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Analysis of stress state of passenger car bodies

The overwhelming majority of compartment cars owned by Ukrzaliznytsia JSC were manufactured in Germany in the 70-80s of the last century. They have exhausted their resource. The metal structures of the frame and body are badly worn. Extending the service life of such cars requires a thorough study of the possibilities of their further use. The article discusses the results of an analysis of the stress-strain state of passenger car bodies. A three-dimensional model of the body was built. Body strength calculations were performed using the finite element method using the ANSYS software package. The racks and upper trim of the side walls, roof arches, etc. were considered as rods. The body frame, substructure, side wall cladding, end walls, roof cladding and floor deck were modeled using plate finite elements. Calculations were carried out in accordance with the requirements of current regulatory documents. The maximum speed was assumed to be 160 km/h. The developed model was verified. The results obtained were compared with the results of experimental studies (strength tests). The similarity of the results confirmed the correctness of the created model. A study was carried out of the stress-strain state of the body at nominal sizes with standard skin thicknesses. It has been established that the stresses arising in the most loaded areas do not exceed the permissible values for structural steels. The resulting model of the body will subsequently make it possible to determine the wear limits of the load-bearing structures of the frame and body. It also allows, using the calculation-probabilistic method, taking into account the probabilistic nature of all existing loads, to calculate the reliability indicators of the car and its final life.

Key words: *passenger car, body, resource, wear, stresses.*

Introduction. Ukraine's movement into the European Union poses various challenges for the country's society and economy. But for railway transport, the primary task is the integration of domestic 1520 mm gauge railways into the European transport system [1].

This issue is especially relevant for ensuring passenger transportation. Passenger cars of JSC "Ukrzaliznytsia" were mainly inherited from the former USSR. The level of wear in the vast majority of cars exceeds 90%. The rolling stock primarily used by Ukrzaliznytsia is not only physically outdated but also morally obsolete.

But, in addition to physical wear and tear, passenger rolling stock is morally outdated and does not meet even the minimum requirements for comfort systems. The compartment width, fire safety system, ventilation system, toilets, and smoothness of movement do not meet European standards.To successfully compete with road transport, the railway must provide passengers with more comfortable conditions along the route, and the duration of a train trip should not exceed the time spent on a bus.

Passenger cars of the Kryukov Carriage Works fully comply with European sanitary standards and have improved design and comfort. However, the factory's production capacity and limited funding do not allow for the replacement of the entire fleet of passenger cars.

Another problem facing railway workers is ensuring the required speeds. To do this, it is necessary that the load-bearing elements of the body and frame comply with the requirements of current regulatory documents. Therefore, for cars that have already been in use for many years and have exhausted their service life, it is necessary to study the stress-strain state of the body and frame, taking into account wear.

The aging of the cars continues at a rapid pace, and it is not compensated by the arrival of new cars. Extending the service life of passenger cars through modernization, reconstruction, and modification is not a temporary measure but a fundamental requirement of market economic relations. However, while these cars still meet normative requirements in terms of passenger comfort, their operation is unacceptable in terms of ensuring safe movement due to a decrease and even loss of the body's load-bearing capacity.

Analysis of recent research and problem statement. A large number of studies have been devoted to increasing the strength and durability of passenger cars. Problems and prospects of passenger carriage construction are discussed in article [2]. Standard [3] contains structural and crashworthiness requirements for railroad passenger equipment of all types

The authors of article [4, 5] consider the technical condition of frames and bodies of passenger cars with a service life that exceeds the standard. A statistical analysis of the dependence of wear on the duration of operation for various types of cars was carried out.

The study [6] states that in conditions of systematic underfunding of the industry, carrying out overhaul repairs of passenger cars is a possible alternative to purchasing newly manufactured cars. At the same time, it is necessary to ensure the necessary level of strength, reliability and modern level of comfort.

Articles [7, 8] discuss possible options for organizing the repair and maintenance of passenger cars after major overhauls.

Works [9, 10] discuss the issues of reducing the weight of the body of a passenger car built by the Kryukov Carriage Plant, model 61-779. The authors built a three-dimensional computational model. Then, using the finite element method, strength calculations of the car body were performed.

Research [11, 12] is devoted to the analysis of the residual life of passenger cars, taking into account the strength of the bodies of open and compartment type cars.

In [13, 14], using the finite element method, a collision of a passenger car with a rigid wall was simulated. Structural weaknesses in the original design were identified. The authors assessed the accident rate and developed proposals for modernizing the passenger car.

