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Modelling the suspended monorail route stresses and deflections during the transport of heavy loads with use of diesel locomotives

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Abstract:

Based on the results of tests of the monorail transport system using suspended diesel locomotives with traditional transport beams and with the use of an innovative system of transport beams for the delivery of heavy loads, it was found that to reduce the dynamics of the load to the elements of the suspended route segments fastened to the arches of the arch support, it is beneficial to use the proposed an innovative technical solution that increases the reliability of the route catches to the support arches, which is important when transporting heavy loads. The new solution significantly reduces the dynamic loads to the route catches to the support arches by redistributing the load over a greater number of sections of the suspended monorail route. It has been proven that during the period of intensification of preparatory work, these technical solutions make it possible to keep to the timely preparation of new mining pillars and are perceived as a promising direction for improving the existing transport system for the mines of the region and ensuring the operational parameters of mining transport equipment at a high technical level in the specific conditions of the mines of Western Donbass

Keywords: arch support, heavy loads, dynamic loads, auxiliary transport, lifting and transport system, transport and technological system, solidworks simulation

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1. Introduction

The use of suspended monorail diesel locomotives (PDM) as the only vehicle in the coal mining industry significantly increases the advance of longwall mining at coal mines. However, in the specific conditions of thin coal seams of the Western Donbass mines the traditional schemes of attaching the monorail route to the arch suport lead to bending the arches and changes the profile of the SMR route. Tests [1] showed that when transporting the heavy loads on a deformed monorail route, dynamic loads occur, which initiate the roof fall [2]. Moreover, in the conditions of intensification of mining operations, traditional auxiliary transport required the development and implementation of innovative technical solutions improving the technical condition of the route [3]. The expediency of implementing such solutions is especially relevant when preparing new mining pillars. This is due to the need of transporting heavy loads such powered roof supports, shearers, etc. to the assembly chambers and to the workplaces. In the foreign practice of coal seams development by high-performance mechanized systems, similar problems are solved by introducing alternative types of auxiliary transport and methods for determining their technical condition [4]. Suspended monorail with diesel locomotives is currently one of the most effective types of transport in the coal mining industry. In the specific conditions of WD mines, transport effectiveness is determined by improvements of technological solutions in the area of transport-technological system PDM – route fastening – rock mass, hereinafter reffered to as "PDM-KV-GM"

2. Materials and Methods

It has been experimentally confirmed that the parameters of interaction between the elements of the technological system PDM-KV-GM are currently poorly investigated [5]. In this regard, the problems regarding the operational control of the monorail route technical condition and a determination of their maximum permissible dynamic loads in real conditions of the mine environment require special observations and theoretical studies.

It is recommended to solve non-traditional technical tasks for the industry by modelling the conditions of interaction of the elements of the PDM-KV-GM system using the methods of mathematical analysis of technical systems and the licensed SolidWorks Simulation software. The gained experience of transporting the heavy loads through extensive networks of workings allowed to define the tasks related to the special mine studies of the parameters of the new generation SMR in the specific conditions of WD mines, namely:

- features of monorail route profile changes under the impact of dynamic loads and deformations
- the amount of deflection and the technical condition of the monorail beams;
- the consequences of the negative impact of dynamic loads to the route sections and centers of beams of a monorail route sections during the transportation of heavy loads.

According to the results of testing the technical condition of the route of the SMR monorail route, it was established that the main deformations in its profile, deflections in the arch support and the roof fall of the rock mass are concentrated in the zones of the supporting arches to which the monorail route section is suspended (Fig. 1). In the zones of intermediate arches, rockfalls were not observed. Thus it can be stated that during the transportation of heavy loads, the areas of frontal contact of the monorail route sections are the zones of increased dynamic loads to the arch support and the rock mass. This is caused primarily by the design features of monorail route sections, the ends of which are beveled to compensate the longitudinal deformations during the transport operation. The negative factors also include emergency braking of the railway, which initiate dynamic overloads to the monorail beams, which are transmitted through suspensions to the suport arch and in the result to the roof rock.

