Arch. Min. Sci. **66** (2021), 3, 437-455

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.24425/ams.2021.138599

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ANALYSIS OF THE POSSIBILITIES OF USING COMPOSITE STRUCTURAL C-CHANNELS AS LINING FOR AN ARCH SUPPORT IN MINING EXCAVATION

The article is the result of a project aimed at developing and implementing a design of composite accessories for support in excavations located in underground hard coal mines. The research team verified the possibility of using elements made of prefabricated composite structural profile as an alternative to steel and reinforced concrete lining elements used to improve support's stability and protect against rockfall.

This paper includes a research experiment on the possibilities of using a composite C-profile element as lining made in the pultrusion technology with a longitudinal position of the roving. The prefabricated structural profiles were adapted to the function by designing seatings for fitting the flanges for arch support's V-profiles. Prototypes of these elements were subjected to bench tests in compliance with the guidelines for testing mesh linings. In addition, computer simulations using the finite element method were carried out.

The values obtained during the tests were compared with the requirements for lightweight mesh and included the Polish standard PN-G-15050 and reinforced A-type concrete lining defined in the standard PN-G-06021. The team determined the areas where material strength exceeded and the structure was damaged.

Despite the limited quantity of laboratory tests and lack of field tests in actual mining conditions, it was possible to address the argument of the research and determine whether it is possible to use C-profile made in the pultrusion technology as a lining element.

Keywords: research, lining, arch support, composite c-channels

1. Introduction

Steel arch structure is used for support of underground excavations. Its fundamental elements are steel curved profiles connected with clamps. This support system is applied in galleries subjected to heavy loads and excavated in the soft rock mass. Its extensive possibilities of customisation ensure that it can be used in various conditions. Depending on mining conditions, a cross-section of steel profile, type of steel profile, the geometry of the arches, number of clamps

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and spacing between subsequent arches may be changed or redesigned. Because of the specificity of application possibilities, it is the most commonly used support system in Polish hard coal mines. It is also popular in other countries worldwide, including Ukraine, the Czech Republic, Russia, Turkey, China, and Vietnam [6-9].

The characteristics of steel arches may be subjected to change depending on different conditions. The types of steel arches and the use of accessories of a support system may also be freely modified. One of the accessories is the lining which is located on the arch support (between the arches and rock mass), it is used to improve the stability of the support and protect the excavation against rockfall from the roof and the sidewall [4]. The lining is a crucial element of the chock support in galleries as it transfers loads imposed by the rock mass from the space between the arches. According to designers will it may consist of elements made of wood, sheet metal, mesh or prefabricated reinforced concrete. Although, adequate strength and stiffness parameters resulting from the structure or method of construction are required.

As every element of the arch support system, the lining is exposed to the factors of the external environment, which may be aggressive. The reinforced concrete lining is characterised by better corrosion resistance than steel and mesh types of lining. The steel reinforcement embedded in concrete is isolated from the aggressive environment, the lining maintains its parameters for a longer time. The corrosion occurs only in case of concrete damage resulting in exposing the reinforcement. This is presented in Figure 1. Lining in the form of welded steel meshes, which are elements with small cross-sections, are most exposed to corrosion and are the first to be damaged, as presented in Figure 2.

Fig. 1. Damaged reinforced concrete lining

Replacing damaged elements of lagging is an inconvenient and time-consuming task, and therefore costly. In such cases, as a remedy, repair sets are most often used, such as those shown in Figure 3. Such sets have only a shielding function because they do not have direct contact with the excavation breakage. For those reasons, efforts towards implementing a corrosion-resistant type of accessories are carried out.

Fig. 2. Corroded MM mesh lining

Fig. 3. Repair set

2. Construction of composite profile lining

A research experiment was conducted for this paper to see the possibilities of the functionality of the finished – C-section product made using pultrusion technology as an element of the lining. Such a possibility would accelerate the research on developing a new composite arch support accessory.

For the purposes of the study, the prefabricated structural channel was adapted as an element of the lining. The product is available from Polish manufacturers and distributors for purposes unrelated to mining. Three structural channels were selected from the available sizes:

- C150×40×6,2,
- C205×44×7,
- C254×70×13.

Figure 4 shows the dimensions of the C254×70×13 profile.

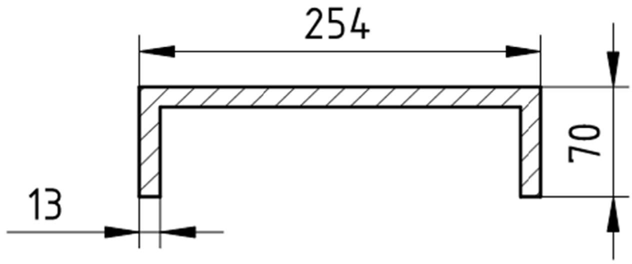


Fig. 4. Dimensions of the C254×70×13 profile

The only consideration for the design process was the ability to install the lining elements between the arches to enable its proper function. Application of this criterion resulted in three designs with different locations of the seatings for flanges cupped in V-profiles. The lining was prepared for arch support built-up in a spacing of 0,75 m. It was assumed that strength tests would be carried out for linings with three seating variants differing in geometry and the number of covered flanges of the profile, such as shown in Figure 5. Figure 6 shows a photograph of the lining with a single A-type profile. Special profiling of seatings, in addition to increasing strength, is primarily to improve the stability of the arch support.

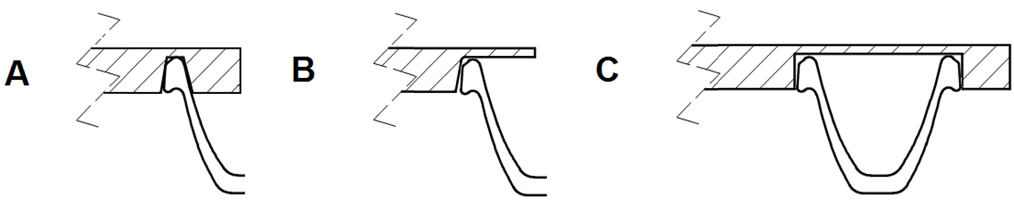


Fig. 5. Variants of seating for a V-profile. A – covering one flange, closed; B – covering one flange, open; C – covering two flanges

Next, various ways of arranging the lining elements on the support arches were considered. It is possible to use composite structural channels in the form of full lining – in the case of using seats with one flange, as in Figure 7, or as openwork lining for elements with both single and double seats, as in Figure 8. The arrangement options for composite lining elements in this respect reflect the arrangement of reinforced concrete lining used in hard coal mines.