A method to analyze the impact of design features of the integral scheme of passenger cars bodies on their stiffness and strength characteristics is proposed in [15].

Article [16] is devoted to the results of modeling the load of urban rail rolling stock. The calculations simulate various loading modes. The authors come to the conclusion that the resulting stresses are 75% of the permissible ones.

In this framework, the paper [17] proposes a new dynamic optimization approach to support the design of railway vehicle car bodies subject to static loads. The proposed methodology aims to minimize the mass of the metallic structure.

The purpose and tasks of the study. The purpose of this work is to study the effectiveness of improving the structures of the bodies of passenger cars that have exhausted their resource (the stress-strain state of compartment cars bodies that have exhausted their resource). To do this, it is necessary to build a calculated 3D model of the body and frame of the 47D car without a spinal beam in the middle part and, using the finite element method, determine the stress-strain state of the load-bearing elements of the body and frame, taking into account possible wear and tear in operation.

Materials and methods of research. The finite element method (FEM) is currently a fundamental method for solving solid mechanics problems using numerical algorithms. The method is based on discretization of the object in order to solve the equations of continuum mechanics under the assumption that these relationships are satisfied within each of the elementary regions. These areas are called finite elements. They can correspond to a real part of space or be a mathematical abstraction, like the elements of rods, beams, plates and shells. Within the finite element, the properties of the area of the object limited by it are assigned (this could be, for example, characteristics of the rigidity and strength of the material, density, etc.) and the fields of quantities of interest are described (in relation to solid body mechanics, these are displacements, deformations, stresses, etc.). d.). Parameters from the second group are assigned at the nodes of the element, and then interpolating functions are introduced, through which the corresponding values can be calculated at any point inside the element or on its boundary. The task of a mathematical description comes down to connecting the factors acting at the nodes. In continuum mechanics, these are, as a rule, displacements and forces.

The problem of determining the displacement field in the design of an axle box unit can be reduced to the problem of minimizing the total potential energy based on nodal displacements,

Body strength calculations were performed using the finite element method using the ANSYS software package in accordance with the requirements of DSTU [18]. The body was considered as a system of rod and plate finite elements. The calculation scheme is shown in Fig. 1 and in Fig. 2.

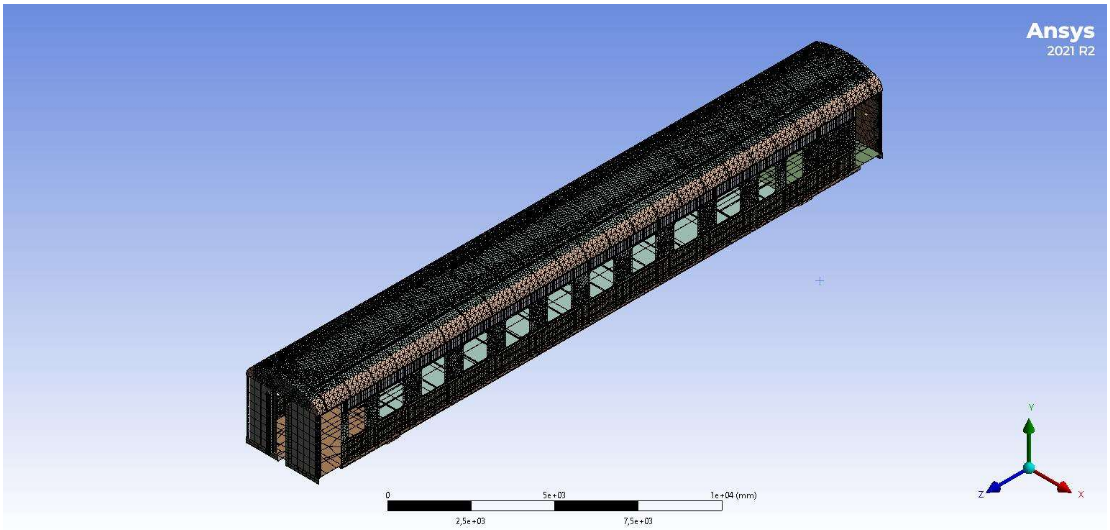

Fig. 1. **Passenger car 47Д body model**

As the rods, the racks and upper strapping of the side walls, roof arches, etc. were considered. The body frame, lower trim, side wall cladding, end walls, roof cladding and flooring were modeled using plate finite elements.