Fig. 1. Mechanical failure due to dynamic loads and local deformation of the roof

Currently, the most available methods of analyzing the loads and the resulting deformations of the route of suspended transport systems in the conditions of their installation in mine workings are the methods of mathematical and computer modeling using SolidWorks Simulation and Multi Body System (MBS) software [6].

3. Results

3.1. Problems of interaction among the components of the PDM-KV-GM system

According to the observations of the actual routes of suspended monorails, focusing on the deformations of the route sections and support arches, and based on the SolidWorks Simulation software, the interaction of the "PDM-KV-GM" transport system and its strength reserves for typical operating conditions were determined. It was found that the support arches and the middle sections of the route are the most susceptible to mechanical damage in a result of dynamic loads (Fig. 1).

The actual data on the conditions of cooperation of the components of the "PDM-KV-GM" transport system and the results of modelling its technical condition using the SolidWorks Simulation software allowed to determine the specificity of transportingt the large, heavy loads along the suspended monorail route and to develop assumptions as to how to reduce the dynamic loads to route sections of the suspended monorail and arches of the support to increase capacity of the transport and technological system in specific conditions of mining the coal seam.

Tests of the operating parameters of the suspended rail routes [7, 8] showed that to reduce the dynamic loads to the fasteners of the route sections, it is necessary to ensure redistribution of dynamic loads to the adjacent beams of the monorail route during the passage of the rolling stock, so that only the minimum permissible deflection of the route segments occurs as a result.

In this regard, the method of modelling deformations of the monorail route sections joints under the impact of heavy loads provides:

- identification of zones of maximum deflection of route segments when transporting heavy loads;
- forecasting possible negative consequences and meyhods to prevent them.

3.2. Input data for interaction among the components of the PDM-KV-GM system

According to recommendations [1], the tasks were realized in stages.

At the first stage, to determine the technical condition of the track of suspended monorail, a base of input data is formed, which includes physical and mechanical properties of the steel I-beam in operation, as well as data characterizing the mine environment has been created.

The most important factors include: deformation of the roof rocks, which lead to a forced spatial displacement of the monorail route from the assumed position; physical and mechanical properties of steel monorail sections; mass of heavy loads and their dimensions, which significantly affect the speed of transportation espcailly at the route turns.

Design, construction and operational documentation of mines [9, 10], monitoring and diagnostics of the technical condition of the monorail route, as well as the results of testing the deformation characteristics of the rock mass in the real conditions of the mine environment are the main sources for the collection of input data.

In accordance with the program and methodology of comprehensive tests, in order to obtain initial information about the technical condition of the suspended monorail transport system and stresses of its components, it was necessary to determine the most heavily loaded sections of the monorail track as well as the real forces acting on them, to establish the compliance of the calculated indicators of the safety margin of these sections with the normative ones.

According to recommendations [11], spatial changes in the track of suspended monorail roads are considered taking into account the isotropic properties and physical and mechanical characteristics of steel monorail beams, which are deformed in all directions equally. In this regard, the deformations of their material in the process of spatial change of the route of mine suspension roads are analysed identically, but taking into account the impact of the rock mass behavior.

To generate the initial data on the components of the PDM-KV-GM system operation in real conditions of the mine environment and to analyse the monorail route, a linear-elastic model of the I-beam material was adopted, and the parameters of the elastic properties of the material (G) were described by standard parameters, such as Young's modulus and Poisson's ratio [12]:

$$G = \frac{E}{2 \cdot (1 + \nu)} \tag{1}$$

where:

E – Young's modulus,
v – Poisson's ratio.

The formed database enabled assessment of the loads, the impact of which leads to plastic deformation and destruction of the integrity of the I-beam structure.

In fundamental studies [13, 14], the Huber-Mises-Genki hypothesis of deformation energy is used to describe the deformation models of a monorail track. Practical calculations and the equivalent stresses are determined by the following relationship:

$$\sigma_i = \frac{1}{\sqrt{2}} \cdot \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_4)^2} \tag{2}$$

where:

$\sigma_1, \sigma_2, \sigma_3, \sigma_4$ – Main values of the stress tensor.

