of the tested types of frames of the closed continuous and circular support. The support and load scheme for the arched components of the continuous support model is presented in Figures 10 and 11. The same procedure was used for the model of the frames of the circular roof support. Taking into account the requirements of the standard, the support arches were stabilized transversely to their main axis (Figure 10), and the roof arch was loaded (Figure 11) according to the diagram shown in Figure 11. Moreover, in the case of a model of the frames of continuous support, the ends of the side wall arches were fixed in a rigid way.

![Figure 10. Diagram of the support of arched components. 1—arched component, 2—side wall, 3—rigid installation.](image)

The roof arch is subject to a continuous load, replaced by three equivalent concentrated forces. Defining the static load of the analyzed models of the closed frames consisted in replacing the concentrated forces with a kinematic load. Three models of cylinders acting on the roof arch of the frames of the were loaded in accordance with the load diagram shown in Figure 11. The modelled extension speed of the cylinders loading the tested frames, was 0.02 m/s and remained constant throughout the numerical analysis.

According to the guidelines included in the standard [18], the roof support frames, in a yielding state were tested, until the height of support frames was reduced by 300 mm, as a result of a yield in joints. However, due to the scale of tests, duration of static load was limited to 5.1 s.
Figure 11. Diagram of distribution of forces acting on the roof arch of the yielding roof support’s frame.

2.3. Modelling of Dynamic Load

Modelling of the dynamic load acting on the frames of roadway support was based on the guidelines contained in the testing methodology, used in the laboratory of the Central Mining Institute (GIG) [35]. During the stand tests, the dynamic load acting on the stabilized support frames was exerted by a hammer, weighing 10,000 kg or 20,000 kg, thrown from a height of $0.15 \div 0.5$ m.

The diagram of the numerically analyzed dynamic load is presented in Figure 12, on the example of the model of the circular support. Similarly to the static load, the models of the frames of the continuous and circular support, were stabilized transversely (Figure 10a) in relation to their main axis.

A 20,000 kg hammer was used in numerical tests to dynamically load both models of the support’s frames. To shorten the calculation time, the hammer was placed 10 mm above the roof arch of the roof support’s frame and an initial speed corresponding to the speed it would reach if it fell freely from a height of 150 mm was given to it. The initial
speed of the hammer loading the roof arch of the support’s frame was calculated basing on the relationship (1).

\[ v_0 = \sqrt{2 \cdot g \cdot h} \]  

(1)

where: \( g \) — acceleration due to gravity, \( h \) — height.

3. Results

The results of numerical tests for static loading, in the form of von Mises reduced stress maps, displacement maps of arched components of the frames and plastic deformation maps are presented in Figures 13–15. Additionally, Figure 15 shows the places of plastic deformation in the analyzed models of the frames.

![Figure 13. Maps of reduced stresses in the support frames models: (a) continuous, (b) circular.](image)

![Figure 14. Displacement maps for support frames models: (a) continuous, (b) circular.](image)

Table 1. Parameters defining the response of the analyzed models.

| FEM Modelling | Cylinders Extension | Speed [m/s] | Reduction in the Frames Height [mm] | Maximum Plastic Deformation \( \varepsilon_{pl} \) |
|---------------|---------------------|------------|------------------------------------|-----------------------------------|
| continuous    |                     | 0.02       | 112                                | 0.73                              |
| circular      |                     | 0.02       | 114                                | 0.67                              |

Table 2. Parameters defining the response of the analyzed models.

| Hammer Mass [kg] | Reduction in the Frames Height [mm] | Maximum Plastic Deformation \( \varepsilon_{pl} \) |
|-----------------|------------------------------------|-----------------------------------|
| 20,000          | 7.2                                | 0.23                              |
| 20,000          | 8.0                                | 0.22                              |
The remaining parameters of response to the given kinematic load of both numerically analyzed models of the roadway support frames, i.e., frame convergence and the maximum plastic deformation of the arched components are listed in Table 1.