Rod finite elements work in tension (compression), bending, torsion and displacement. Flat finite elements work for bending (like plates) and for stretching (compression) under the action of forces whose lines of action lie in the middle plane.

In total, the design scheme contains 1,659,958 nodes and 722,470 finite elements.

Normative documents [18] provide for the need for calculations according to three calculation modes:

- I calculation mode corresponds to touching from a place, emergency braking at low speeds, collision during maneuvering, etc.;
- II calculation mode - train movement on the calculation climb (for passenger cars when they are included in freight trains);
- III calculation mode - movement with design speed and adjustable braking.

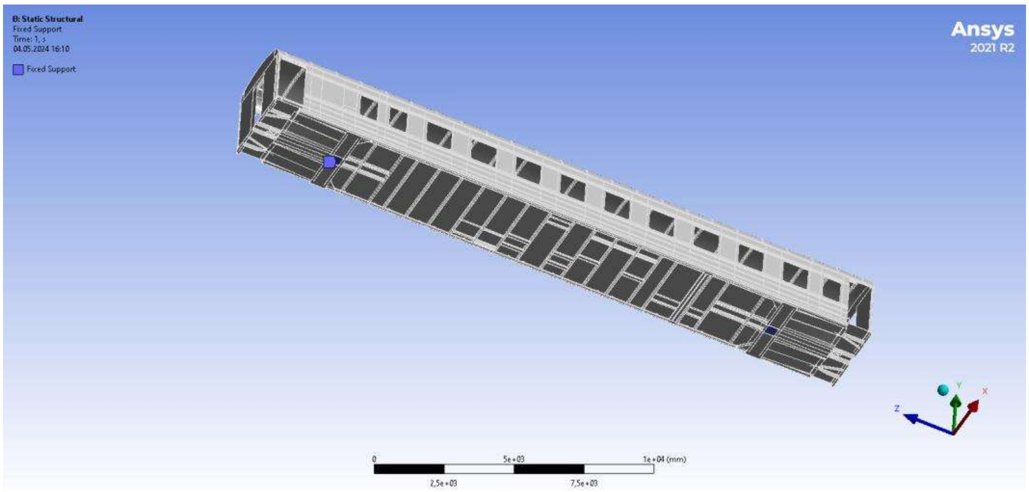

Fig. 2. **Passenger car 47D frame model**

Each of these calculation modes corresponds to a combination of loads that are added to the car body. Three groups can be distinguished: about longitudinal, vertical and lateral loads. Below is a description of each group.

Longitudinal loads are the longitudinal tensile or compressive force applied to the front or rear gussets, respectively. When calculating according to mode I, a compressive force of 2.5 MN is applied, mode II is not considered by the authors, when calculating according to mode III, the strength of the body is separately evaluated both under the action of a tensile force of 1 MN and under the action of a compressive force of the same magnitude (the case is considered action of a stretching force).

The group of vertical loads is formed by the gravity of the car body, the gravity of the internal equipment, equipment and passengers with luggage. This group, in addition to the static loads listed above, also includes additional dynamic components caused by the acceleration of the body in the vertical direction during the carriage movement.

The force of gravity Q acting on the car body is equal to the difference between the gross weight of the car and the weight of the trolleys. During the calculations, the car body was initially loaded by the force of gravity acting on the body's metal structure and by the gravity of large equipment units. A force equal to the difference between Q and the weight of the metalwork and equipment was applied to a uniformly distributed load acting on the floor of the car (Fig. 3).