According to (2), the equivalent stresses arising in the linear parts of the I-beam monorail joint lead to the transition of the material to the plastic state and at ($\sigma_i = \sigma_T$) reach the yield point, and at ($\sigma_i = \sigma_в$) the strength limit and can lead to the destruction of the structure.

Thus, this model of plasticity can be successfully used as a criterion for determining the limit states and failures of I-beam sections of the SMR monorail joint under different conditions of their operation.

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For the mathematical modeling of the interaction conditions of the PDM-KV-GM system, a section of the monorail route is represented as a beam of length L, fixed on both sides, and a weight (F) is applied to it. The deformation energy of the PDM I-beam joint is determined by the following relationship:

$$\delta V = \frac{1}{2} EL \left(\frac{d\theta}{dx}\right)^2 \delta x \tag{3}$$

where:
E – modulus of elasticity;

The potential energy of a curved I-beam is determined by the following expression:

$$V = U - \frac{1}{2} F \int_0^l \varphi^2 dx \tag{4}$$

where:
U – potential energy of deformation;
F – compressive force.

Previous studies [5] established that as a result of the deformations of the rock mass, spatial changes occur in the mine monorail route, which leads to an increase in dynamic loads in the butt joints of I-beam beams and the deflection of the monorail route and, as a result decreasing the carrying capacity of the transport and technological systems.

It should be noted that the interactions among the components of the PDM-KV-GM system is an understudied problem of mining production and requires special tests to establish the maximum stresses and deformations in the linear parts of the monorail route and its nodal connections. In this regard, the further examination of the technical task, which is not traditional for the mining industry, was carried out comprehensively, through testing the interactions among the components of the PDM-KV-GM system and their simulation using the SolidWorks Simulation software.

The initial data for modeling the linear deformations of the PDM route under the impact of dynamic loads arising during the transportation of heavy loads were obtained from the results of testing the deformations of rock mass and the arch attachment as well as changes in the profile of the monorail route (Fig. 2).

Fig. 2. Measuring station for recording the deformations of arch fastening during transportation of heavy loads

In the process of modeling, the deformed section of the I-beam was analysed in the SolidWorks Simulation program using the finite element method (FEM) [15]. The tests consisted in determination of maximum allowable deflections and stresses in the butt joints of the sections of the track using the generated CAD models. A similar approach enabled a structural analysis of the behavior of the system under dynamic loads and predict changes in the technical condition of the beams of the monorail route in the complex conditions of the mine environment.

The simulated section of the monorail track consists of I-beams 3.0 m long. I-beams are made of alloy steel without any special coating. The physical and mechanical properties of the I-beam material included in the generated CAD models are shown in Table 1.

Table 1. Parameters of the alloy steel

Properties	Amount	Unit
Modulus of elasticity	2.1e+11	N/m^2
Shear modulus	7.9e+10	N/m^2
Mass density	7800	kg/m^3
Tensile strength limit	$8{\cdot}10^8$	N/m^2
Poisson's ratio	0.28	
Yield point	590593984	N/m^2
Coefficient of thermal expansion	1.1e-0,5	
Thermal conductivity	14	W/(m·K)
Specific heat capacity	440	J/kg·K

To simulate the conditions of interaction of the components of PDM-KV-GM technical system in the CAD environment, the straight line section of the route of the underground monorail, as in Fig. 3, was assumed.

