Вісник Тернопільського національного технічного університету
https://doi.org/10.33108/visnyk_tntu
Scientific Journal of the Ternopil National Technical University
2022, № 4 (108) https://doi.org/10.33108/visnyk_tntu2022.04
ISSN 2522-4433. Web: ***visnyk.tntu.edu.ua***

UDC 631.373:519.6

ANALYSIS OF THE STRESS-STRAIN STATE OF THE VEHICLE FRAME BY FINITE ELEMENT METHOD

Mykola Stashkiv[1]; Ivan Pidgurskyi[1]; Oleh Pidluzhnyi[1]; Mykola Pidgurskyi[1]; Mykhaylo Levkovych[1]; Ruslan Skliarov[1]; Andriy Mushak[2]

[1]Ternopil Ivan Puluj National Technical University, Ternopil, Ukraine
[2]West Ukrainian National University, Ternopil, Ukraine

Summary. *Analysis of load-bearing structures of vehicles is carried out. The peculiarities of the operation of vehicles and their bearing systems are considered. It is noted that the loads acting on the structure are time-varying; their amplitude and frequency characteristics depend on the real load, the speed of the vehicle, the condition of the road surface and other factors. This can cause a high level of stress in the areas of structural and technological concentrators and result in the occurrence of fatigue cracks and frames destruction in these areas. The researching methods of operational loads and the stress-strain state of frame structures under static and dynamic loads are analyzed. It is noted that the finite element method is the most universal for the implementation of static, modal, harmonic and other types of analyzes of frame structures.*

The finite element method is used to investigate the stress-strain state of bearing structure of the 2PTS-2 trailer under different static load options. The full-scale CAD model of the trailer and its finite-element model are developed using specialized software SolidWorks. Calculations of the stress-strain state of the trailer frame are carried out for typical types of loads: straight-line movement, turning and lifting of the vehicles body with load. The analysis of the safety factors by stresses is carried out in order to take into account the uncertainties of the frame structure model and the uncertainties of the operational load. It is established that when considering the investigated options for loading of the frame structure, the most dangerous are those related to the unloading of the cargo, which requires further research into the specified processes.

Key words: *trailer, frame, finite element method, stress-strain state, stress, deformation, displacement, safety factor.*

https://doi.org/10.33108/visnyk_tntu2022.04.089 *Received 19.12.2022*

Statement of the problem. The bearing system of the vehicle is one of the most responsible, metal-intensive and expensive systems. Such important elements as the body, engine, suspension and transmission elements are fastened to the bearing system, creating complete structure of the vehicle [1].

The bearing system design depends, first of all, on the machine purpose. At present, the frame bearing system is used mainly in the production of comfortable high-class passenger cars, off-road vehicles, trucks, trailers, and tractors. Frame structures are divided into ladder frame, backbone frame and combined ones.

The most popular are ladder frames. They consist of two or more longitudinal members, several cross members and local reinforcements. Backbone frames with central load-carrying tube or box section have central beam with transversely located brackets for units fastening. Combined frames join elements of both ladder and backbone frames, that is, they have central beam, short ladder frames and crossbars. It should be noted that in ordinary passenger cars, the frame structure is replaced by self-bearing body.

Corresponding author: Mykola Pidgurskyi; e-mail: pidhurskyy@gmail.com

Analysis of advantages and disadvantages of the vehicle load-bearing structures is presented in papers [1, 2]. It should be noted that ladder-type frames are characterized by high strength and have multi-purpose nature of application. Backbone-type frames have greater torsion stiffness in comparison with the ladder frames and are used in special cases, for example, in massive power beet harvesters [3].

The peculiarity of the operation of vehicles and their bearing systems is that the forces acting on the structure are time-varying, and their amplitude and frequency characteristics depend on the operational load, speed of movement, road condition and other factors [1, 3]. All these factors can contribute to the occurrence of significant stresses in the areas of structural and technological concentrators. This can result in the initiation of fatigue cracks in the indicated areas. Crack propagation can cause the destruction of frames [4, 5].

Analysis of available investigation and publication. Static and (or) dynamic analysis methods [6, 7] are used to estimate the operational durability and reliability of frames, depending on the nature of machine load. With significant cyclic loads, dynamic methods of structural analysis are used. In the case of quasi-static operational loading of mobile machines, which does not cause significant inertial and damping effects, static analysis of the stress-strain state of the frames is used. At the same time, the safety factors, maximum stresses, strain and displacements in the structures of the machine load-bearing systems are determined. The limiting values of safety factors in various publications [8, 9] differ significantly.

Objective of the paper. The objective of the given investigation is the implementation of the algorithm for estimating the stress-strain state of the trailer frame structure using the finite element method under static loading for its main operational maneuvers and determining the safety factors by stresses.

Methods of the investigation. A large number of methods with different complexity and accuracy of the obtained results, which take into account the specific features of the structures, have been developed for the calculation of the load-bearing systems of mobile machines. They are characterized by irregular spatial structure, application of different types of elements, complex and ambiguous nature of the load. The basic principles of calculation and design for bearing systems of mobile machines are highlighted in paper [1].

Analytical methods of the theory of elasticity, particularly, methods based on the theory of thin-walled rods developed by V. Z. Vlasov are used to estimate the SSS of frame structures. This theory determines the general law of stress distribution in the cross-section of thin-walled rod under the action of torsion. Based on this theory, methods of calculating the frames made of thin-walled rods with the cross section of open (D. V. Bychkov) and closed (A. A. Umanskiy) contour are developed.

The methods of calculating frames with deformable and non-deformable contours are the most commonly used ones. But the high degree of static indeterminacy of calculation schemes significantly complicates the process of calculating frame structures. While developing the theoretical basis for eliminating «extra» ties of the main load-bearing structural structures, especially mobile agricultural machines, the method based on the principle of the minimum potential energy of deformation turned out to be quite effective [10].