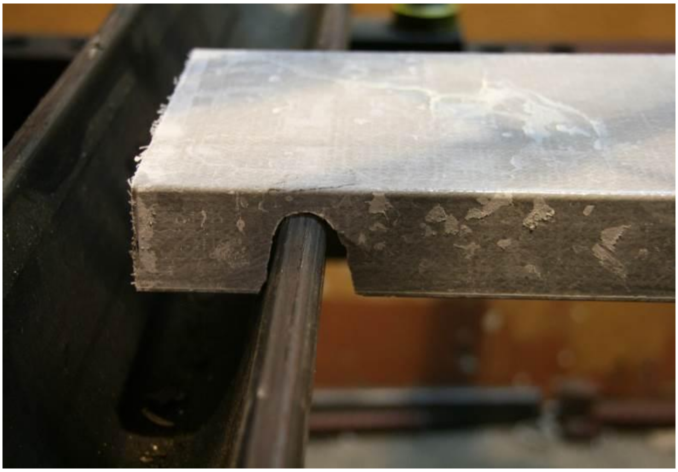


Fig. 6. Structural C-channel lining with a single gap

The use of composite lining with profiled seatings, limits the number of spreaders while maintaining or even improving the stability of the support, and thus improving the conditions of the maintenance of the galleries. The use of these linings arranged without spacing may also facilitate drilling of the excavation where rockfall occurs. Lagging made of such lining can also be used as formwork for filling voids left after a rockfall. This eliminates the need to place a cloth on lining meshes prior to filling the void, which is inconvenient.

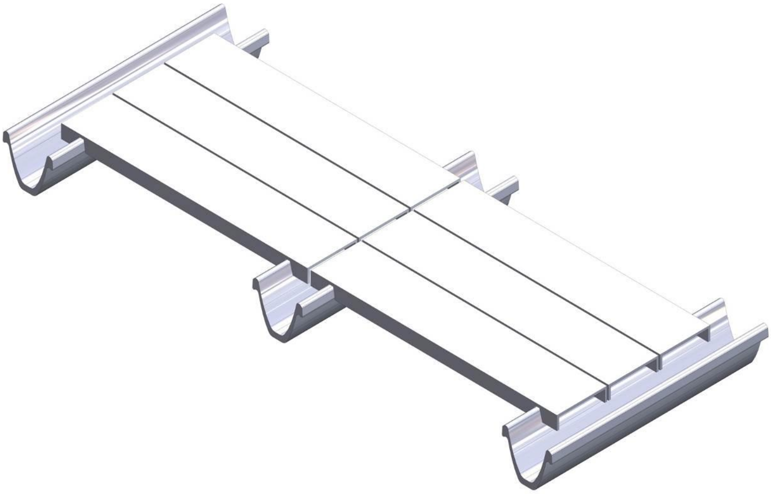


Fig. 7. Composite linings with a single seat arranged without spacing

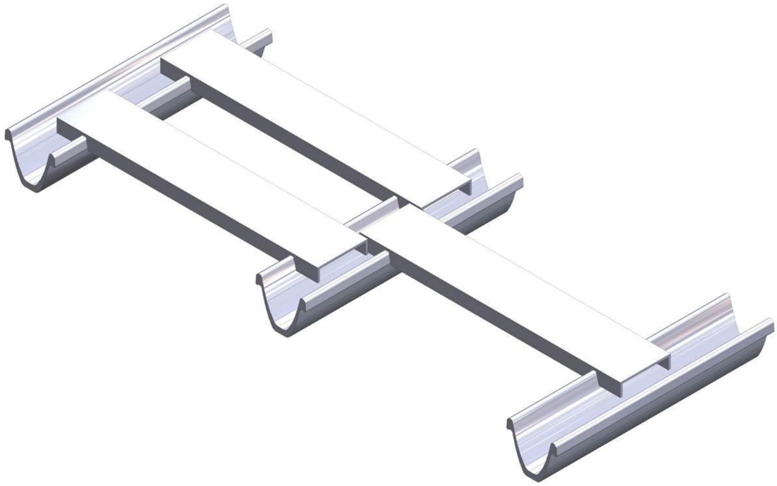


Fig. 8. Composite linings with a single seat arranged as openwork

3. Lining research methodology

The requirements concerning mining support are regulated mainly by domestic standards. This includes the manufacturing process, assembly, as well as methodology of bench tests which results are used to determine whether the individual elements and designs meet the adopted requirements. The standards regulate the course of tests of whole structures of arch supports [16] as well as individual components of arch support such as spreaders [17], clamps [18], supporting base [19], lining elements [1,2], friction props [21] and anchors [20]. The methodology of bench tests defined in Polish standards may also be used to check and compare the operation of complex constructions of gallery supports. This includes elements such as arches of arch support reinforced by anchoring [15] or determining the resistance of support to various loads and rock mass loads such as ones resulting from using a suspended monorail [14].

The methodology of bench tests of mining linings and the manner of their loading results from the design of individual elements were reflected in the relevant standards (PN-G-15050 [1] and PN-G-06021 [2]). These standards, among other things, describe the test methodology and parameters that particular types of lining should meet. Reinforce concrete lining generates only the bending of individual elements. In the case of hook meshes, the loads initially have the character of bending, followed by stretching combined with bending after eliminating spaces between flanges of the channel and hooks of the mesh. Only in the case of chain type mesh, after eliminating the space on the nodes, there is mainly stretching – the most favourable load scheme for this type of element. In such cases, the chain type nets work like tension members. This is presented in Figure 9.

In the case of mesh lining, due to the small cross-sections of the rods resulting in low bending strength indexes, the appropriate installation reducing the load on the rods for stretching allows for better working conditions.