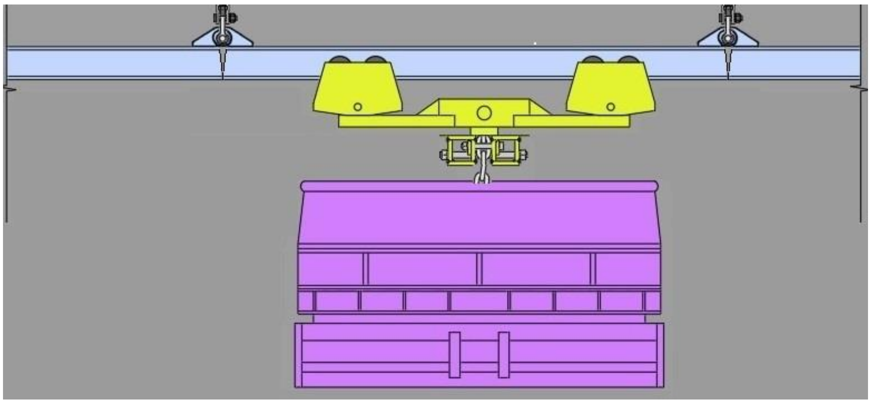

Fig. 3. Load diagram of a route segment using a traditional transport trolley

3.3. Modeling the technical condition of a monorail using SolidWorks Simulation software

A straight section of the monorail track consists of I-beams with a length of l = 3 m, which are attached to the arches of the support with chain slings. The route segments are connected to each other in such a way that the bending moments at the connections are equal to zero. Such a constructive solution allows to treat each segment of the route as a beam, attached individually, end-to-end, to the arches of the support.

The tests of the technical condition of the suspended monorails in the mine showed that the areas most exposed to deformations are the butt joints of the route sections and the central sections of the route. The tests results were used as the basis for theoretical analyses on the conditions of interaction of the PDM-KV-GM technical system components during the transport of heavy loads. In order to calculate the loads and deformations in the characteristic nodes of the butt joints of the route sections, they were divided into elementary meshes. The CAD model of dynamic loads in the articulated nodes of the monorail beams is shown in Fig. 4.

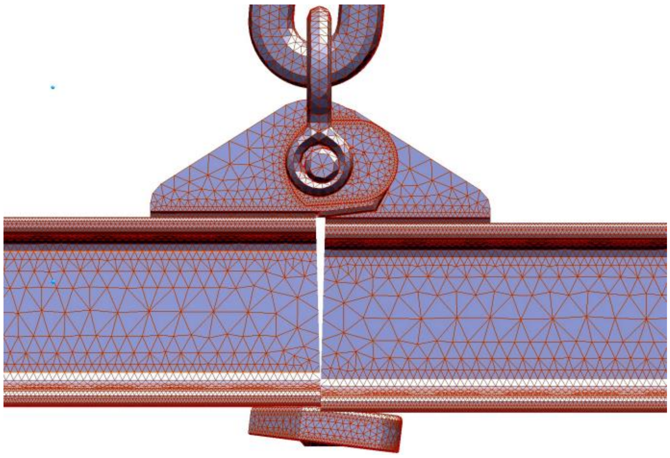

Fig. 4. CAD tetrahedral finite element mesh at route segment junction developed to analyze stresses and strains

Loads to the central parts of the sections was modelled for the traditional transport trolleys (Fig. 3) and for a new lifting and transport system, the principle of operation of which is described below.

Using the SolidWorks Simulation software, the maximum deformations in the segments of the monorail route (Fig. 5) and stresses (Fig. 6) during the transport of a heavy loads were determined.

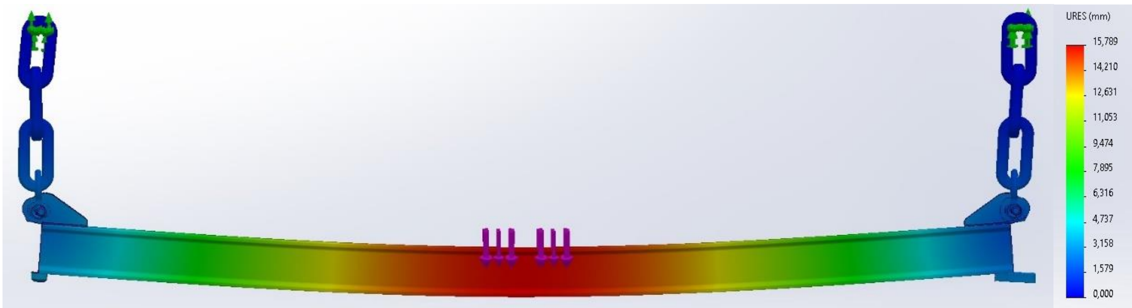

Fig. 5. Deflection of the monorail beam when transporting heavy loads in a traditional way