In modern engineering practice, due to the development of computer technology and the development of universal application programs based mainly on the finite element method (FEM), calculations for determining the SSS of complex structural structures are significantly accelerated. The advantages of FEM compared to traditional numerical methods are the simplicity of algorithmization, the possibility of complete automation of setting up the equations and obtaining solutions for any complex combined systems. This makes the method of finite elements the most universal method which, to a large extent, meets the requirements of the frames calculation [5, 8].

FEM implements the idea of object research based on the consideration of its individual parts – finite elements (FE). Thus, solid medium with infinite number of degrees of freedom is approximated by a certain set of simple elements having finite number of degrees of freedom and are interconnected at nodal points.

Therefore, continuous systems are divided into separate elements, the operation of which is approximately or precisely investigated, and then the stress-strain states of these elements are combined with each other in such a way as to ensure the conditions of deformations compatibility and equilibrium conditions. FEM makes it possible to represent the solution as a set of continuous functions for each FE.

The algorithm for solving the corresponding system of equations relative to the function value at the nodes is easily found by replacing the above mentioned system of differential equations with the corresponding variational differentials [11]. In particular, for problems of elastic deformation of bodies under the action of various forces, Lagrange functional is used:

$$\varPi_L(\bar{U}) = S_v \left\{ \frac{1}{2} \varepsilon^T \cdot \sigma - \vec{U}_T \cdot \vec{F} \right\} dV - S_s \bar{U}^T \bar{P} \cdot dS\,. \tag{1}$$

It should be noted that $\varPi_L$ value is the potential energy of the body, the first summand determines the energy of deformation, and the others – the work of external forces on movements. Further, integral (1) is represented as the sum of integrals over the volumes of FE sets. After substitution of approximations of deformations ε, stresses σ, and forces $\bar{P}$ and $\bar{F}$, functional (1) is transformed into the function of nodal displacements:

$$\varPi_L\{v\} = \frac{1}{2}\{v\}^T \cdot K\{v\} - \{v\}^T \cdot \{Q\}, \tag{2}$$

where *K and {Q}* are, respectively, the stiffness matrix and FE load vector in the local coordinate system.

The above mentioned algorithm is the mathematical basis of a number of software for structural strength analysis, such as SolidWorks, ANSYS, NASTRAN, «Lira» and others.

FEM is used for implementing static, dynamic (modal, harmonic) and other types of analysis. In the given paper, static analysis is implemented for the investigation of the stress-strain state of bearing structure of 2PTS-2 trailer under 20 kN static load, which corresponds to the nominal value of the load capacity for this trailer model (2 tons).

The development of full-size CAD model of 2PTS-2 trailer and the investigation of the stress-strain state of its frame are carried out using SolidWorks [12] software complex for solid modeling and engineering analysis in the following sequence (Fig. 1).

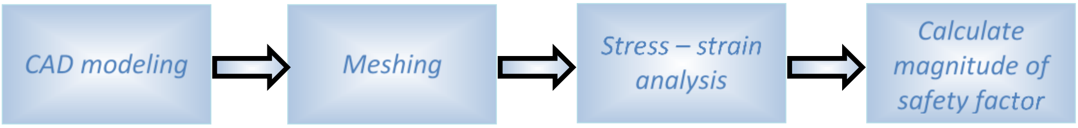

Figure 1. The sequence of modeling and analysis execution

In order to simplify the process of investigation the stress-strain state of the trailer frame, only the model of bearing structure without the body and wheels, replaced by conditional elements, which, in turn, are subjected to fastening conditions and external load, is considered.

A mesh of finite elements with 20 mm global element size and 1 mm tolerance is created for the frame model (Fig. 2).

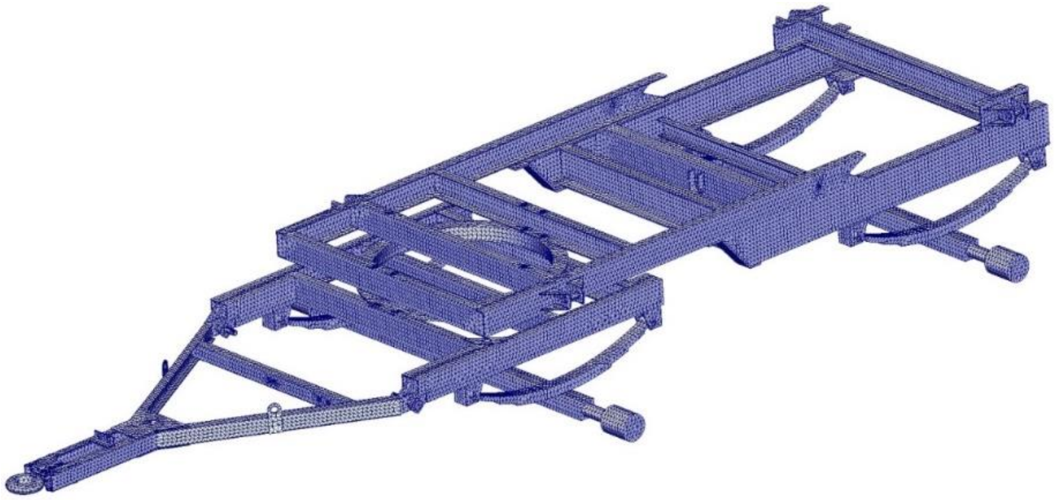

Figure 2. Mesh of finite elements of 2PTS-2 trailer frame

SSS calculations of the trailer frame are carried out for the following load options (Fig. 3):

I – the external load from the weight of the material in the body is evenly distributed along four supports of the body; traction force is applied along the axis of the trailer frame (straight-line movement);

II – the external load from the weight of the material in the body is evenly distributed along four supports of the body, the traction force is applied at an angle to the axis of the trailer frame (non-linear movement – turning);

III – the external load from the weight of the material in the body is applied to the hydraulic body lifting cylinder;

IV – the external load from the weight of the material in the body is applied partly to the two supports of the body and partly to the hydraulic body lifting cylinder.