The analysed composite lining is a solution combining the features of hook net (according to PN-G-15050 [1]) and reinforced concrete lining (according to PN-G-06021 [2]). This type of

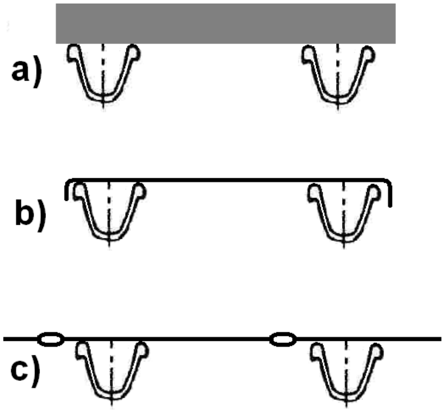


Fig. 9. Various technical solutions for mining linings
a) reinforced concrete lining subjected to bending; b) hook net lining subjected to bending and stretching
c) chain type net lining subjected mainly to stretching

lining has sockets in the form of gaps (seatings), similar to the net lining, and just as reinforced concrete lining, is characterised by significant transverse rigidity. This assumption was considered while adopting the test pattern similar to the hook meshes, but the test results also referred to the reinforced concrete lining. Figure 10 shows the method of testing net lining, and Figure 11 shows the course of laboratory tests of the composite lining. The tests were carried out on linings intended for support with an arch support pitch d = 0,75 m.

Fig. 10. Method of testing lining meshes

A sample was put on props of V-profiles arranged with 0,75 m spacing and then loaded with a transverse force applied in the middle of the element. In such a load scheme, the 0,5 m wide net lining should carry a load of 3,0 kNm (lightweight mesh) or 6,25 kNm (heavyweight mesh)

Fig. 11. Method of testing composite lining

with consideration of the arches spacing. For meshes intended for installation on arch supports with a spacing of 0,75 m, this corresponds to a loading force of 16 kN for lightweight mesh and 33,3 kN for heavyweight mesh.

The tests were conducted for nine composite lining elements of various sizes and different types of V-profile flange seats, as presented in Figure 5. Data characterising the tested prototypes are included in Table 1.

TABLE 1

Characteristics of composite linings subjected to laboratory tests

Lining No.	**Dimensions**	**Variant of a profile's seat**
1	C150×40×6.26	A
2	C150×40×6.26	A
3	C150×40×6.26	B
4	C205×44×7	A
5	C205×44×7	A
6	C205×44×7	B
7	C254×70×13	A
8	C254×70×13	B
9	C254×70×13	C

The results of bench tests of composite structural channel linings are presented on three graphs, including samples of the same cross-section, Figures 12÷14. In addition, the charts were supplemented with graphic characteristics of light and heavy nets [3] and the load value to be carried by reinforced concrete [2] and mesh linings [1] during the bending test. All values of required loads were referred to the width of the tested composite element. The values corresponding to the plane arrangement of concrete elements with a spacing of 0,75 m were taken into account in the case of reinforced concrete lining.

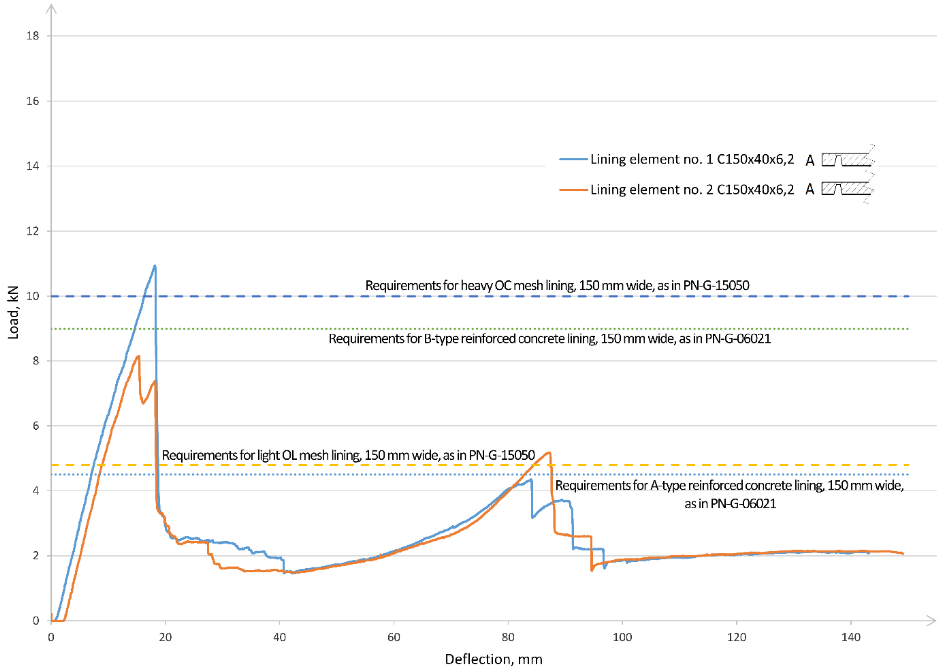


Fig. 12. Test results for lining made of composite structural channels, C150×40×6,26