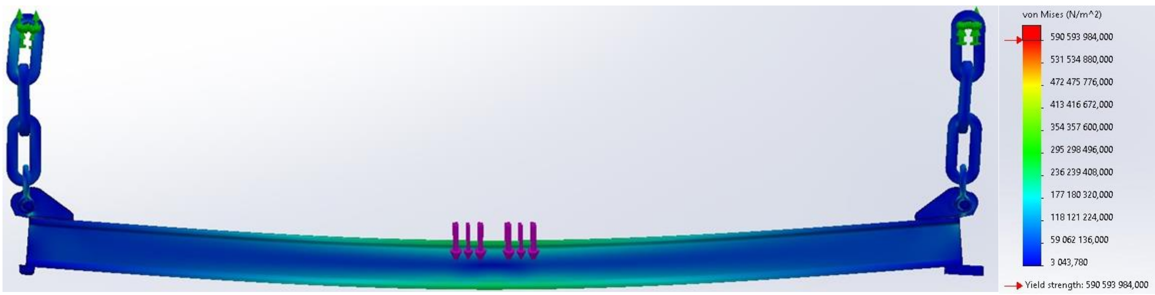

Fig. 6. Stresses in the beam of the monorail track resulting from the transportation of heavy loads in a traditional way

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Equivalent stresses at the centers of monorail joint beams (Von Mises stresses) are shown in Fig 6. The Von Mises stresses obtained from the simulation results are calculated according to the following formula:

$$\mathrm{VON} = \{0.5 \cdot [(\mathrm{SX}-\mathrm{SY})^2 + (\mathrm{SX}-\mathrm{SZ})^2 + (\mathrm{SY}-\mathrm{SZ})^2] + 3 \cdot (\mathrm{TXY}^2 + \mathrm{TXZ}^2 + \mathrm{TYZ}^2)\}^{(1/2)} \quad (5)$$

where:

VON - Von Mises stress;
SX - the normal stress along X;
SY - the normal stress along Y;
SZ - the normal stress along Z;
TXY - Y-displacement in the YZ plane;
TXZ - displacement along Z in the YZ plane;
TYZ - displacement along Z in the XZ plane.

$$\mathrm{VON} = \{0.5 \cdot [(\mathrm{P1}-\mathrm{P2})^2 + (\mathrm{P1}-\mathrm{P3})^2 + (\mathrm{P2}-\mathrm{P3})^2]\}^{(1/2)} \quad (6)$$

where:

P1 - the first major stress (the largest);
P2 - the second main tension;
P3 - the third main tension.

Based on the obtained equivalent stresses, it was found that the centres of I-beam chains, where the stresses reach 413 MN/m^2 are the most susceptible to fracture.

Based on the analyses of the obtained stresses, it was found that the most susceptible to damage are the middle fragments of the route section, in which the stresses reach 413 MN/m^2.

In order to reduce the loads during the transport of heavy loads, a technical solution was developed and an application for a Ukrainian patent was submitted [16]. The idea behind this solution is to distribute the load over a larger number of route sections, which reduces the deflection of each section and increases operational reliability during the transport of heavy loads. The diagram of the lifting and transport system for moving heavy loads (1) consisting of load-carrying trolleys (2), rolling trolleys (3) and suspensions to the support arches is shown in Fig. 7.

