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LOAD OF A SEMI-CAR HAVING THE DISMOUNTABLE ROOF OF COMPOSITES

Purpose. Creation and substantiation of the measures for adopting the supporting structure of the multipurpose semi-car to carry cargoes that need weather protection.

Methodology. For the adaptation of supporting constructions of semi-cars to carriage of cargoes that need weather protection, it was proposed to apply a removable roof manufactured from composites. As the application of a removable roof enlarges the volume of the container of the semi-car, the authors defined the load on its construction with the help of mathematical modeling. The authors see semi-car as a system which includes three components – a supporting construction having a roof with two carts. The Runge-Kutta method was used to calculate the main dynamic parameters of the semi-car. These defined dynamic parameters were accounted during calculation of the strength of the dismountable roof. Graphic spatial modeling of a semi-car with a dismountable roof was performed in the SolidWorks software kit. The calculation of solidity is implemented by the method of ultimate elements using the SolidWorks Simulation program kit. The original frequencies and forms of vibrations of the supporting construction of the semi-car are performed in this research.

Findings. The outcomes of a mathematical model of the dynamic loading of the supporting construction of the semi-car having a dismountable roof set that the obtained dynamic parameters are not higher than the allowable values. The acceleration of the semi-car supporting construction in the gravity center made approximately 4.5 m/s^2. The vertical dynamic ratio amounts to 0.53. The car motion is evaluated as "excellent". It was found that when the vertical load acts on the dismountable roof, the maximum tension emerging inside is 173.2 MPa. When concentrated load affects the dismountable roof, the biggest tensions are focused on the zones of its attachment to the upper strapping of the casing, and makes 205.7 MPa. It can be seen from the modal analysis that the first original frequency of the semi-car casing is equal to 9.6 Hz, which is more than the allowable value – 8 Hz.

Originality. Models for determining the loading of the supporting construction of the semi-car having a dismountable roof from composites within the general modes of loading operation are given in this study.

Practical value. The study results allow expanding the applicability of semi-cars by adapting them to the carriage of cargoes, which need protection from weather effects and can increase the performance of railroad carriage.

Keywords: *gondola car; removable roof; construction load; stressful state; indicators of dynamics*

Introduction. Prospects for the improvement of the railroad carriage necessitate the increasing performance of its operation to maintain the main place in the carriage service market. Contemporaneously, there are a lot of requirements to the updated locomotive equipment, which are mainly the development of technical-economic indicators by improving its construction by adding new substances, and also ensuring environmental friendliness and safety of freight carriage services.

The work of locomotive equipment can also be improved by expanding its functionality and adapting constructions for the carriage of an expanded range of goods.

The well-known fact is that the famous type of cargo wagons in exploitation is multifunction semi-cars. To enable cargo carriages that need protection from weather conditions, semi-cars have dismountable roofs.

However, it makes the packaging of supporting construction of the semi-car bigger, and, accordingly, its sprung mass also increases. This causes raising of the load on the supporting construction of the semi-car. Thus, the possibility to apply alternative substances in the manufacturing of dismountable roof of a wagon with the provision of exploitation strength conditions should be studied. It will help to expand the applicability of semi-cars and provide their exploitation security.

Literature review. Issues of optimization and increasing performance of wagons are considered in the study [1]. These improvements focus on extending the operational durability of locomotives. This study also considers a new system of wagon technical diagnostics.

Theoretical studies on locomotive casing improvement were performed in the research [2]. The calculation of tension affirms these suggested technologies. The pilot model was the BOXN25 semi-car.

Simultaneously, the technologies do not give the possibility to carriage freights that need security against down-falls in wagons.

This publication [3] covers the problem of defining the tension and weariness period of the wagon casing. Suggested technologies of improvement of exploitation conditions for locomotives are substantiated. Calculation of the tension of the supporting construction of Zans wagon is performed in the study [4]. This wagon has an improved design and improved technical-economical parameters. The tension was defined using the techniques of end elements. As the result, calculations have affirmed the expediency of the decision obtained in the process of engineering.