For the first and second calculation options, 20 kN external load is evenly distributed along four supports of the body. 14 kN traction force is applied to the drawbar (Fig. 3, a, b). In these cases, the trailer movement is simulated. For the third version of the calculation, 20 kN external load is concentrated on the rod of hydraulic cylinder, which simulates the initial moment of the cargo unloading process (Fig. 3, c). For the fourth version of the calculation, 13 kN external load is equally distributed between two left supports of the body and is partially concentrated on the rod of the hydraulic body lifting cylinder (7 kN), which simulates the intermediate moment of the cargo unloading process (Fig. 3, d).

For all calculation options, fastening conditions – the fixed hinge are imposed on the axles at the wheels places. Structural carbon steel of ordinary quality St3sp with the following mechanical characteristics: yield strength σ_y = 220 MPa; ultimate strength σ_u = 370 MPa; relative residual elongation δ = 26 % is used for the frame structure. Structural spring steel 50XFA with the following mechanical characteristic: σ_y = 1080 MPa; σ_u = 1270 MPa; δ = 8 % is used for the spring suspension systems.

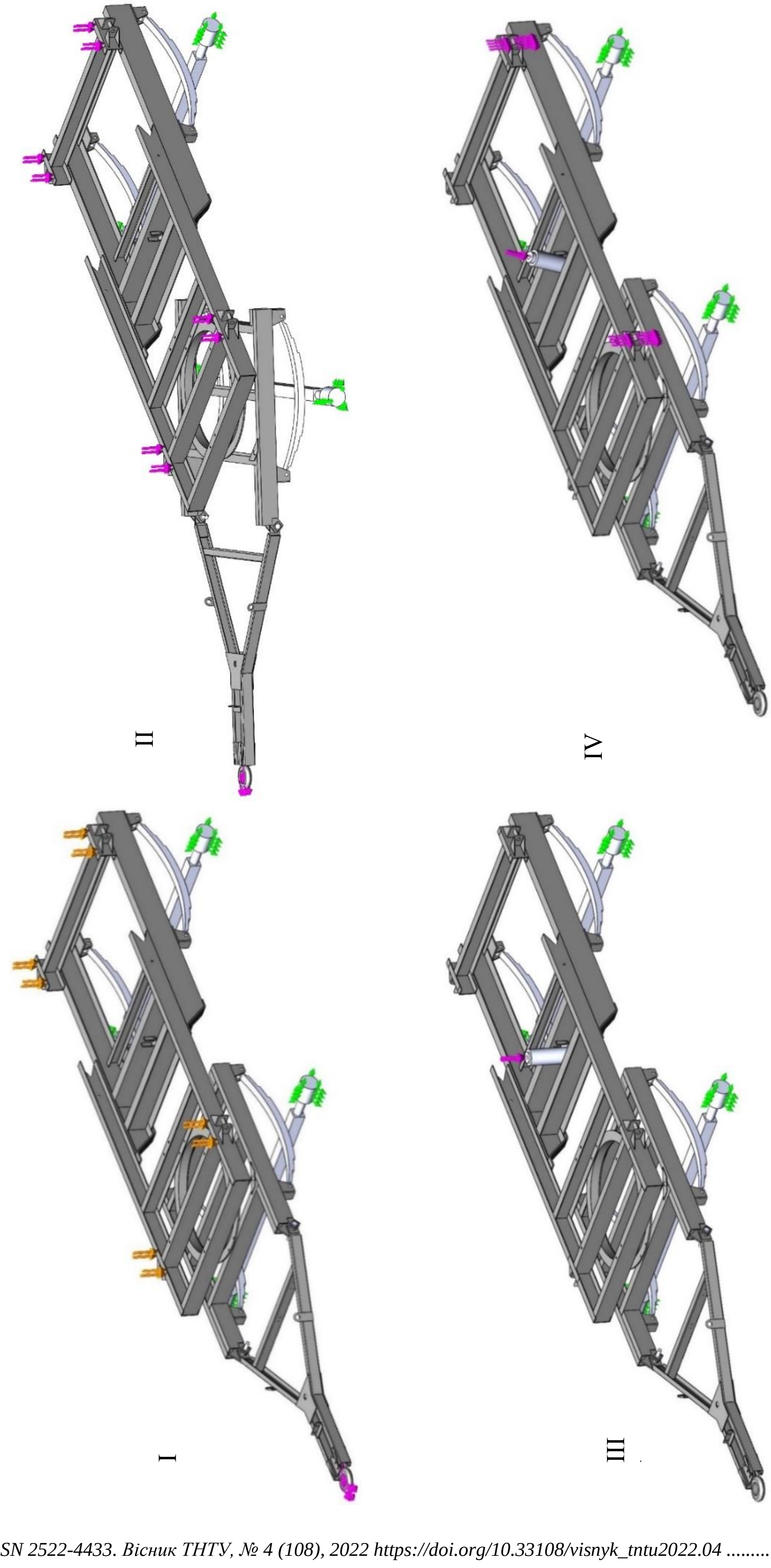

Figure 3. Calculation models of the 2PTS-2 trailer frame according to different load options

Investigation results and their analysis. The results of the investigation of the stress-strain state of 2PTS-2 trailer frame according to the first calculation option are presented in Fig. 4. Maximum stresses of 72.52 MPa are observed in the spring suspension systems (Fig. 4, a). In the main frame of the trailer, the maximum stresses are 70.97 MPa at the point of the second cross member fastening. The maximum movements of 1.27 mm are observed in the front part of the main frame above the rotary carriage ring (Fig. 4, b). The safety factor of the frame structure is 3.11 (Fig. 4, c), in the spring suspension systems – 14.89.