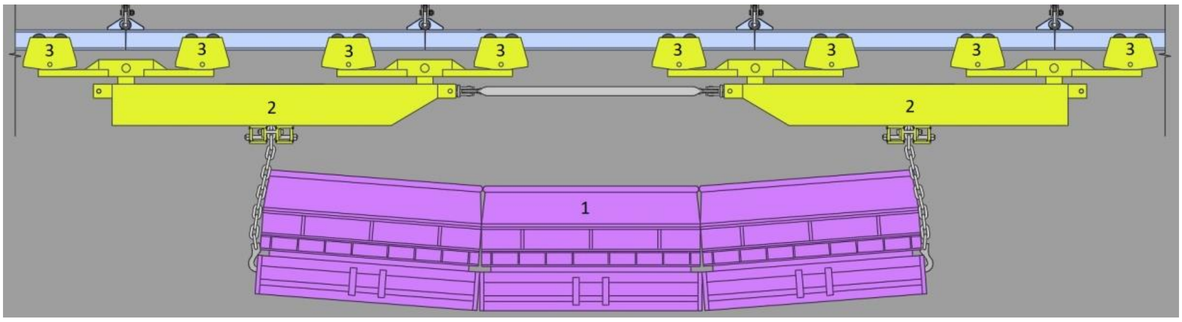

Fig. 7. Diagram of the crane and transport system with the load on the suspended monorail track

The results of simulation of interaction of the components of the lifting and transport system with the arch support enabled determining the zones of equivalent deformations and indicators of the safety margin of the monorail sections joints. Fig. 8, 9 show the equivalent stresses and deflection of a monorail beam during the transportation of heavy loads (M ≥ 4000 kg) using a lifting and transport system.

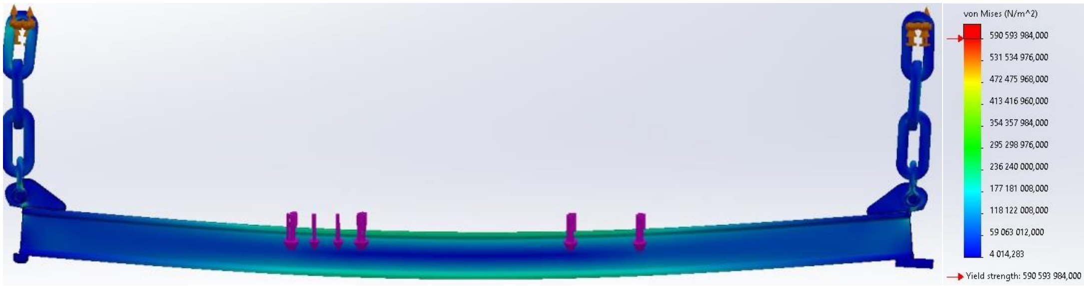

Fig. 8. Equivalent stresses of the beam of the monorail route from transportation of heavy loads when using the lifting and transport system

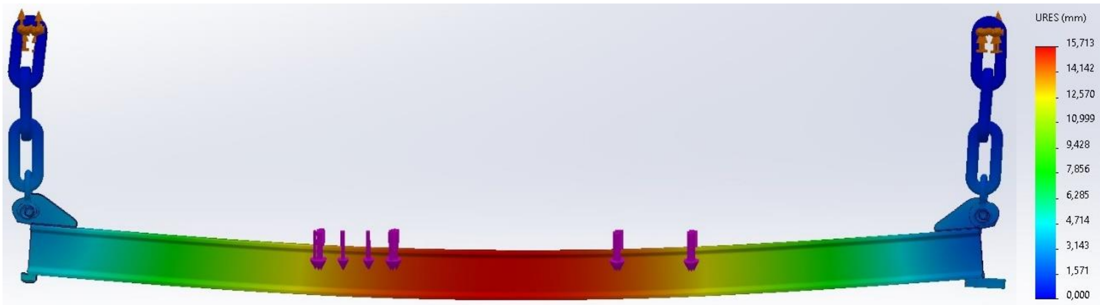

Fig. 9. Deflection of the monorail beam during transportation of large-tonnage cargo using the lifting and transport system

Based on the results of the simulation of the deflection of the monorail beams, it was found that the redistribution of loads to the monorail route due to the introduction of a lifting and transport system will allow safe transportation of heavy loads weighing up to 16 tons in the difficult conditions of the mine environment. The results of testing the deflection of monorail beams and forecasting their technical condition using the traditional transportation scheme and with the use of a lifting and transport system are shown in Fig. 10.