However, when designing these wagon constructions, it is impossible to increase their functionality with the application of dismountable roof.

Features of upgrading the supporting construction of semi-car to make traffic safer when carrying freights with the height exceeding their upper sizes, are given in the study [5]. A bar option inside extending rack is offered. Although, the given construction is not able to withhold significant loads that occur during operation.

To increase the tension of the wagon casing in conditions of operating loads, it was suggested to modernize it in the publication [6]. Herewith, the authors performed a numerical calculation of the load on it, and the experimental research affirmed their results.

The research on the general firmness parameters of modernized wagon casing is performed in the study [7]. The calculation outcomes proved that the suggested modernization is appropriate. This study also shows what changes and modernization the existing park of locomotives requires.

It is worth noting that the upgrading of locomotives foreseen by these studies [6, 7] does not make it possible to transport frights that need weather protection.

This publication [8] highlights the outcomes of the wagon casing improvement. It could be seen from the firmness calculation results that the suggested technologies help to ensure their firmness in conditions of the general exploitation loads.

Peculiarities of modernization of cargo wagons during their periodic repairs are considered in this study [9]. Herewith, the authors focused on improving the exploitation conditions of cargo wagons. However, the proposed upgrades cannot help to expand the variety of frights they carry.

Unsolved aspects of thr problem. Reference analysis [1–9] enables one to make a conclusion that studying of the loading of the semi-car having a dismountable roof of composites is quite relevant, as no one has considered it properly yet. Thus, an appropriate study in this area is needed.

Purpose. The aim of this study is to substantiate measures for adapting the supporting construction of the multifunctional semi-car to transport freights that need weather protection.

Research methodology description. In order to reach this goal, these tasks are determined:

- performing mathematical modeling of the dynamical load of the semi-car which has a dismountable roof of composites;
- determining the tension of the supporting construction of the semi-car which has a dismountable roof of composites;
- performing the modal analysis of the supporting construction of the semi-car which has a dismountable roof of composites.

Basic material presentation. We use removable roofs to expand the applicability of semi-cars by adapting them to the carriage of freights that need weather protection. The most widespread roof designs, which were used on wide gauge cargo wagons are presented in Fig. 1.

Herewith, roof option 1 is most often used on semi-cars of newly updated construction. It consists of a metal carcass and cladding. The roof is attached to the casing of the semi-car with the help of the bolted connection. It is also possible to fasten a roof to the upper strap-ping using magnets. Although, the given method requires appropriate technology and tooling, it consequently raises the expenses for technical support of semi-cars in exploitation. It is worth noting that the application of a removable roof can enlarge the capacity of the wagon container in comparison with the archetype by 2–3 %. It makes a contribution to the raising of the sprung weight of a wagon, and, accordingly, changes in its movement dynamics. Therefore, the authors advise using a removable roof produced of the substance that has a lower weight compared to steel, accounting for the tension conditions with applied operating loads. Composite can be used as such material.

Composites with titanium matrix are the most promising, which are reinforced by fibers of boron, boron alloys, silicon carbide, beryllium, and molybdenum. This helps to reduce roof container capacities by 17 % in comparison with a typical design. This composite has a tensile firmness: along fibers – 1100–1300 MPa, across the fibers – 650 MPa. This material is also thermally resistive.

For substantiation of the suggested technology, the authors determined the dynamic load of supporting construction of the semi-car with dismountable room made of composites.

Fig. 2 displays the scheme of calculations. The model of mathematical analysis developed by Professor Yu. V. Dyomin and associate professor G. Yu. Chernyak was used. However, within this research, the authors finalized the model accounting for the additional wagon freedom degree, namely in a lengthwise plane.