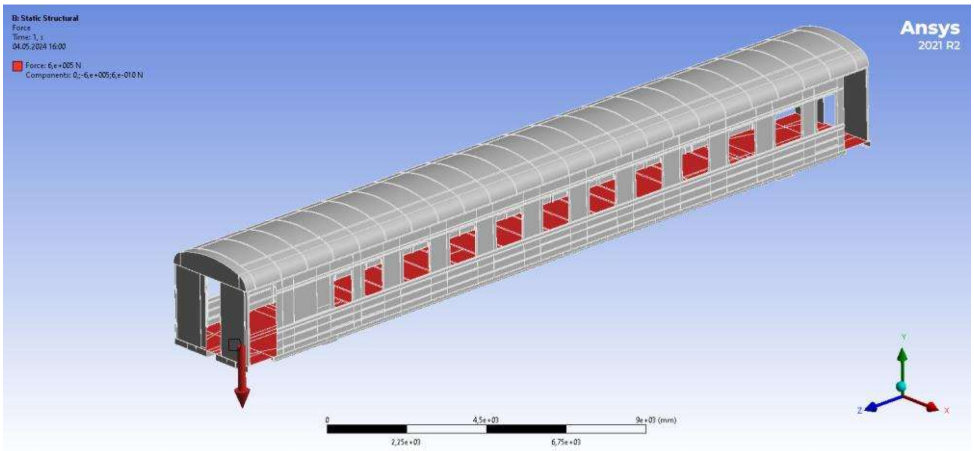

Fig. 3. **Scheme of application of a vertical load on the body of a passenger car**

When calculating according to the I mode, only the vertical static load is taken into account. When calculating according to mode III, the dynamic component is also taken into account by multiplying the static load by a factor $1 + k_{dv}$, where k_{dv} – calculated value of the coefficient of vertical dynamics for the car body.

The value k_{dv} is calculated according to known formulas [18].

$$k_{dv} = \overline{k}_{dv} \sqrt{\frac{4}{\pi} ln \frac{1}{1 - P(k_{dv})}}, \tag{1}$$

where $\overline{k}_{dv}$ is the average value of the vertical dynamics coefficient (mathematical expectation of the random process of changing the vertical dynamics coefficient $k_{dv}(t)$;
$P(k_{dv})$ – confidence probability. It is equal to $P(k_{dv})$=0.97.

The average value of the vertical dynamics coefficient $\overline{k}_{dv}$ визначається за наступною формулою

$$\overline{k}_{dv} = a + 3{,}6 \cdot 10^{-4} \cdot b \frac{V - 15}{f_{ст}}, \tag{2}$$

where a is an empirical coefficient, which for car bodies is equal to a=0.05;
b – coefficient depending on the number of axles in the cart (for biaxial carts b is equal to 1);
f_{st} – static deflection of spring suspension ($f_{st} = 0{,}15\ v$);
V – speed of movement in m/s.

During the calculations, it was assumed that the car moves at a maximum speed of 160 km/h and the third calculation mode is used.

Thus, for movement at a speed of 44.4 m/s, the average value of the coefficient of vertical dynamics $\overline{k}_{dv}$ was

$$\overline{k}_{dv} = 0{,}05 + 3{,}6 \cdot 10^{-4} \cdot 1 \frac{44{,}4 - 15}{0{,}15} = 0{,}121$$

$$k_{дв} = 0{,}121 \sqrt{\frac{4}{3{,}14} ln \frac{1}{1 - 0{,}97}} = 0{,}25.$$

The action of the lateral load should be taken into account only when calculating according to mode III. The force, which is equal to the difference of the centrifugal force and the horizontal component of the gravity force, which arises as a result of the elevation of the outer rail, for passenger cars is 10% of the gross force of gravity, i.e. 61 kN. Also taken into account is the force of wind pressure, which divides the area of the side projection of the body by the specific wind pressure (500 N/m^2), which for this car is equal to 38.6 kN. Thus, the total lateral load will be 99.6 kN. It is applied to the upper and lower lining of the side walls.

When carrying out calculations, two options for applying loads were considered. The first option corresponds to the I calculation mode, the second option – to the III calculation mode at a speed of 160 km/h.

The following options for changing the design and parameters of the body were considered:

– the thickness of the sheathing of the side walls and roof is 2.5 mm;
– the thickness of the sheathing of the side walls and roof is 2 mm;
– the thickness of the sheathing of the side walls and roof is 1.5 mm;

The developed model was verified. At the first stage, the calculation of the body with standard skin thicknesses was carried out. The obtained results were compared with the results of experimental studies (strength tests). The similarity of the results confirmed the correctness of the created model.