The results of the investigation of the stress-strain state of 2PTS-2 trailer frame according to the second calculation option are presented in Fig. 5. Maximum stresses of 85.12 MPa are observed in the spring suspension systems (Fig. 5, a). In the main frame, the maximum stresses are 77.58 MPa in the area of the second crossbar fastening. The maximum movements of 2.0 mm are observed in the front part of the drawbar (Fig. 5, b). The minimum safety factor of the frame structure is 2.84 (Fig. 5, c), the minimum safety factor of the spring suspension systems is 12.69

The results of the investigation of the stress-strain state of 2PTS-2 trailer frame according to the third calculation option are presented in Fig. 6. The maximum stresses of 115.90 MPa are observed in the crossbar of the upper belt of the trailer main frame at the point of the swivel ring fastening(Fig. 6, a). The maximum movements of 2.35 mm are observed in the transverse beam of the lower belt of the main frame (Fig. 6, b). The minimum safety factor of the frame structure is 1.9 (Fig. 6, c), the minimum safety factor of the spring suspension systems is 11.91.

The results of the investigation of the stress-strain state of 2PTS-2 trailer frame according to the fourth calculation option are presented in Fig. 7. Maximum stresses of 116.18 MPa are observed in the spring suspension systems (Fig. 7, a). In the main frame, the maximum stresses are 104.43 MPa in the front left body mounting bracket. Maximum movements of 2.12 mm are observed in the same bracket (Fig. 7, b). The minimum safety factor of the frame structure is equal to 2.11 (Fig. 7, c), the minimum safety factor of the spring suspension systems is 9.30.

The results of the investigation for all calculation options are summarized in Table 1.

Table 1

Modeling results of the stress-strain state of the load-bearing structure of 2PTS-2 trailer and the evaluation of safety factors according to stresses

	Option I		Option II		Option III		Option IV	
	frame	spring suspension systems	frame	spring suspension systems	frame	spring suspension systems	frame	spring suspension systems
Maximum movements, mm	1.27	–	2.0	–	2.35	–	2.12	–
Maximum stresses, MPa	70.97	70.52	77.58	85.12	115.90	90.69	104.43	116.18
Minimum safety factors	3.11	14.89	2.84	12.69	1.90	11.91	2.11	9.30