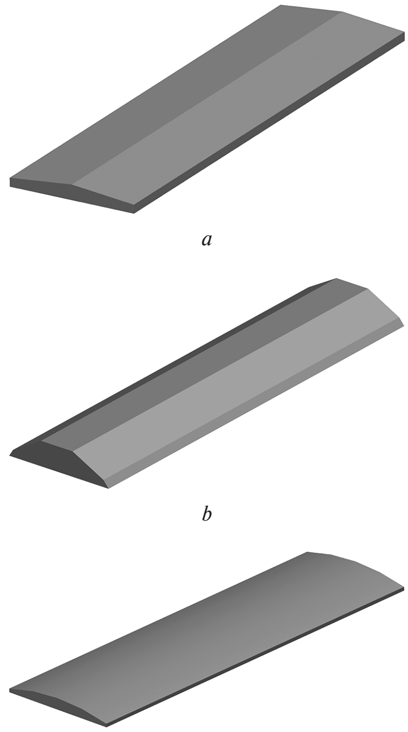

Fig. 1. Roofs of cargo wagons:

a – option 1; b – option 2; c – option 3

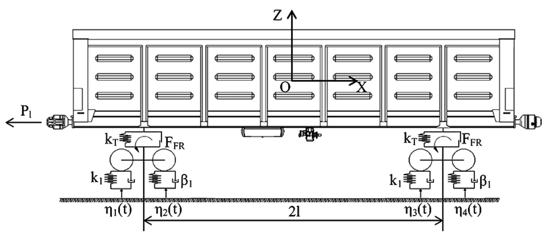

Fig. 2. Scheme of the semi-car calculations

A plane system of coordinates was used in this study. It was foreseen that the wagon moves unevenly being empty, as the greatest dynamic load of it is traced. The gauge of the rail is considered as elastic-viscous.

Semi-car model 12-757 was used to perform these studies. The proposed construction of the semi-car is universal and aims at the carriage of bulk cargoes and raw products. Light cargoes are unloaded through hatch covers forming their floor (14 pieces).

$$M_1' \cdot \frac{d^2}{dt^2} q_1 + M_1 \cdot h \cdot \frac{d^2}{dt^2} q_3 = P_l;$$

$$M_1 \cdot \frac{d^2}{dt^2} q_1 + C_{1,1} \cdot q_1 + C_{1,3} \cdot q_3 + C_{1,5} \cdot q_5 =$$
$$= -F_{FR} \cdot \left(\text{sign}\left(\frac{d}{dt} \delta_1 \right) + \text{sign}\left(\frac{d}{dt} \delta_2 \right) \right);$$

$$M_2 \cdot \frac{d^2}{dt^2} q_2 + C_{2,2} \cdot q_2 + C_{2,3} \cdot q_3 + C_{2,5} \cdot q_5 =$$
$$= F_{FR} \cdot l \cdot \left(\text{sign}\left(\frac{d}{dt} \delta_1 \right) + \text{sign}\left(\frac{d}{dt} \delta_2 \right) \right);$$