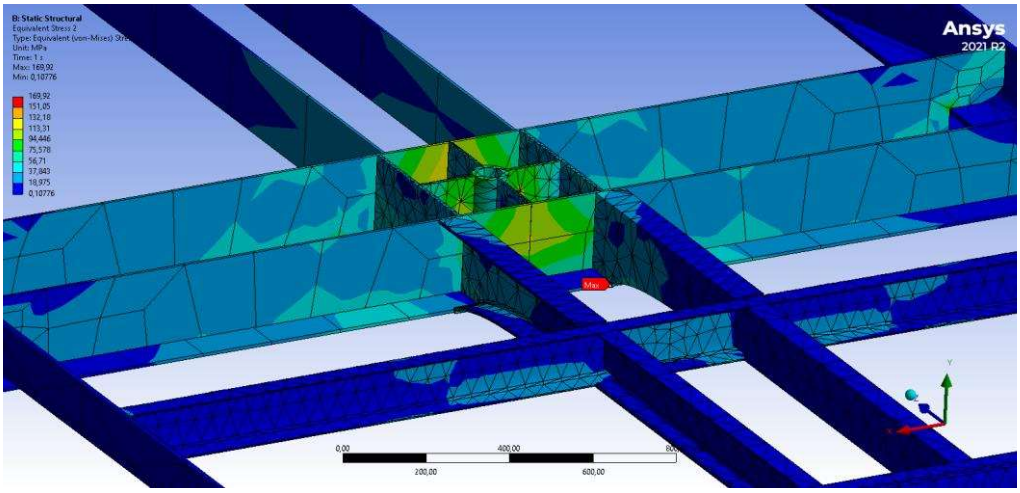

Fig. 4. **Diagram of stress distribution in the frame pivot assembly**

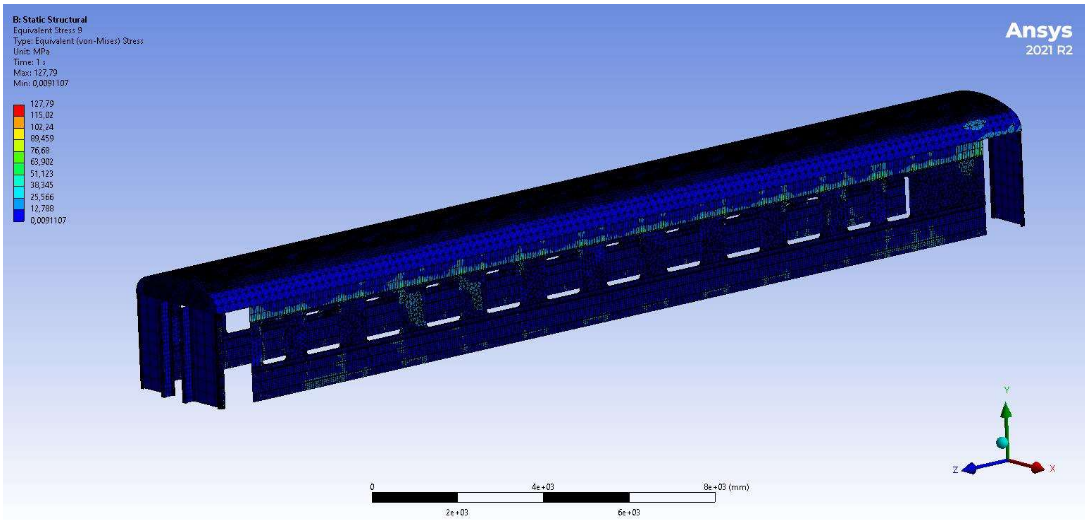

Fig. 5. **Diagram of stress distribution in the body of passenger car**

It has been established that the most loaded part of the structure is the thrust bearing unit. The maximum stress in the frame occurs at the junction of the pivot and center beams. When calculated according to 3 calculation mode, it reaches a value of 203 MPa.

The greatest stress in the body occurs in the upper corners of window openings, which are natural stress concentrators. With a sheathing thickness of 2.5 mm, it is 114 MPa. When the sheathing thickness is reduced to 1.5 mm, the stress increases to 178 MPa.

In the area above the window openings at the boiler end, when calculated according to 3 calculation mode , the maximum stress was 105 MPa with a sheathing thickness of 2.5 mm. When the sheathing thickness is reduced to 1.5 mm, the stress increases to 171 MPa, which is acceptable for the 09G2Kh steel grade used.

The dependences of stress on thickness are presented in Fig. 6 and 7.