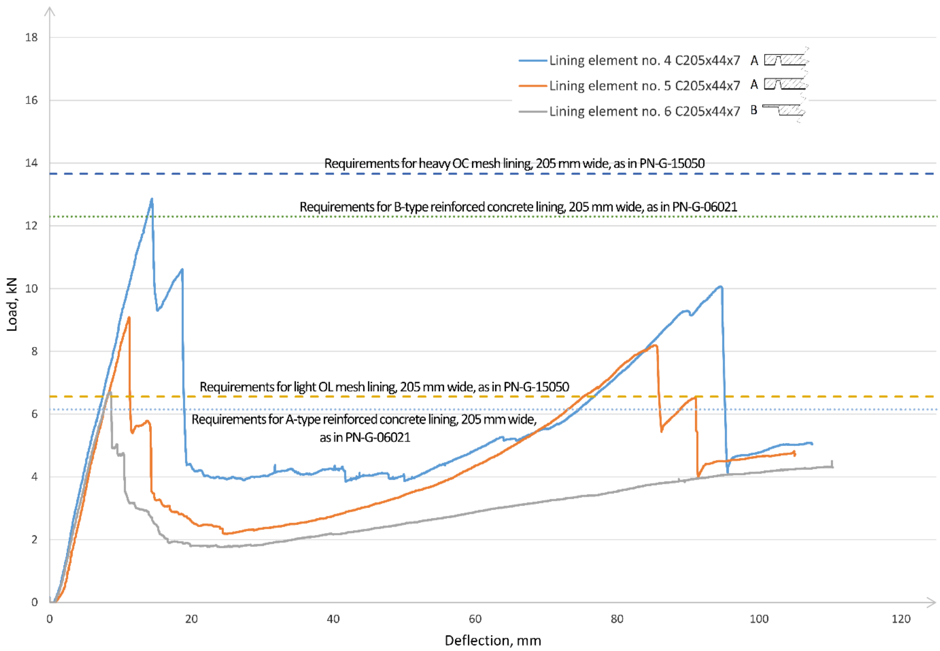


Fig. 13. Test results for lining made of composite structural channels, C205×44×7

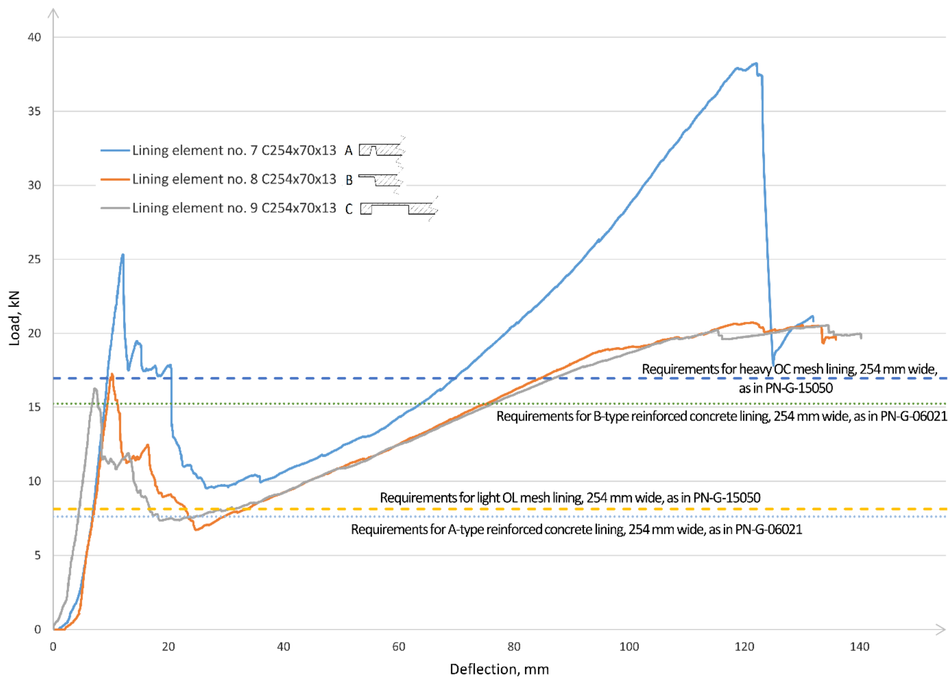


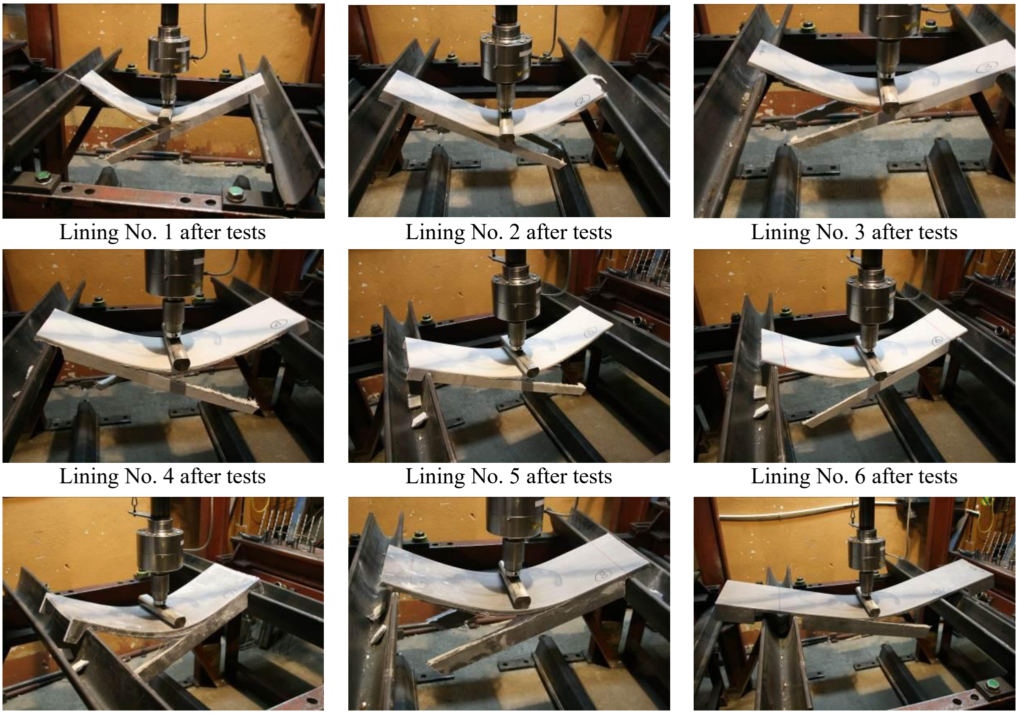
Fig. 14. Test results for lining made of composite structural channels, C254×70×13

Figure 15 shows the prototype lining after testing. It is visible that the damage occurred as a result of tearing the structural C-channel flanges from the web. This is due to the profile structure made in the pultrusion process, especially the longitudinal location of the roving and the lack of fibres laid across the profile. Considering the character of the deformation before the occurrence of damage (tearing the flanges from the web – range as in Fig. 16), it can be stated that in all cases, the lining made of composite C-profiles met the requirements for lightweight mesh linings (OL) and A-type reinforced concrete lining. Additionally, some of the tested linings also met the requirements for heavyweight nets (OC) and B-type reinforced concrete lining. In addition, it can be seen that the C-channel lining meets the stiffness condition specified for the mesh lining where the deflection does not exceed 100 mm at maximum force.