$$M_3 \cdot \frac{d^2}{dt^2} q_1 = H_1;$$

$$M_3 \cdot \frac{d^2}{dt^2} q_3 + C_{3,1} \cdot q_1 + C_{3,2} \cdot q_2 + C_{3,3} \cdot q_3 + B_{3,3} \cdot \frac{d}{dt} q_3 =$$
$$= F_{FR} \cdot \text{sign}\left(\frac{d}{dt}\delta_1\right) + k_1(\eta_1 + \eta_2) + \beta_1\left(\frac{d}{dt}\eta_1 + \frac{d}{dt}\eta_2\right);$$
$$M_4 \cdot \frac{d^2}{dt^2} q_1 = H_2;$$
$$M_4 \cdot \frac{d^2}{dt^2} q_4 + C_{4,4} \cdot q_4 + B_{4,4} \cdot \frac{d}{dt} q_4 =$$
$$= -k_1(\eta_1 - \eta_2) - \beta_1 \cdot a \cdot \left(\frac{d}{dt}\eta_1 - \frac{d}{dt}\eta_2\right);$$
$$M_5 \cdot \frac{d^2}{dt^2} q_5 + C_{5,1} \cdot q_1 + C_{5,2} \cdot q_2 + C_{5,5} \cdot q_5 + B_{5,5} \cdot \frac{d}{dt} q_5 =$$
$$= F_{FR} \cdot \text{sign}\left(\frac{d}{dt}\delta_2\right) + k_1(\eta_3 + \eta_4) + \beta_1\left(\frac{d}{dt}\eta_3 + \frac{d}{dt}\eta_4\right);$$
$$M_6 \cdot \frac{d^2}{dt^2} q_6 + C_{6,6} \cdot q_6 + B_{6,6} \cdot \frac{d}{dt} q_6 =$$
$$= -k_1 \cdot a \cdot (\eta_3 - \eta_4) - \beta_1 \cdot a \cdot \left(\frac{d}{dt}\eta_3 - \frac{d}{dt}\eta_4\right),$$

where M_1, M_2 are weight and insertion moment of the supporting construction; M_3, M_4 are mass and insertion moment of the *1st* cart in its motion; M_5, M_6 are mass and insertion moment of the *2nd* cart in its motion; C_{ij} is elasticity characteristics of the components in the oscillating chain that can be defined by the spring rigidity ratio values k_h; B_{ij} is the function of scattering; a is cart basing half (cart model 18–100); k is gauge stiffness; β is a damping factor; $i(t)$ is a function describing the rail gauge unevenness; i is distortion of leaf suspension elastic components; F_{FR} is absolute shear force in the spring set; H_1, H_2 are horizontal force values applied to the foot of the *1st* and *2nd* carts; h is mass center height of the wagon supporting construction.

$$M_1' = M_1 + (M_3 + M_5) + \frac{nI}{r^2},$$

where n is cart capacity; I is wheel pair inertia movement; r is wheel radius.

The lengthwise force value that affects the semi-car autocoupling is supposed to amount to 2.5 MN, which means that the calculations were made in the wagon motion state as a part of a cargo train [10].

The movement differential equations are solved using the classical method of Runge-Kutta [11, 12]. Starting conditions, i. e. the original shifts and speeds were set to zero [13, 14].

The calculation outcomes showed that the main dynamic parameters of the semi-car do not outreach allowable indicators. The speed-up of the load-bearing construction of the semi-car in the mass center of mass is approximately 4.5 m/s^2 (Fig. 3).

The vertical dynamic ratio makes 0.53 (Fig. 4). The semi-car course was assessed as "perfect" [10].

The received parameters of dynamics are accounted in the determination of the dismountable roof firmness. The computation modelling of the supporting structure of the semi-car having a removable roof is given in the Fig. 5. Graphic study on the building of a dimensional model of a semi-car having a removable roof was performed in the software kit SolidWorks [15, 16]. Herewith, the authors used an album of drawings of the semi-car, which allowed creating a refined dimensional model for it. It is worth noting that the building of caps for its unloading hatches are not considered. Such assumption is long-lasting, because they have a hinged interaction with the wagon supporting construction. Thus, when creating a dimensional model, the construction components, interacting with each other strongly, are considered. Moreover, the model does not account for welds, so it is regarded as a monolithic structure.

The determination of firmness is implemented by the method of end elements in the program SolidWorks Simulation.