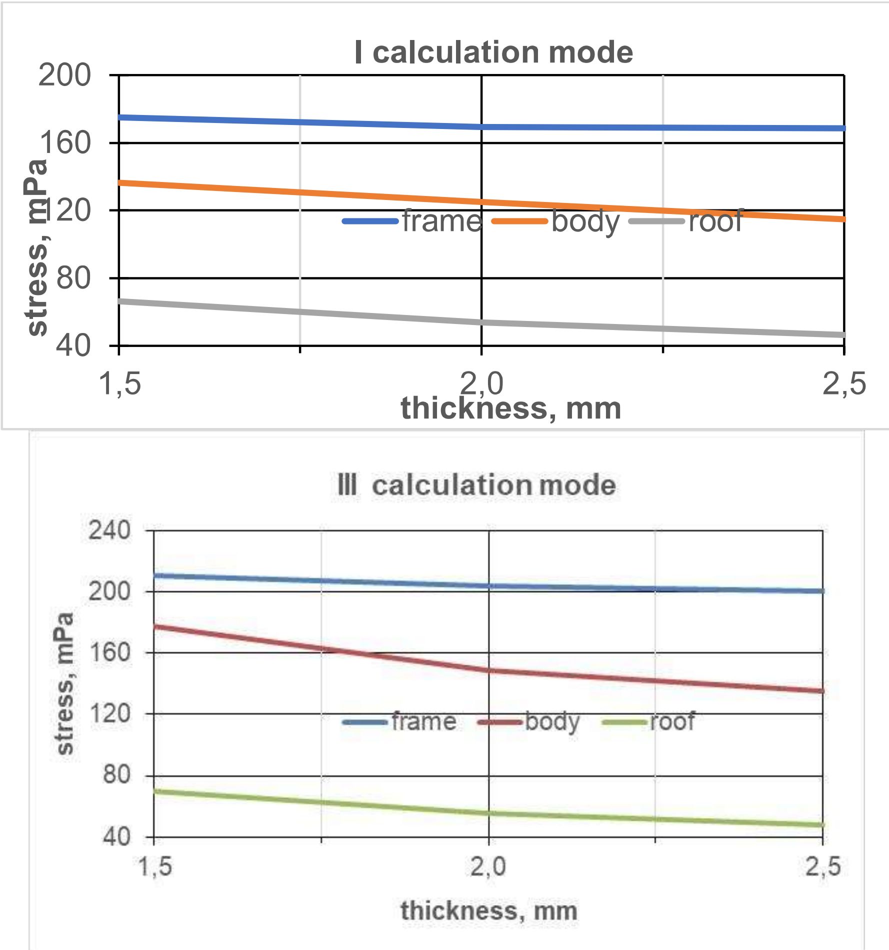

Fig. 6. **Diagram of stress distribution in the body of passenger car (speed 160 km/h)**

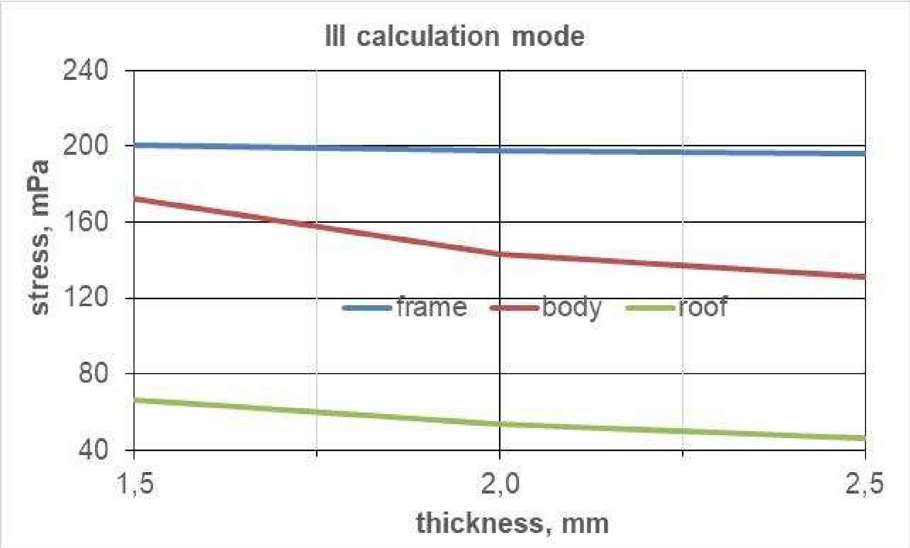

Fig. 7. **Diagram of stress distribution in the body of passenger car (speed 120 km/h)**

Analyzing the obtained dependencies, we can conclude that such body elements as the frame, roof and end walls, regardless of the design mode, have a sufficient margin of safety.

Thus, based on the results obtained, it can be concluded that the decrease body skin thickness up to 2 mm is significant does not affect the stress-strain joint standing.