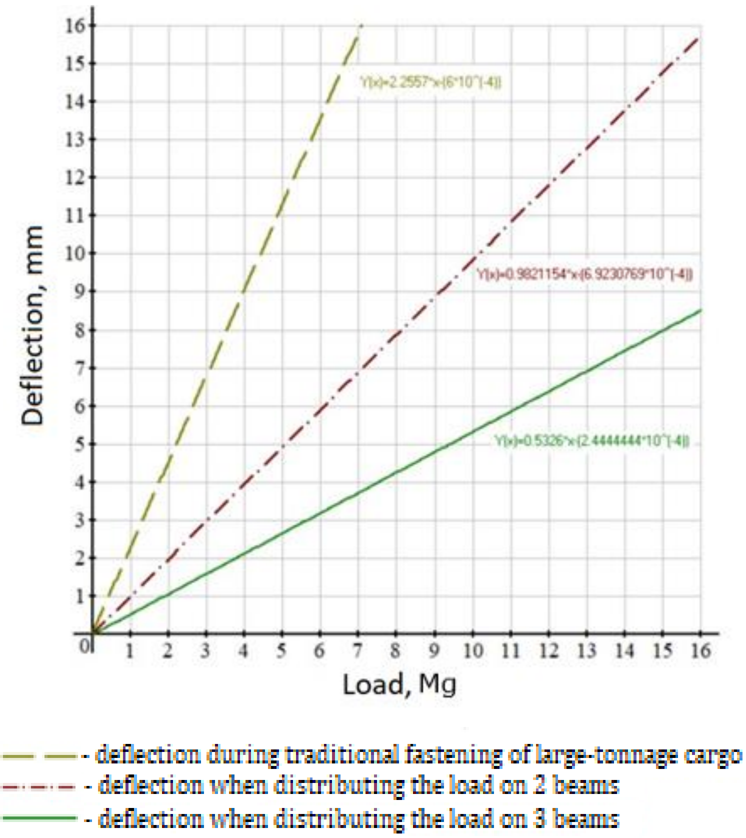

Fig. 10. Comparative curves of deflection of route sections during the transport of heavy loads by the traditional and lifting-transport system with load distribution into 2 and 3 route sections

4. Conclusions

Based on the results of modeling the interaction of the system components, the strength reserves of the suspended monorail route sections were determined for typical operating conditions. It has been experimentally proven that the most susceptible to dynamic loads and mechanical damage are the butt connections of the route sections and the middle parts of these sections of the suspended monorail route.

The analysis of the results of the simulation of interaction of system components shows that dynamic loads appear during the transport of heavy loads, the negative impact of which on the beam route sections and arch fastening is significantly reduced when using the developed lifting and transport system

The obtained parameters of cooperation of the system components and the results of the assessment of the technical condition of the connections of the monorail route segments allowed to conclude that in the real conditions of the mine environment, the designed profile of the suspended monorail track is a complex transport and technological system, which, under the impact of dynamic loads, continuously changes its initial state both in vertical and horizontal planes. Based on the results of mathematical and computer modeling of the PDM-KV-GM transport system, it was found that dynamic loads can be significantly reduced by distributing them over several segments of the suspended monorail route.

The recommended technical solutions allow to increase the potential reserves and the area of effective use of suspended monorails in the real conditions of the mine environment and to predict the permissible loads to the monorail route when moving the heavy loads.

References

[1] Shyrin L.M., Rastsvietaiev V.O., Koval O.I.: Pidvyshchennia efektyvnosti roboty monoreikovykh dorih pid chas pidhotovky zapasiv vuhillia do ochysnoi vyimky. Monohrafiia. Nats. horn. un-t. D.: NHU. 2014, 144 s.

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[2] Dychkovskiy R., Bondarenko V.: Methods of Extraction of Thin and Rather Thin Coal Seams in the Works of the Scientists of the Underground Mining Faculty (National Mining University). International Mining Forum 2006, New Technological Solutions in Underground Mining, 2006, 21–25. https://doi.org/10.1201/noe0415401173.ch3

[3] Tokarczyk J.: Metodyka identyfikacji wybranych zagrożeń mechanicznych w pomocniczym transporcie podziemnych zakładów górniczych. Prace Naukowe – Monografie KOMAG, Monografia nr 52, Instytut Techniki Górniczej KOMAG, Gliwice 2017; ISBN 978-83-65593-08-5