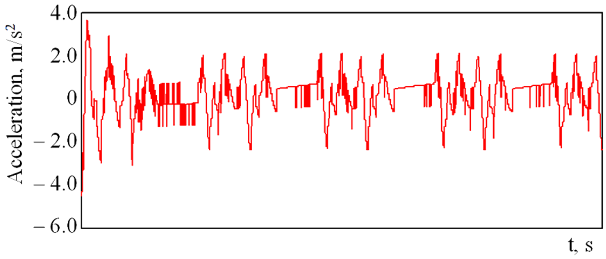

Fig. 3. Speed-up of the supporting construction of the semi-car in the mass center

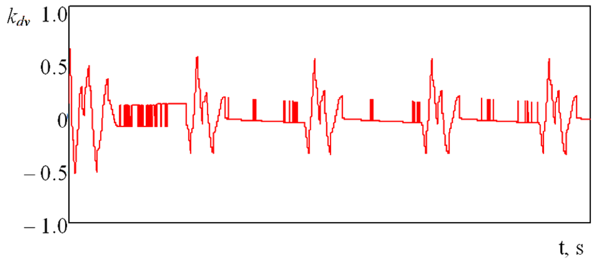

Fig. 4. The vertical dynamic ratios of the supporting construction of the semi-car

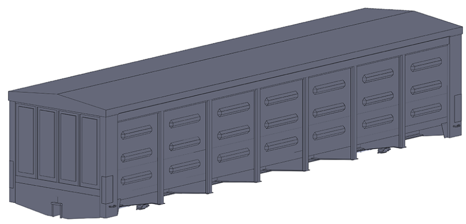

Fig. 5. Dimensional model of the supporting construction of a semi-car having a removable roof

The authors took into account isoparametric tetrahedra creating the model of end elements [17, 18]. The best quantity of elements of the model is defined by the graphical-analytical method [19, 20]. The quantity of the model units was 178,845, elements – 550,106. The maximum element dimensions made 80 mm, while the minimum – 16 mm. The percentage of elements which have a coefficient smaller than three was 24.9 %, more than ten – 36. The minimum element quantity in a circle made 9, the percentage of enlarging the element dimensions – 1.7.

The model was fixed in the zones of the bearing of the supporting construction on the running gear.

The supporting construction material is made from 09G2S steel and the roof – from composites. Thus, the calculation of the model was carried out as an assembly.

Under the rules of regulatory documents, the roof is designed for reinforcement affected by two forces, each of 1 kN, distributed on a 0.25 x 0.25 m site and added at the 0.5 m distance from each other at any roof piece. This roof is additionally defined using the III mode of calculation.

Since the main part of the supporting construction of the car is made of steel, which is an isotropic material, and the composite is orthotropic, the calculation is based on two criteria – Mises (IV energy theory) and maximum stresses. The main roof load modes were calculated. Figs. 6 and 7 show the stress condition of the load-bearing construction for the semi-car at the most loaded modes.

According to the calculations, the roof firmness in all the considered calculation schemes is assured.

Affected by the vertical load on the removable roof, the maximal equal tensions occurring in it amounted to 173.2 MPa.

Affected by the concentrated load on the removable roof, the maximal equal tensions concentrated within the areas of its interaction with the upper body harness are 205.7 MPa.

When calculating the criterion of maximum stresses, the authors found that affected by the vertical load on the roof, the maximal tensions appear within the longitudinal direction and amount at 187 MPa, while in the transverse direction – 123 MPa.

Affected by the concentrated load on the roof, the maximal tensions are also recorded in the longitudinal direction. Their numerical value was 198 MPa. The maximal tensions are equal to 135 MPa acting transversely.

This study also foresees that the natural periodicities and forms of fluctuations of the supporting construction of the semi-car having a removable roof were defined. The calculation was performed using the SolidWorks Simulation software under the calculation scheme compiled to define the tensions in the supporting construction of a semi-car affected by the vertical load acting on a roof. Fig. 8 shows some forms of natural fluctuations of the supporting construction of the semi-car having a removable roof.

It was set that the first original periodicity of fluctuations of the supporting construction of the semi-car having a removable roof has the value of 9.6 Hz, which is higher than the allowable value – 8 Hz. Thus, the security of a semi-car is ensured [10].