4. Numerical analysis of lining

To identify the state of exertion of the tested prototype linings, computer simulations using the finite element method (FEA, FEM) were conducted [10,11] using the COSMOS/M software [12,13].

COSMOS/M is a modular system for calculations and analysis based on the finite element method. The software was developed by Structural Research and Analysis Corporation. From the user's point of view, modelling in the COSMOS/M system comes down to introducing the geometry of the entire tested system and determining the parameters of each. These parameters



Lining No. 1 after tests | Lining No. 2 after tests | Lining No. 3 after tests
Lining No. 4 after tests | Lining No. 5 after tests | Lining No. 6 after tests
Lining No. 7 after tests | Lining No. 8 after tests | Lining No. 9 after tests

Fig. 15. Photographs of composite lining prototypes after bench tests

are material properties, cross-section parameters, and in the case of nonlinear analysis, material curves. The geometry of the system can be set by creating it in the GEOSTAR module or by importing a three-dimensional drawing.

First, the material parameters of the composites used for channel sections were determined. For this purpose, 5 samples along the fibres and 5 transverse samples were cut from the 254×70×13 web of the structural C-channel. These samples were subjected to tension to determine the modulus of elasticity in two directions, longitudinal and transverse. Tests of mechanical properties were carried out using the INSTRON 4465 H 1937 and FPZ 100/1 testing machines, with a tensile speed of 1 mm/min and 50 mm/min, based on PN-EN ISO 527, PN-EN ISO 14125 and PN-EN ISO 178 standards with the use of standardised fittings cut from composite channel sections. Statistical calculations were made using Blue Hill software. The ambient temperature and humidity were checked before testing. The measurements were carried out at a temperature of 23 ± 2°C and a relative air humidity of 50 ± 10%. The average modulus of elasticity for the range of relative deformations 0,05% ÷ 0,25% is $E_{\parallel}$ = 33 418 for stretching along the fibres and $E_{\perp}$ = 5 085 MPa for stretching across the fibres. In addition, material strength was determined for both directions. The samples had average tensile strength along the fibres $R_{\parallel}$ = 243,9 MPa and $R_{\perp}$ = 31,4 MPa across the fibres. The determined stiffness parameters were adopted as a material model. In the first stage of analysis, the laboratory tests were mapped to the first extreme (the first peak) occurring just before the legs detachment from the structural channel's web. The mapped fragment of the characteristics is shown in Figure 16. Within this range, the lining behaves linearly, so the analysis was also performed as linear.

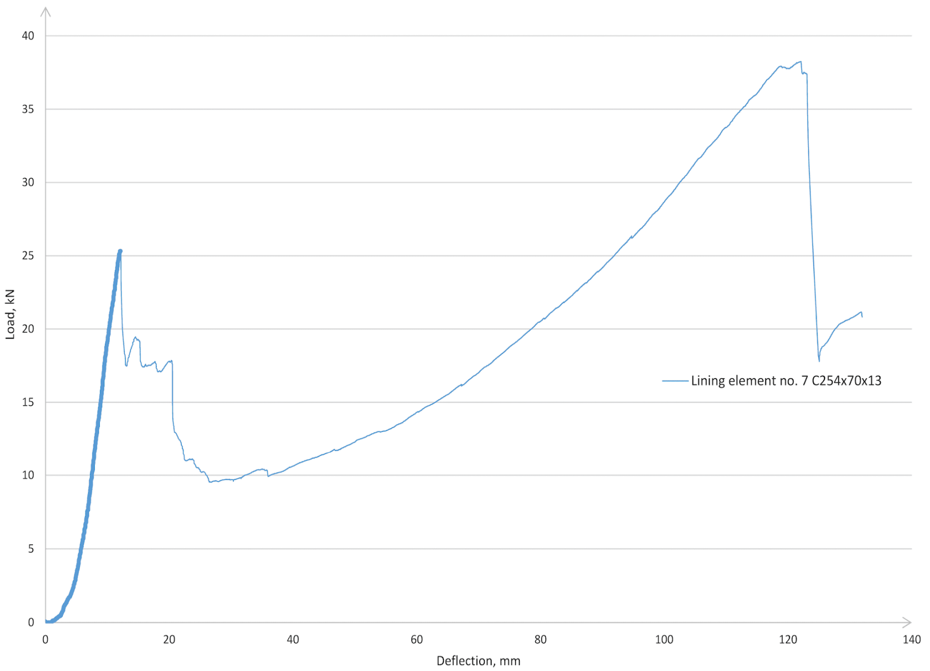


Fig. 16. Course of laboratory tests

In order to perform calculations, a geometric model was built that reflects the geometric form of the lining made of composite structural channels. For this purpose, SHELL type coating elements were used, which were given the appropriate thickness and material parameters by those previously determined in individual directions. The model was supported in the places where the lining rests on the flanges of the V-profile and was loaded in half-length by an additional steel loading element, as is the case in laboratory tests. This load was implemented by forcing the displacement. The model prepared for calculations is shown in Figure 17. The load pattern was consistent with the method of testing net lining according to Polish Standard PN-G-15050:2018-01 and consistent with bench tests of nine composite structural channel linings in the previous part of the research.

The calculations determined the stress distribution in the analysed model. Figure 18 presents a stress distribution for the value of load corresponding to destructive stress in the area of the seating for V-profile flanges ($F = 25$ kN).