[4] Dychkovskyi R., Falshtynskyi V., Ruskykh V., Cabana E., Kosobokov O.: A modern vision of simulation modelling in mining and near mining activity. E3S Web of Conferences 2018, (60): 00014. https://doi.org/10.1051/e3sconf/2018600001

[5] Herasymenko A.O., Rastsvietaiev V.O., Shyrin A.L.: Selection of the means of auxiliary transportation facilities and adaptation of their parameters to specific operation conditions. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu 2023, (2): 40–46. https://doi.org/10.33271/nvngu/2023-2/040

[6] Szewerda K., Krenicky T.: Use of the MBS method in mining industry R&D projects. Mining Machines, 2022, Vol. 40 Issue 2, pp. 110-120 https://doi.org/10.32056/KOMAG2022.2.6

[7] Shyrin A., Rastsvetaev V., Morozova T.: Estimation of reliability and capacity of auxiliary vehicles while preparing coal reserves for stoping. Paper presented at the Geomechanical Processes during Underground Mining – Proceedings of the School of Underground Mining 2012,105-108. https://doi.org/10.1201/b13157-18.

[8] NPAOP. Safety requirements for the technology of installation and dismantling of mechanized complexes for gentle and inclined layers. Luhansk: Vuhlemekhanizatsiia. 2011 Retrieved from http://mpe.kmu.gov.ua/minugol/control/publish/article?art_id=210138

[9] SOU-P 10.1.00174088.018:2009 Sistema upravleniya proizvodstvom i ohranoj truda v ugolnoj promyshlennosti Ukrainy (tipovoe rukovodstvo): Utverzhdeno Prikazom Ministerstva ugolnoj promyshlennosti Ukrainy ot 21.01.2010 g. № 7. Kiev, 2010. 200 s.

[10] Shyrin L. N., Koroviaka Ye. A., Posunko L. M., Rastsvietaiev V. O., Sharina B. C.: Poshyrennia oblasti efektyvnoho zastosuvannia pidvisnykh monoreikovykh dorih v umovakh vidpratsiuvannia pokhylykh vuhilnykh plastiv. Zbirnyk naukovykh prats Natsionalnoho hirnychoho universytetu № 55. 2018, (pp. 255–266). http://nbuv.gov.ua/UJRN/znpngu_2018_55_27

[11] Stalevi konstruktsii. Normy proektuvannia: DBN V.2.6-198:2014. – K.: Minrehion Ukrainy, 2014. – 199 s.

[12] Gavrić L.J.: Computation of propagative waves in free rail using a finite element technique / L. J. Gavrić // Sound and Vib. - 1995. - №185(3). - P. 531-543. – ISSN 0022-460X.

[13] Shmyh R. A.: Rozrakhunok budivelnykh konstruktsii v obchysliuvalnomu kompleksi SCAD: navch. posib. / R. A. Shmyh, I. M. Dobrianskyi; za zah. red. R. A. Shmyha. – Lviv: Liha Pres, 2015. – 79 s.

[14] Han H. Teoriya uprugosti: Osnovy linejnoj teorii i ee primenenie: Per. s nem. / H. Han. – M.: Mir, 1988. – 344 s. 12 Gere J. M. Mechanics of materials / J. Gere, B. Goodno. – Stamford: Cengage Learning, 2012. – 620 p.

[15] Ovcharenko V.A., Podlyesnij S.V., Zinchenko S.M.: Osnovi metodu kincevih elementiv i jogo zastosuvannya v inzhenernih rozrahunkah: Navchalnij posibnik. – Kramatorsk: DDMA, 2008. – 380 s. ISBN 978-966-379-224-8

[16] Shyrin L.N., Herasymenko A.O., Shyrin A.L., Yehorchenko R. R., Koptovets O.M., Diachkov P.A., Iniutkin I.V.: Pidiomno-transportna systema dlia dostavky vantazhiv (Ukraina/Dnipro Zaiavka na vynakhid a2022 02487 vid 14.07.22). Natsionalnyi tekhnichnyi universytet «Dniprovska politekhnika».

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