A further direction of these studies will be to determine the strength of the roof in the areas of bolted joints with the top strapping. It is also necessary to conduct experimental tests of the strength of the proposed design of the removable roof. Such tests are planned to be performed on a field sample using the method of similarity in the laboratory.

A promising area of this study is the creation of a universal roof design, adapted for use on different types of freight cars, taking into account their geometric features. Such a roof will work on the principle of a transformer and will have the ability to adapt to the set geometry of the body. These issues will be developed in further studies by the group of authors.

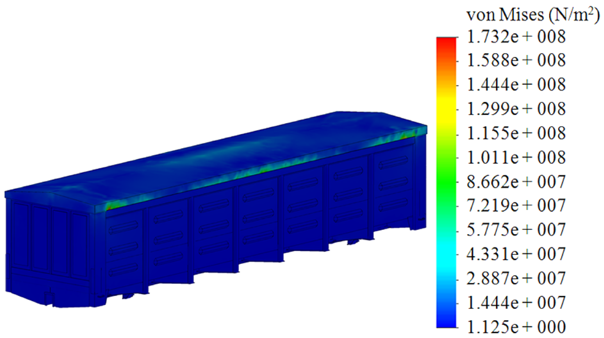

Fig. 6. Stress condition of the supporting construction of the semi-car having a removable roof affected by the vertical load

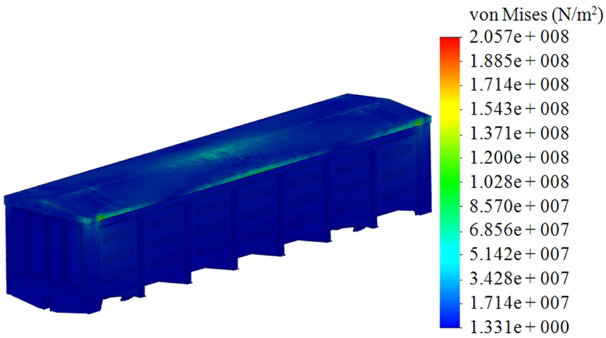

Fig. 7. The condition of the supporting construction of the semi-car having a removable roof affected by the concentrated load

Conclusions and recommendations on further implementation.

1. Mathematical modeling of the dynamical load of the semi-car having a removable roof from composites was performed. The calculation results allowed making conclusions that the calculated dynamic parameters do not overreach the allowable values. The acceleration of the load-bearing construction of a semi-car in the center of mass made approximately 4.5 m/s^2. The vertical dynamic ratio is equal to 0.53. The movement of a wagon is assessed as "excellent".

2. The firmness of the supporting construction of a semi-car having a removable roof from composites is defined. According to the calculations, the roof firmness in all the considered calculation schemes is assured. Affected by the vertical load on the removable roof, the maximal equal tensions occurring in it were 173.2 MPa. Affected by the concentrated load on the removable roof, the maximal equal tensions are concentrated within areas of its interaction with the upper body strapping and make 205.7 MPa.

3. The modal analysis of the supporting construction of the semi-car having a removable roof from composites is performed. The authors set that the first original periodicity of fluctuations of the supporting construction of a semi-car is 9.6 Hz, which is higher than the allowable value – 8 Hz. Therefore, the safety of the gondola car is ensured.