The proposed option for reducing metal containers of the car body structure together with other activities will increase travel speed, reduce electrical consumption energy for traction and thereby increase the technical economic characteristics of passenger car.

Conclusion:

1. A finite element model of the body of a rigid compartment car 47D has been constructed. Beam and plate finite elements were used for modeling.
2. A study of the stress-strain state of the body at nominal dimensions with standard sheathing thicknesses was conducted. It was found that the stress occurring in the most loaded areas do not exceed the permissible values for structural steels.
3. The obtained body model will further allow determining the limit values of wear for the load-bearing structures of the frame and body and calculating, by probabilistic methods considering the probabilistic nature of all acting loads, the reliability indicators of the car and its ultimate service life.

REFERENCES

1. Kirpa, G. M. (2003) Intehratsiya zaliznychnoho transportu Ukrayiny u yevropeys′ku transportnu systemu: Monohrafiya. *Art-Pres*, 268 p. [in Ukrainian].

2. Loboyko, L. M. (2006) Problemy i perspektivy pasazhirskogo vagonostroyeniya v Ukraine. *Zaliznychnyy transport Ukrayiny,. 3*, 3-9. [in Ukrainian].

3. Design and Construction of Passenger Railroad Rolling Stock. *STANDARD American Public Transportation Association. APTA PR-CS-S-034-99, Rev. 3*, 2020.

4. Martynov, I. E., Trufanova, A. V., Petukhov, V. M., & Sergienko, M. O. (2019). Doslidzhennya zalezhnostey spratsyuvannya nesuchykh elementiv pasazhyrs′kykh vahoniv. *Zbirnyk naukovykh prats′ Derzhavnoho universytetu infrastruktury ta tekhnolohiy Ministerstva osvity i nauky Ukrayiny: Seriya "Transportni systemy i tekhnolohiyi, 36*, 72-81 [in Ukrainian].

5. Martynov, I. E, Trufanova, A. V, Pavlenko, Yu. S., & Sergienko, M. O. (2018) Analiz tekhnichnoho stanu kuzoviv pasazhyrs′kykh vahoniv. *Visnyk Natsionalnoho tekhnichnoho universytetu "KHPI". Seriya: Novi rishennya v suchasnykh tekhnolohiyakh. Transportne mashynobuduvannya, 45*(*1321*), 41-46 [in Ukrainian].

6. Yezhov, Y. V., Pavlenko, Yu. S., Voytenko, O. I., & Rechkalov, V. S. (2018) Kapital′no-vidnovlyuval′nyy remont pasazhyrs′kykh vahoniv lokomotyvnoyi tyahy yak zasib zabezpechennya zaliznyts′ reykovym rukhomym skladom. *Zbirnyk naukovykh prats "Reikovyi rukhomyi sklad",17*, 51-61 [in Ukrainian].

7. Barash, Yu. S. (2006) Stratehiya ratsional′noho onovlennya pasazhyrs′koho vahonnoho parku v umovakh de-fitsytu investytsiy. *Visnyk Dnipropetrovs'koho natsional'noho universytetu zaliznychnoho transportu imeni akademika V. Lazaryana, 10*, 130-140 [in Ukrainian].

8. Ostapyuk, B. Ya. (2004) Podovzhennya terminu eksplua-tatsiyi pasazhyrs′kykh vahoniv. *Visnyk Dnipropetrovs'koho natsional'noho universytetu zaliznychnoho transportu imeni akademika V. Lazaryana*, *4*, 165-173 [in Ukrainian].

9. Myamlin, S. V., Yahoda, P. A., Dedayeva, T. A., & Shkabrov, O. (2006). Snizheniye vesa metallokonstruktsii passazhirskikh vagonov dlya skorostnykh perevozok. *Nauka ta prohres transportu, 13,* 118-120 [in Ukrainian].

10. Prikhod'ko, V. I., Shkabrov, O. A, Myamlin, D. V., & Yagoda, P. A. (2007) Sovershenstvovaniye konstruktsii kuzovov passazhirskikh vagonov dlya skorostnykh perevozok. *Visnyk Dnipropetrovs'koho natsional'noho universytetu zaliznychnoho transportu imeni akademika V. Lazaryana, 14*, 152-156. [in Ukrainian]. https://doi.org/10.15802/stp2007/17870.