The maximum stress values act in the middle of the length on the edge of the C-profile flanges, and it reaches approximately 138 MPa. These are mainly tensile stresses of the direction of the fibre, and their values reach 56% tensile strength (R‖ = 243,9 MPa). However, for such a load, stresses in the area of the seatings for the V-profile, in the corners of the web and the legs of the structural channel are considered dangerous. These stresses reach significant values in relation

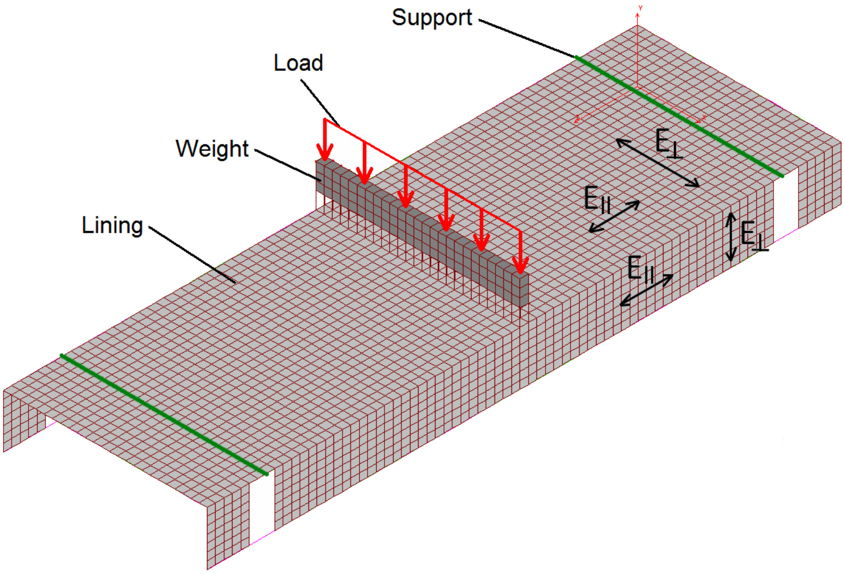


Fig. 17. The model prepared for calculations with the marked elastic modulus directions

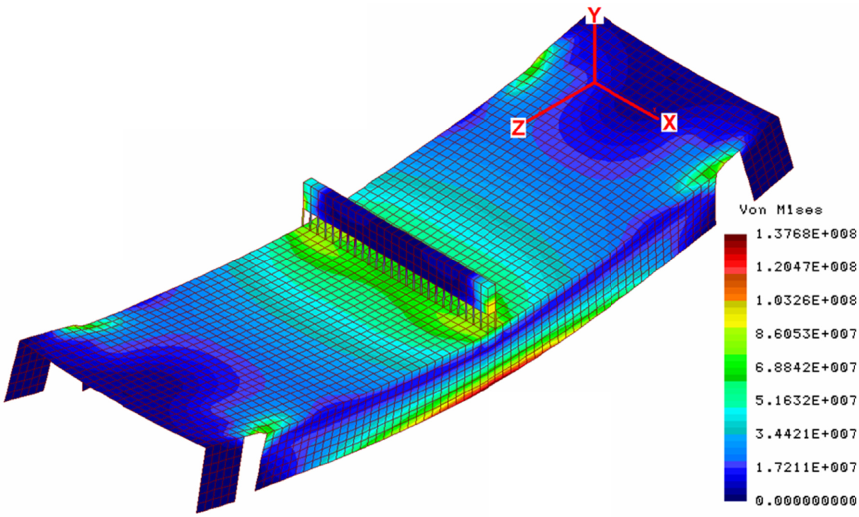


Fig. 18. Von Misses stresses for loads reaching point A in Figure 16
(stress in Pa, deformation scale 10×)

to the tensile strength, depending on the direction $\sigma_X = 18{,}5$ MPa and $\sigma_Y = 43{,}3$ MPa. In the case of tensile stress acting in the *Y* direction, the tensile strength ($R_\perp = 31{,}4$ MPa) was exceeded, which was associated with a break in the material during the laboratory test. Figures 19 and 20 show the distribution of tensile stress in the *X* and *Y* directions.

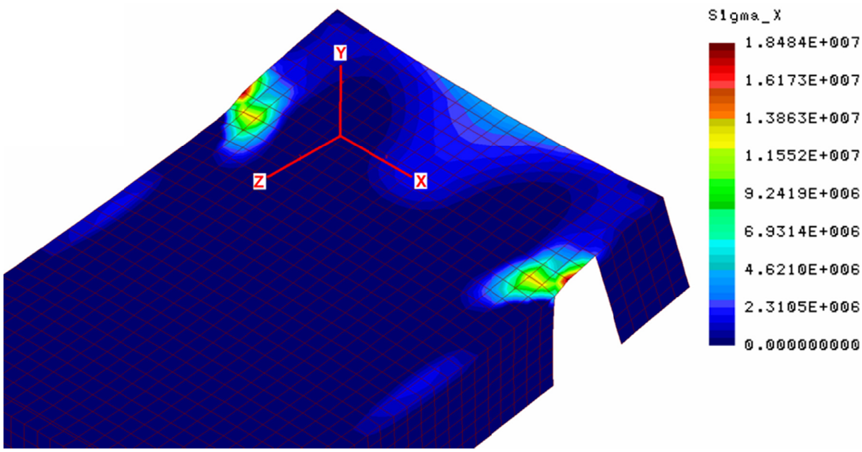


Fig. 19. Distribution of tensile stress in the X direction (stress in Pa, deformation scale 10×)

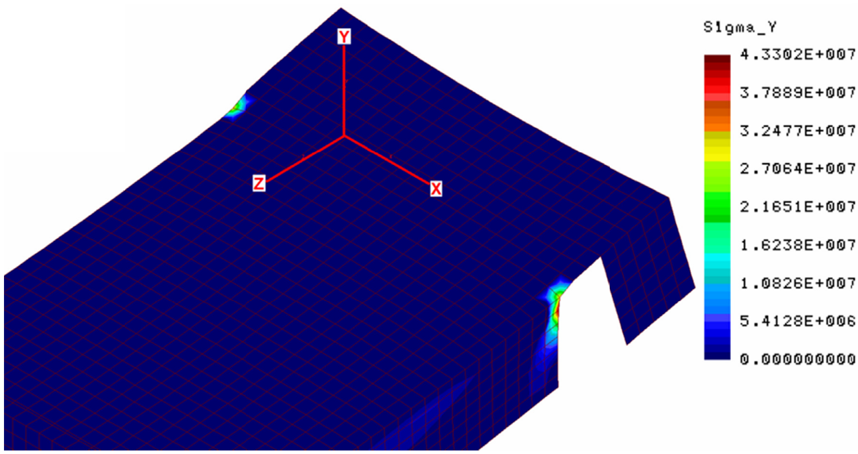


Fig. 20. Distribution of tensile stress in the Y direction (stress in Pa, deformation scale 10×)

The obtained stress maps clearly indicate the areas where the material strength is exceeded and the structure is damaged, which was also confirmed by the results of laboratory tests (Fig. 21). The character of damage is due to the much lower tensile strength of the tested composite across the fibres than along the length.