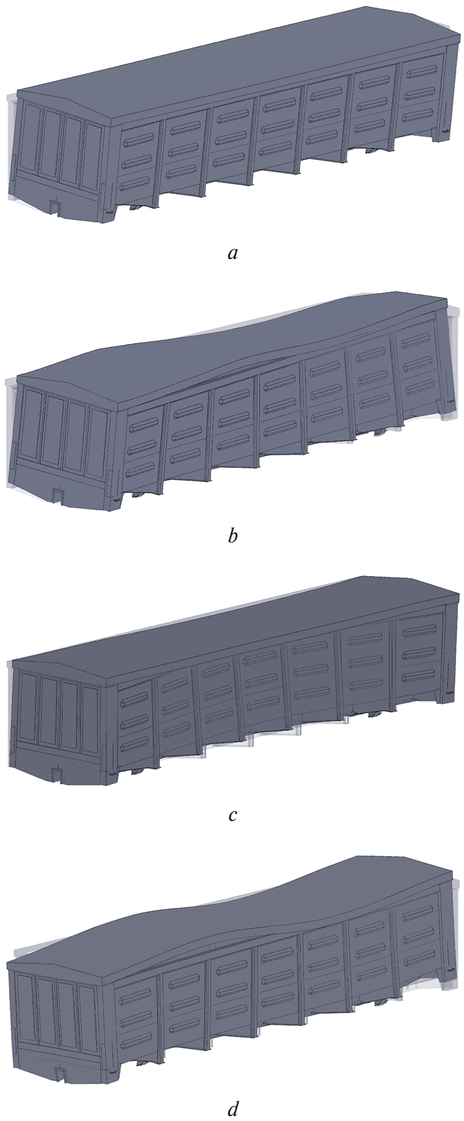

Fig. 8. Some forms of fluctuations of the supporting construction of the semi-car having a removable roof (scale of deformations 20 : 1):

a – second mode; b – forth mode; c – fifth mode; d – sixth mode

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Навантаженість напіввагону зі знімним дахом із композиту

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Мета. Створення та обґрунтування заходів щодо адаптації несучої конструкції універсального піввагону до перевезень вантажів, що потребують захисту від атмосферного впливу.

Методика. Для пристосування несучих конструкцій напіввагонів до перевезень вантажів, що вимагають захисту від атмосферного впливу, запропоновано використання даху, який знімається, із композитного матеріалу. Оскільки використання даху, що знімається, збільшує тару напіввагону, то авторами проведене визначення навантаженості його конструкції шляхом математичного моделювання. При цьому напіввагон розглянутий як система, що включає три складові – конструкція з дахом і два візки. Основні показники динаміки напіввагону розраховані методом Рунге-Кутта. Розраховані показники динаміки враховані при розрахунках на міцність даху, що знімається. Графічні роботи зі створення просторової моделі напіввагону зі знімним дахом проводились у програмному комплексі SolidWorks. Розрахунок на міцність реалізований методом кінцевих елементів у програмному комплексі SolidWorks Simulation. У рамках дослідження проведене визначення власних частот і форм коливань несучої конструкції напіввагону.

Результати. Результати математичного моделювання динамічної навантаженості несучої конструкції напіввагону зі знімним дахом встановили, що розраховані показники динаміки не перевищують значення, які допускаються. При цьому прискорення несучої конструкції напіввагону у центрі мас склало близько 4,5 м/с^2. Коефіцієнт вертикальної динаміки дорівнює 0,53. Хід руху вагона оцінюється як «відмінний». Встановлено, що за дії вертикального навантаження на знімний дах максимальна еквівалентна напруга, що виникає в ній, становила 173,2 МПа. За дії зосередженого навантаження на знімний дах максимальна еквівалентна напруга виникає в зонах її взаємодії з верхньою обв'язкою кузова та становить 205,7 МПа. Результати модального аналізу встановили, що перша власна частота коливань кузова напіввагона має значення 9,6 Гц, що вище за допустиме значення – 8 Гц.

Наукова новизна. Запропоновані моделі для визначення навантаженості несучої конструкції напіввагону зі знімним дахом із композиту при основних експлуатаційних режимах навантаження.

Практична значимість. Результати проведених досліджень дозволять розширити функціональність напіввагонів шляхом їх адаптації до перевезень вантажів, що потребують захисту від атмосферного впливу, та сприятимуть покращенню ефективності експлуатації залізничного транспорту.

Ключові слова: *напіввагон, знімний дах, навантаженість конструкції, напружений стан, показники динаміки*

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