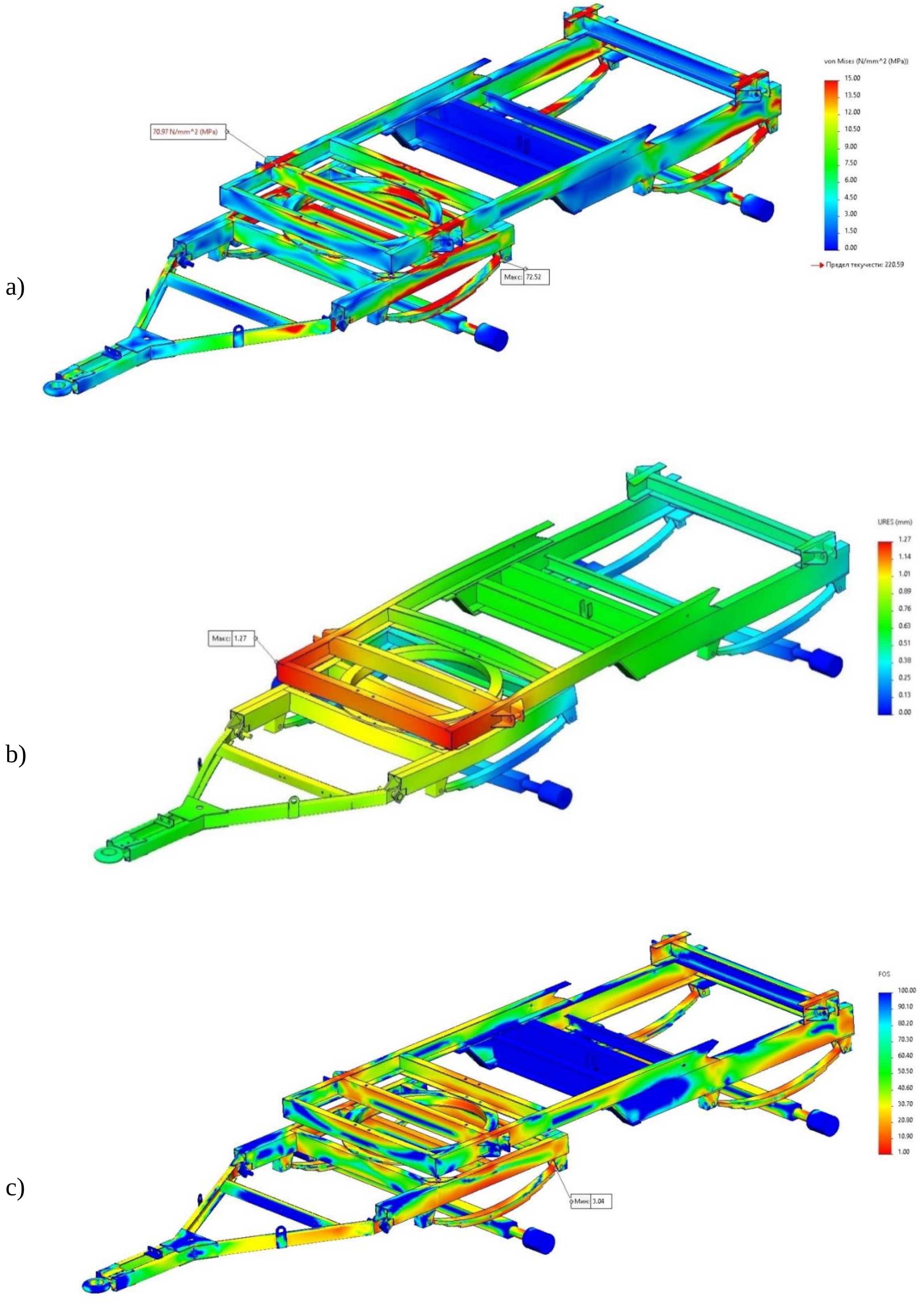

Figure 4. Modeling results of the stress-strain state of 2PTS-2 trailer frame according to option I:
a – stress state, b – strain state, c – safety factor

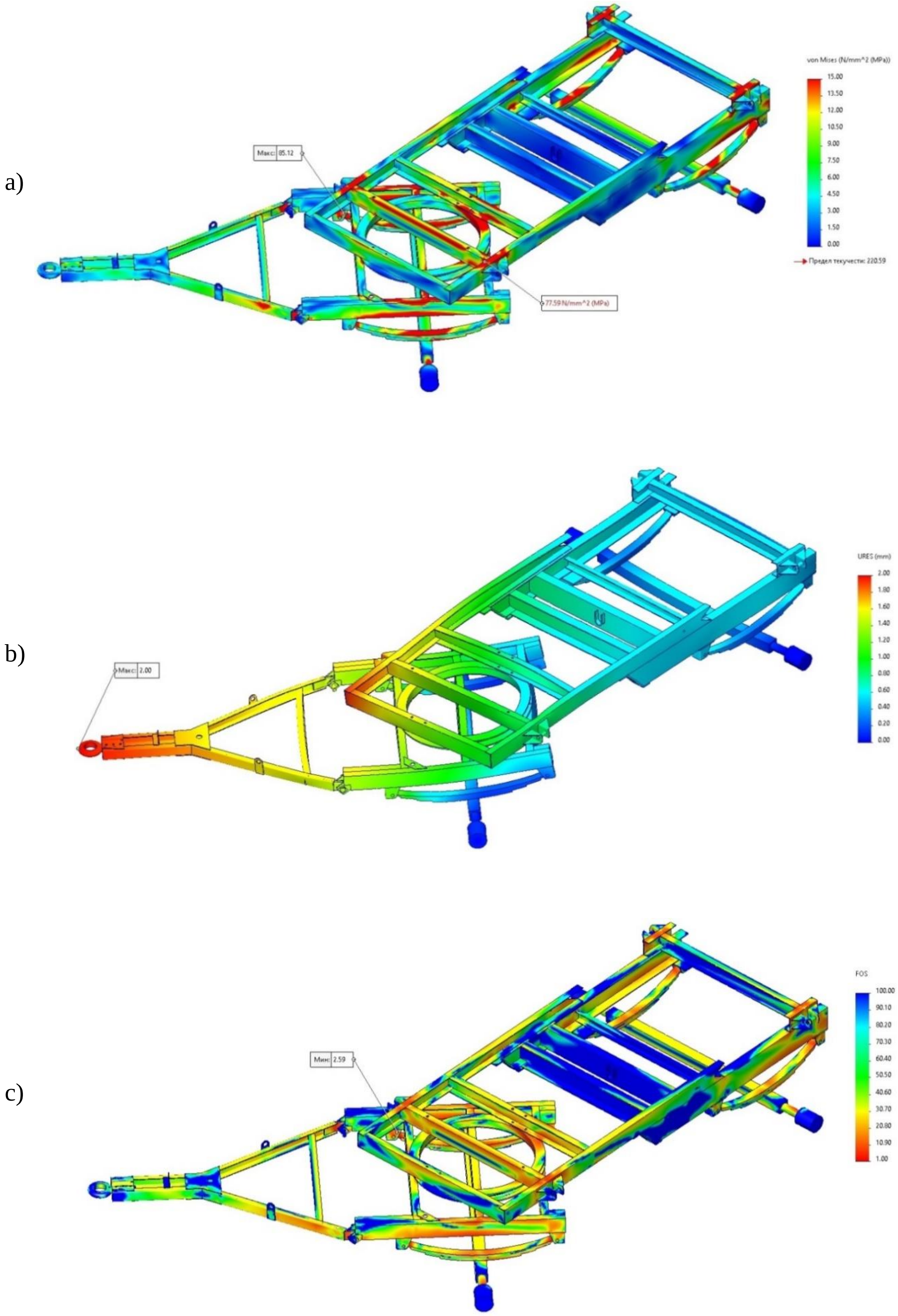

Figure 5. Modeling results of the stress-strain state of 2PTS-2 trailer frame according to option II: a – stress state, b – strain state, c – safety factor