In order to determine the required mechanical parameters of the material in the transverse direction, additional analyses were carried out. To obtain a structure with similar bending strength in sensitive places, areas of seatings for fitting the flanges for arch support's V-profiles and in the middle of the span, it was necessary to increase the strength of the material across the grain. The analyses were carried out on the previous model by modifying only the Young's modulus and assuming correspondingly higher strengths of the material across the fibres. By the method of successive approximations with the use of FEM analysis, the parameters were selected to

Fig. 21. Typical damage to a structural channel in the area of the V-profile's seat (sample 7)

obtain stress values that were close to the strength. As a result of the tests, the tensile strength and Young's modulus were determined:

- for stretching along the fibres: $R_{\parallel}$ = 243,9 MPa, $E_{\parallel}$ = 33 418 MPa, (the same),
- for stretching across the fibres: $R_{\perp}$ = 120,0 MPa, $E_{\perp}$ = 19 500 MPa, (changed).

Figure 22 shows the state of stress of the element with changed mechanical parameters under conditions of almost simultaneous achievement of strength in the place of the seating and in the middle of the span. Figures 23÷25 show the tensile stresses in the element in the *X*, *Y* and *Z* directions.

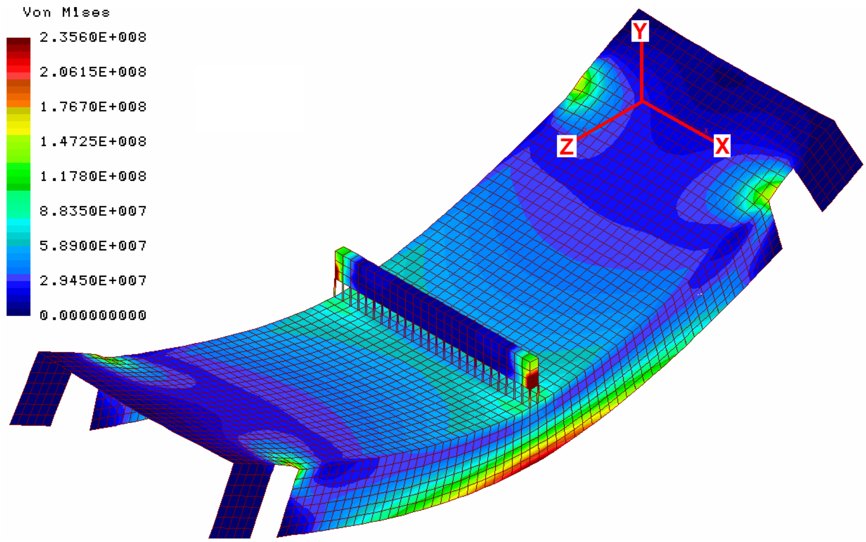


Fig. 22. Von Misses stresses for model of a modified element with similar strength in the span and in the seat (stress in Pa, deformation scale 10×)

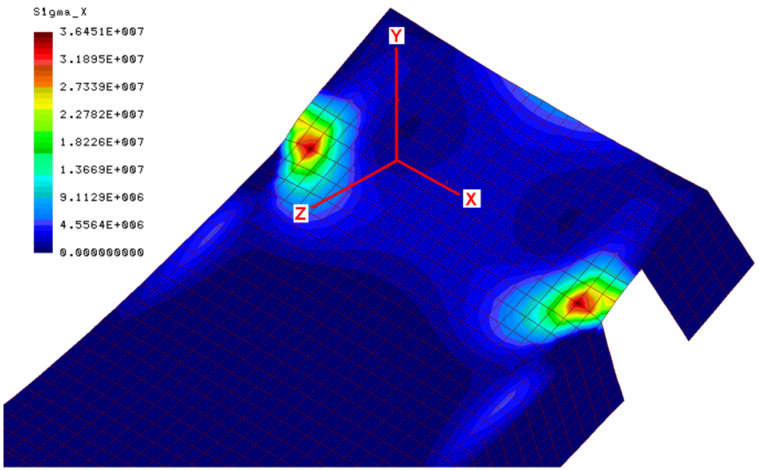


Fig. 23. Distribution of tensile stress in the *X* direction (stress in Pa, deformation scale 10×)

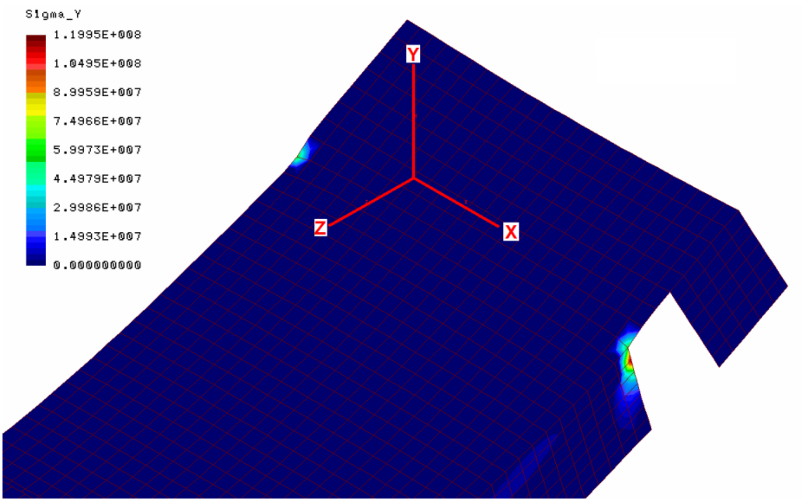


Fig. 24. Distribution of tensile stress in the *Y* direction (stress in Pa, deformation scale 10×)

At the moment of reaching the maximum stress values, the element of lining carries a load of 48 kN, while it bends by 8,55 mm. The analyses show that in order to achieve uniform strength, the values of the mechanical parameters (tensile strength and Young's modulus) in the transverse direction should be approximately 50% of the parameters in the longitudinal direction.