Table 1. Parameters defining the response of the analyzed models.

| FEM Modelling        | Cylinders Extension Speed [m/s] | Reduction in the Frames Height [mm] | Maximum Plastic Deformation εpl |
|----------------------|---------------------------------|-------------------------------------|---------------------------------|
| continuous frames    | 0.02                            | 112                                 | 0.73                            |
| circular frames      | 0.02                            | 114                                 | 0.67                            |

The results of numerical analyses for the dynamic load, using the von Mises stress maps, are presented in Figure 16. The remaining parameters defining the response of the tested models to the given external load are listed in Table 2.

Table 2. Parameters defining the response of the analyzed models.

| FEM Modelling        | Hammer Mass [kg] | Reduction in the Frames Height [mm] | Maximum Plastic Deformation εpl |
|----------------------|------------------|-------------------------------------|---------------------------------|
| continuous frames    | 20,000           | 7.2                                 | 0.23                            |
| circular frames      | 20,000           | 8.0                                 | 0.22                            |

By analyzing the results of computer simulations for two sets of static loads of the frames of the continuous and circular supports, the following conclusions can be drawn:

- Excessive stresses in the arched components of both models of the frames of support were compensated by the yield in joints, defining the proper operation of the yielding frames. The mutual displacement of the arched components of the support frames (Figure 14), on one hand, reduces the stress, but, on the other hand, reduces height of the support frames.
- Plastic deformation appeared in both models of the support frames, in roof arches, subjected to external loads, both static and dynamic. However, in the model of of the circular support, during the simulation of static load, the plastic deformation also appeared at the connection of the roof and sidewall arches (Figure 15).
- Plastic deformation in the model of the continuous support frames is slightly higher compared to the model of the circular support. However, in the model of the continuous support frames, smaller convergence of the frames was reported.

![Figure 16. Maps of reduced stresses in models of the support frames: (a) continuous, (b) circular.](image)

4. Discussion and Conclusions

Supporting the excavations during roadway development in hard coal mines is extremely important; therefore, it is necessary to look for new designs for the roof support, the practical application of which will contribute to increasing the roadway safety and functionality.

KOMAG Institute of Mining Technology has developed a concept of a support designed to protect underground development of tunnels, especially mine roadways at great depths. Continuous, yielding support of a circular cross-section, with a spatial structure of a helix shape was suggested. Even distribution of the rock mass pressure on each of the support’s frame coil is its main advantage.

In the patent description No. DE 3232448 (A1) [30] a concept of a drilling system for a roadway protected by a continuous arch support is presented. However, contrary to the method of installation of the continuous roof support presented in [30], in the new solution the arched components do not require profiling in the shape of a helical line; because the distance of successive arches (coils) is set by a hydraulic cylinder and the arches are bolted with steel sprags.

In the new design of the roadway roof support, the initial setting to load each coil of roof support frame by “unscrewing” the helix formed of arched components. This solution allows for maintaining the stress level in the developed roadway close to the level in the intact rock mass.

The concept of reinforcing the frames by using steel clamps connected with arched components was also developed [29]. These clamps have a positive effect on the local increase in stiffness of the arch components (in their sensitive places), which in turn strengthens the frames and ultimately increases the strength and stability of the entire structure.

Due to the lack of information about testing or practical use of the continuous support, as well as taking into account its expected advantages, numerical analyses were carried out. Numerical calculations of the static and dynamic load to the support arches enabled comparing the strength of the continuous helical support arches with the strength of
the circular support arches. When analysing the results of numerical tests, it can be concluded that both models of the support frames have the same strength. However, the model of the continuous support arches has greater resistance to mass impact, as in the components of circular support model, greater displacements and accompanying deformations were observed.

Development of a concept of a device supporting the helix roof support’s frame advance with the progress of roadway development will be the next stage of research and design work. The possibility of using the roof supports in roadways with cross-roads and branches will also be analysed.

5. Patents

Patent Application PL 66029 (Y1) Continuous reinforced support.

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