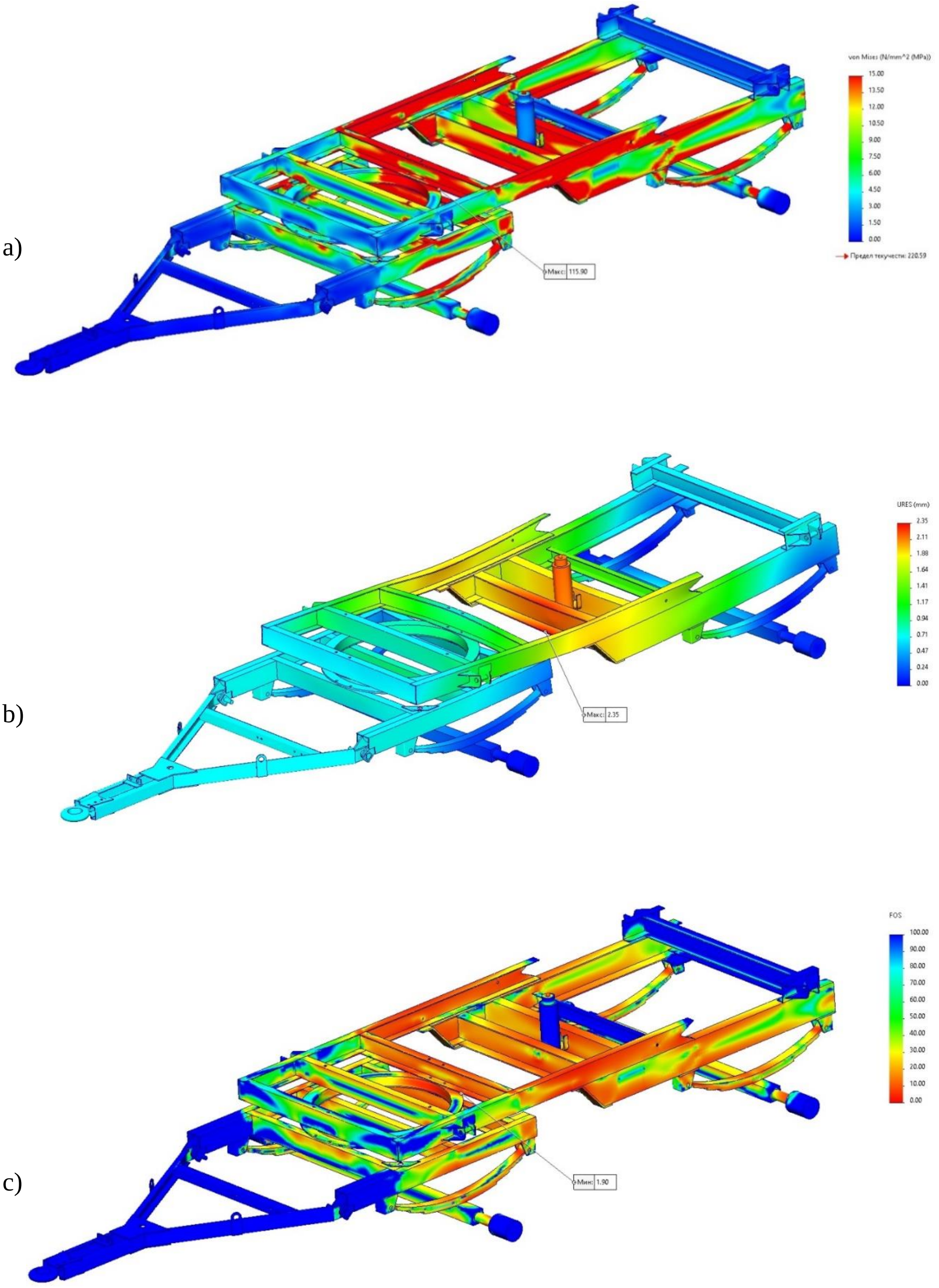

Figure 6. Modeling results of the stress-strain state of 2PTS-2 trailer frame according to option III:
a – stress state, b – strain state, c – safety factor