11. Pullaria, A. L., Loboyko, L. M., & Grichany, M. A. (2008) Vyznachennya mitsnosnykh yakostey kuzova pasazhyrs′koho vahona pislya KVR. *Zbirnyk naukovykh prats' Donets'koho instytutu zaliznychnoho transport – Collection of scientific works Donetsk Institute of Railway Transport*, *13*. 107-111 [in Ukrainian].

12. Shykunov, O. A., Reydemeyster O. H., & Anofriiev V. H. (2012). Doslidzhennya hranychnoho stanu pasazhyrs′kykh vahoniv. Vahonnyy park, 12, 4-6 [in Ukrainian].

13. Baykasoglu, C., Sunbuloglu, E., Bozdag, S. E., Aruk, F., Toprak, T., & Mugan, A. (2012, April). Numerical static and dynamic stress analysis on railway passenger and freight car models. In *International Iron & Steel Symposium*(pp. 579–586).

14. Baykasoğlu, C., Sünbüloğlu, E., Bozdağ, S. E., Aruk, F., Toprak, T., & Mugan, A. (2011). Railroad passenger car collision analysis and modifications for improved crashworthiness. *International Journal of Crashworthiness*, *16*(3), 319-329. https://doi.org/10.1080/13588265.2011.566475.

15. Ashurkova, S. N., Kobishchanov, V. V., & Kolchina, E. V. (2017). Methods used to analyze the impact of passenger cars bodies design features on their stiffness and strength characteristics. *Procedia Engineering*, *206*, 1623-1628. https://doi.org/10.1016/j.proeng.2017.10.688.

16. Wirawan, W. A., Wijaya, F. P., Atmaja, D. S., Rozaq, F., Bagaskara, A. S., & Pamungkas, F. P. (2023, March). Modelling and Structural Analysis of Tram Railway Vehicle Body with Finite Element Method. In *International Conference on Railway and Transportation (ICORT 2022)* (pp. 258-267). Atlantis Press. https://doi.org/10.2991/978-94-6463-126-5_27.

17. Cascino, A., Meli, E., & Rindi, A. (2023). Dynamic size optimization approach to support railway carbody lightweight design process. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, *237*(7), 871-881. https://doi.org/10.1177/09544097221140933.

18. DSTU 7774:2015. Vahony pasazhyrs′ki mahistral′ni lokomotyvnoyi tyahy. Zahal′notekhnichni normy dlya rozrakhuvannya ta proektuvannya mekhanichnoyi chastyny vahoniv. – Chynnyy vid 2016-04-01. – K.: Minekonomrozvytku Ukrayiny, 2017 [in Ukrainian].

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Аналіз напруженого стану кузовів пасажирських вагонів

Переважна частина купейних вагонів власності АТ Укрзалізниця була виготовлена у Німеччині у 70-80-х роках минулого століття. Вони вичерпали власний ресурс. Металоконструкції рами та кузова сильно зношені. Продовження терміну служби таких вагонів потребує ретельного вивчення можливостей їхнього подальшого використання. У статті розглянуто результати аналізу напружено-деформованого стану кузовів пасажирських вагонів. Побудовано тривимірну модель кузова. Розрахунки кузова на міцність виконувались методом скінчених елементів за допомогою програмного комплексу ANSYS. Як стрижні розглядалися стояки та верхня обв'язка бічних стін, дуги даху і т. д. Рама кузова, нижня обв'язка, обшивка бічних стін, торцеві стіни, обшивка даху та настил підлог моделювалися за допомогою пластинчастих скінчених елементів. Розрахунки проводилися відповідно до вимог чинних нормативних документів. Максимальна швидкість руху приймалася рівною 160 км/год. Було здійснено верифікацію *розробленої моделі. Отримані результати порівнювали з результатами експериментальних досліджень (випробувань міцності). Подібність результатів підтвердила правильність створеної моделі. Проведено дослідження напружено деформованого стану кузова при номінальних розмірах зі стандартними товщинами обшиви. Встановлено, що напруги, що виникають у найбільш навантажених місцях, не перевищують допустимі значення конструкційних сталей. Отримана модель кузова надалі дозволить визначати граничні величини зношування несучих конструкцій рами і кузова і розраховувати розрахунково-імовірнісним методом з урахуванням імовірнісного характеру всіх навантажень, що діють, показники надійності вагона і його остаточний ресурс.*

Ключові слова: *пасажирський вагон, кузов, ресурс, спрацювання, напруження.*