Due to the lack of possibility to check the linings in underground conditions, a computer simulation of the lining subjected to a uniformly distributed load caused by the impact of the rock mass was carried out. Numerical calculations were conducted for an element with increased mechanical parameters in the direction transverse to its longitudinal axis. Figure 26 shows the distribution of reduced stresses in the model for maximum loads.

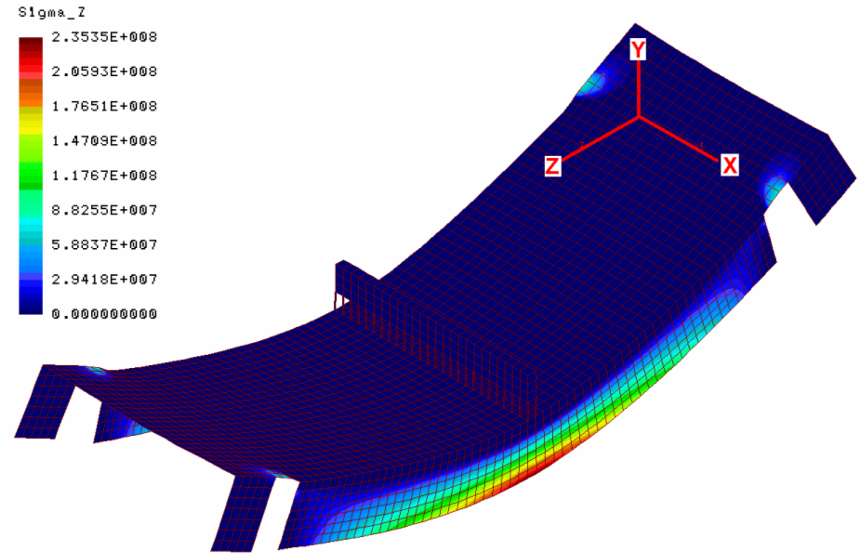


Fig. 25. Distribution of tensile stress in the *Z* direction (stress in Pa, deformation scale 10×)

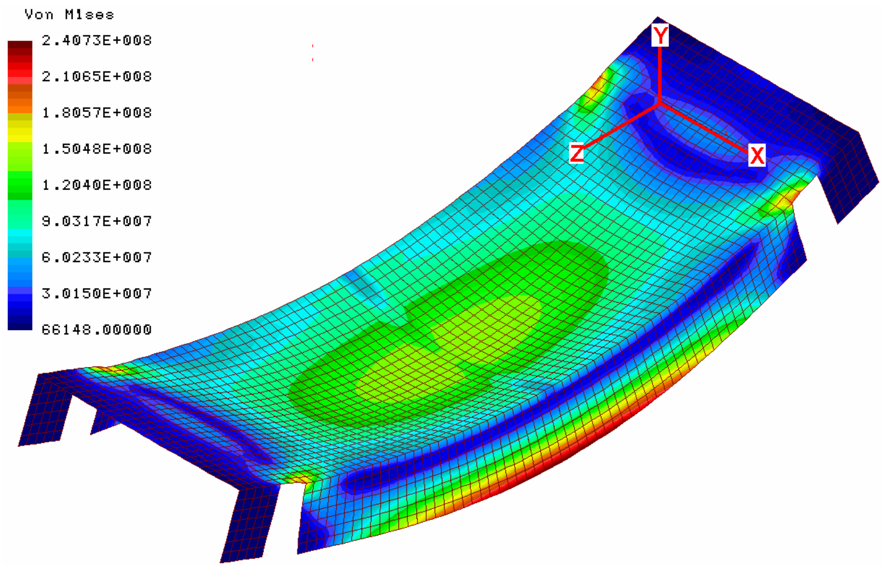


Fig. 26. Von Misses stresses for maximum loads (stress in Pa, deformation scale 5×)

The maximum load of the model is 128,9 kN. Under this load, the element flexes by 16,1 mm. Therefore, it can be concluded that the reinforced cladding in underground conditions will work properly, and its load-bearing capacity will be greater than that determined on the test stand based on the standards.

5. Conclusion

The actions documented in the paper were an attempt to determine the suitability of composite C-profiles made in the pultrusion technology as an element of lining. Such a possibility could shorten the implementation process for the accessories in the underground mine conditions.

In conducted tests, significant stiffness and strength values of the C-profile were established. A spacing of 0,75 m in every repetition of the laboratory test required element width load values for lightweight mesh linings (OL) and A-type reinforced concrete lining to be exceeded. Additionally, some of the tested linings also met the requirements for heavyweight nets (OC) and B-type reinforced concrete lining. In the extreme last case, the composite lining element showed the ability to load with force. This is because the profile structure was made in the pultrusion process, especially the longitudinal location of the roving and the lack of fibres laid across the profile.

In this paper, numerical calculations demonstrated that using a composite lining element with an assumed shape is necessary to determine other material properties. The character of damage is due to the much lower tensile strength of the tested composite across the fibres than along the length. It was necessary to modify Young's modulus and assume correspondingly higher strengths of the material across the fibres. As a result of numerical calculations, it was shown that when reaching the maximum stress values, the element of the lining carried a load of 48 kN. It was presented that to achieve a uniform strength, the values of the mechanical parameters (tensile strength and Young's modulus) in the transverse direction should be approximately 50% of the parameters in the longitudinal direction. Those assumptions exclude the production of the lining elements in the process of pultrusion.

Acknowledgements

The article was created within the statutory work called "Composite accessories for gallery supports" No. 110 60117-151 implemented at Central Mining Institute.

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