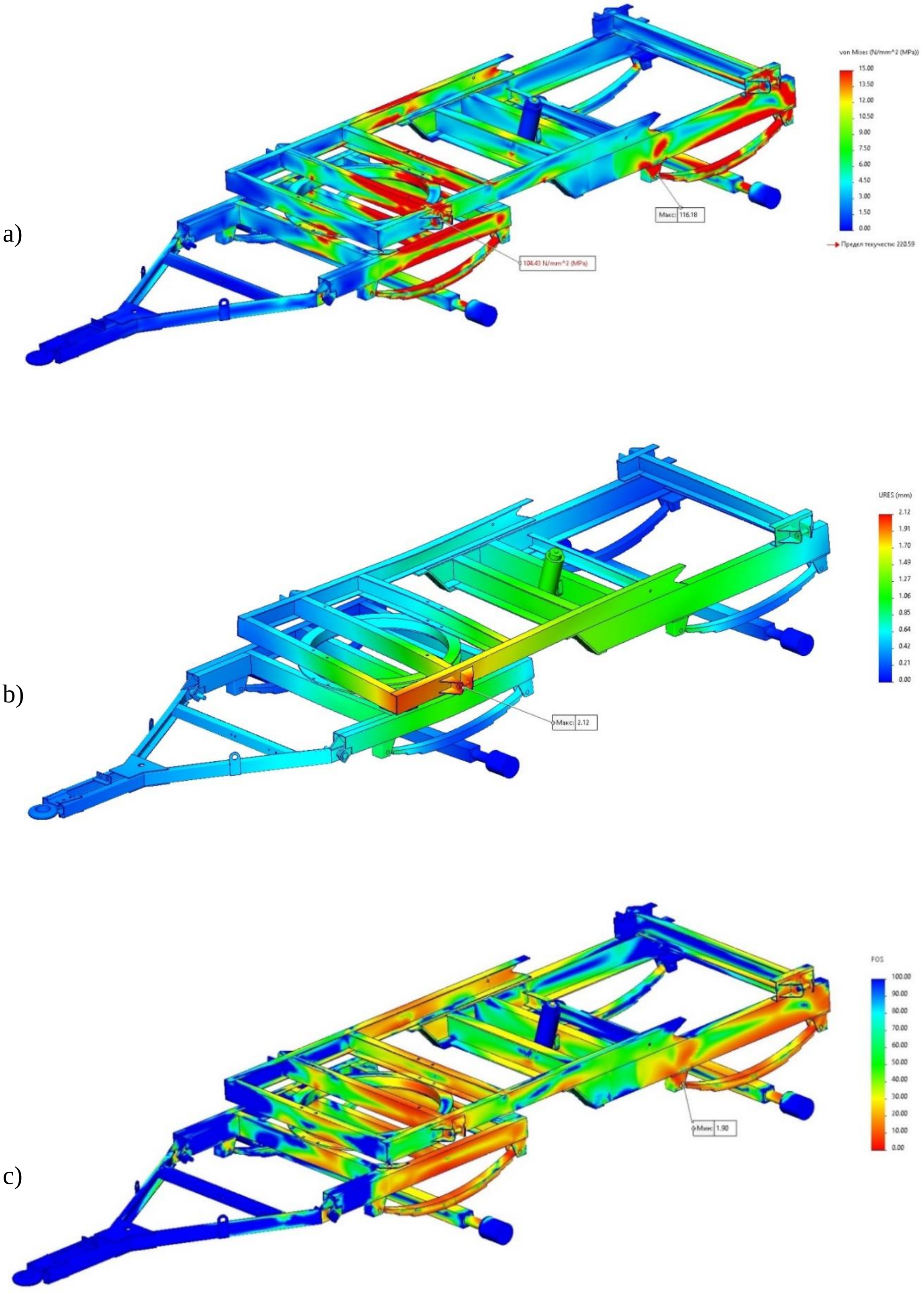

Figure 7. Modeling results of the stress-strain state of 2PTS-2 trailer frame according to option IV:
a – stress state, b – strain state, c – safety factor

Analysis of the obtained data shows that the stress values in the frame structure and trailer spring suspension systems differ insignificantly. However, the safety factors for stresses in the spring suspension systems are significantly smaller. This is explained by significantly higher values of the yield strength of spring steel 50XFA in comparison with steel St3sp, which is used in the manufacturing of load-bearing frame structure.

It should be noted that while considering the four investigated options for the frame structure loading, the options associated with unloading the cargo from the trailer where torque occur are the most dangerous. In this case, the smallest values of the minimum safety factors for stresses are 1.90 (for option III) and 2.11 (for option IV).

Conclusions. The finite-element analysis algorithm of the stress-strain state of 2PTS-2 trailer frame is implemented. The maximum stress values in the elements of the trailer load-bearing structure are obtained for various options of static load.

Analysis of the safety factor by stresses is carried out in order to take into account the uncertainty of the frame structure model and the uncertainties of the operational load. The obtained minimum safety factors by stresses 1.9 and 2.11 under trailer unloading conditions require a high level of reliability of the data regarding trailer unloading operating modes.

References

1. Algin V. B. Raschet mobilnoy tekhniki: kinematika. dinamika. resurs. Minsk: Belaruskaya navuka, 2014. 271 p. [In Russian].
2. Caban J., Nieoczym A., Gardyński L. Strength analysis of a container semi-truck frame. Engineering Failure Analysis. Vol. 127. 2021. 12 p. https://doi.org/10.1016/j.engfailanal.2021.105487
3. Pidgurskyi M., Ripetskyi Ye., Pidgurskyi I. Research and simulation of load modes in the evaluation of mobile machines resource. AIP Conference Proceedings. 2029. 020064. 2018. 7 p. https://doi.org/10.1063/1.5066526
4. Sen Zheng, Kai Cheng, Jixin Wang, Qingde Liao, Xiaoguang Liu, Weiwei Liu Failure analysis of frame crack on a wide-body mining dump truck. Vol. 48. 2015. P. 153–165. https://doi.org/10.1016/j.engfailanal.2014.11.013
5. Thangarasu V. S., Dhandapani N. V., Sureshkannan G. A study on fatigue failure analysis of an off-highway vehicle chassis. International Journal of Applied Engineering Research. Vol. 10. No. 71. 2015. P. 392–400.
6. Garud R. Y., Tamboli S. C., Pandey A. Structural Analysis of Automotive Chassis, Design Modification, and Optimization. International Journal of Applied Engineering Research. Vol. 13. No. 11. 2018. P. 9887–9892.
7. Madhu Ps., Venugopal T. R. Static Analysis, Design Modification and Modal Analysis of Structural Chassis Frame. Int. Journal of Engineering Research and Applications.Vol. 4. Issue 5. May 2014. P. 6–10.
8. Angga Kengkongan Ary, Yuwana Sanjaya, Aditya Rio Prabowo, Fitrian Imaduddin, Nur Azmah Binti Nordin, Iwan Istanto and Joung Hyung Cho. Numerical estimation of the torsional stiffness characteristics on urban Shell Eco-Marathon (SEM) vehicle design. Curved and Layered Structures. Vol. 8. No. 1. 2021. P. 167–180. https://doi.org/10.1515/cls-2021-0016
9. Ruslan Khakimzyanov, Anvar Togaev, and Aziz Rashidov The stress-strain state of the universal chassis of the tractor trailer in T-Flex. E3S Web of Conferences 264, 02008. 2021. 8 p. https://doi.org/10.1051/e3sconf/202126402008
10. Rybak T. I. Poshukove konstruiuvannia na bazi optymizatsii resursu mobilnykh silskohospodarskykh mashyn. Ternopil: Zbruch, 2003. 332 p. [In Ukrainian].
11. Eremenko S. Yu. Metody konechnykh elementov v mekhanike deformiruyemykh tel. Kharkov: Osnova. 1991. 272 p. [In Russian].
12. Matt Lombard Mastering SolidWorks. John Wiley & Sons, Inc., Indianapolis, Indiana, 2019. 1210 p. https://doi.org/10.1002/9781119516743

Список використаних джерел

1. Альгин В. Б. Расчет мобильной техники: кинематика, динамика, ресурс. Минск: Беларуская навука, 2014. 271 с.

2. Caban J., Nieoczym A., Gardyński L. Strength analysis of a container semi-truck frame. Engineering Failure Analysis. Vol. 127. 2021. 12 p. https://doi.org/10.1016/j.engfailanal.2021.105487
3. Pidgurskyi M., Ripetskyi Ye., Pidgurskyi I. Research and simulation of load modes in the evaluation of mobile machines resource. AIP Conference Proceedings. 2029. 020064. 2018. 7 p. https://doi.org/10.1063/1.5066526
4. Sen Zheng, Kai Cheng, Jixin Wang, Qingde Liao, Xiaoguang Liu, Weiwei Liu Failure analysis of frame crack on a wide-body mining dump truck. Vol. 48. 2015. P. 153–165. https://doi.org/10.1016/j.engfailanal.2014.11.013
5. Thangarasu V. S., Dhandapani N. V., Sureshkannan G. A study on fatigue failure analysis of an off-highway vehicle chassis. International Journal of Applied Engineering Research. Vol. 10. No. 71. 2015. P. 392–400.
6. Garud R. Y., Tamboli S. C., Pandey A. Structural Analysis of Automotive Chassis, Design Modification, and Optimization. International Journal of Applied Engineering Research. Vol. 13. No. 11. 2018. P. 9887–9892.
7. Madhu Ps., Venugopal T. R. Static Analysis, Design Modification and Modal Analysis of Structural Chassis Frame. Int. Journal of Engineering Research and Applications.Vol. 4. Issue 5. May 2014. P. 6–10.
8. Angga Kengkongan Ary, Yuwana Sanjaya, Aditya Rio Prabowo, Fitrian Imaduddin, Nur Azmah Binti Nordin, Iwan Istanto and Joung Hyung Cho. Numerical estimation of the torsional stiffness characteristics on urban Shell Eco-Marathon (SEM) vehicle design. Curved and Layered Structures. Vol. 8. No. 1. 2021. P. 167–180. https://doi.org/10.1515/cls-2021-0016
9. Ruslan Khakimzyanov, Anvar Togaev, and Aziz Rashidov The stress-strain state of the universal chassis of the tractor trailer in T-Flex. E3S Web of Conferences 264, 02008. 2021. 8 p. https://doi.org/10.1051/e3sconf/202126402008
10. Рибак Т. І. Пошукове конструювання на базі оптимізації ресурсу мобільних сількогосподарських машин. Тернопіль: Збруч, 2003. 332 с.
11. Еременко С. Ю. Методы конечных элементов в механике деформируемых тел. Харьков: Основа, 1991. 272 с.
12. Matt Lombard Mastering SolidWorks. John Wiley & Sons, Inc., Indianapolis, Indiana, 2019. 1210 p. https://doi.org/10.1002/9781119516743

УДК 631.373:519.6

АНАЛІЗ НАПРУЖЕНО-ДЕФОРМІВНОГО СТАНУ РАМИ ТРАНСПОРТНОГО ЗАСОБУ МЕТОДОМ СКІНЧЕНИХ ЕЛЕМЕНТІВ

Микола Сташків[1]; Іван Підгурський[1]; Олег Підлужний[1];
Микола Підгурський[1]; Михайло Левкович[1];
Руслан Скляров[1]; Андрій Мушак[2]

[1]Тернопільський національний технічний університет імені Івана Пулюя,
Тернопіль, Україна
[2]Західноукраїнський національний університет,
Тернопіль, Україна

Резюме. *Проведено аналіз несучих конструкцій транспортних засобів. Розглянуто особливості експлуатації транспортних засобів та їх несучих систем. Зазначено, що навантаження, які діють на конструкції, є змінними в часі; їх амплітудні та частотні характеристики залежать від експлуатаційного навантаження, швидкості руху транспортного засобу, стану дорожнього покриття та інших факторів. Це може спричинити високий рівень напружень у зонах конструкційних та технологічних концентраторів та призвести до виникнення у зазначених областях втомних тріщин і руйнування елементів рам. Проаналізовано методи досліджень експлуатаційних навантажень та напружено-деформівного стану рамних конструкцій при статичних та динамічних навантаженнях. Зазначено, що для реалізації статичного, модального, гармонічного та іншого виду аналізів рамних структур найбільш універсальним є метод скінчених елементів.*

Методом скінчених елементів проведено дослідження напружено-деформівного стану несучої конструкції причепа 2ПТС-2 за різних варіантів статичного навантаження. Розроблено повнорозмірну CAD-модель причепа та його скінчено-елементну модель за допомогою спеціалізованого програмного комплексу SolidWorks. Розрахунки напружено-деформівного стану рами причепа проведено для характерних видів навантажень: прямолінійного руху, непрямолінійного руху (повороту) та підіймання кузова з вантажем. Проведено аналіз коефіцієнтів запасу міцності за напруженнями для врахування невизначеностей моделі рамної конструкції та врахування невизначеностей експлуатаційного навантаження. Встановлено, що при розгляді досліджуваних варіантів навантаження рамної конструкції, найнебезпечнішими є ті, що пов'язані з розвантаженням вантажу, що вимагає подальшого детальнішого дослідження саме вказаних процесів.

Ключові слова: *причеп, рама, метод скінчених елементів, напружено-деформівний стан, напруження, деформації, переміщення, коефіцієнт запасу міцності.*

https://doi.org/10.33108/visnyk_tntu2022.04.089 *Отримано 19.12.2022*