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This study considers processes resulting in the occurrence and acceptance of loads by the body of a passenger railroad car with a girdle beam under operational conditions. The task addressed is to improve the strength indicators of the girdle beam in a passenger car.

To improve the strength of the frame of a passenger car, it is proposed to introduce a C-shaped profile with perforation as a profile for the girdle beam. The mass of the girdle beam using the proposed profile will decrease by more than 20%. At the same time, the moment of resistance of the cross-section of the girdle beam will increase by almost 14%.

To substantiate such an implementation, a calculation was performed for the strength of the body of a passenger car under the main modes of its loading during operation. It was established that the maximum stresses arising in the girdle beam under the most unfavorable loading scheme are lower than the permissible ones by 20.5%. Under other design loading conditions of the body, the strength of its structure is also maintained. As part of the study, a modal analysis of the passenger car body was conducted. The calculations showed that traffic safety from the point of view of modal analysis is observed.

A feature of the proposed improvement of the passenger car body is that it does not complicate the maintenance and repair of the car using the existing base.

The scope of practical use of the results is railroad transport.

The condition for using the research results is compliance with periodic maintenance of the passenger car body during operation.

The study reported here will contribute to compiling recommendations for the design of new passenger car structures with improved technical and economic indicators

Keywords: *railroad transport, passenger car, body improvement, girdle beam, body strength*

IDENTIFYING REGULARITIES IN THE STRENGTH INDICATORS OF A PASSENGER RAILROAD CAR BODY DEPENDING ON THE USE OF A C-SHAPED PROFILE WITH PERFORATION IN THE GIRDLE BEAM

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1. Introduction

Passenger transportation is an important component of rail transport. For passenger transportation by rail, a wide variety of types of cars are used in terms of their structural features, which is due to the distance of passengers following the given route. The evolution of passenger transportation is constantly accelerating. Currently, they operate not only

within European countries but also have international connections between some of them [1, 2].

Along with the positive experience of operating passenger transportation, it is necessary to note issues that require a solution to maintain the further efficiency of their operation. Passenger cars with a gauge of 1520 mm have a body length beyond the end beams of the frame of more than 20 m. This circumstance causes the generation of natural body vibra-

tions when perceiving external loads, including cyclic ones. Long-term operation of the structure under the influence of such loads causes the accumulation of stresses in the structural components, which can contribute to its damage on the way. Such damage is especially dangerous for the girdle beam of a passenger car body as the main load-bearing element of the structure. Its damage not only necessitates the uncoupling of the car from the train but may also pose a threat to the occurrence of accidents or catastrophes. This, in turn, can lead to damage to vehicles, the rail track [3], as well as the death of people.

Therefore, it is a relevant task to carry out studies aimed at devising solutions that would help improve the strength of the passenger car body by improving the design of the girdle beam.

2. Literature review and problem statement

To elucidate the current state of the issue related to designing and improving passenger car bodies, an analysis of scientific publications was conducted. In work [4], the features of the application of modern numerical analysis methods in determining the strength of cars are highlighted. The results of computer simulation of the strength of car bodies are reported, confirmed by experimental studies. The work certainly has scientific value. However, the authors did not propose solutions to improve the strength indicators of car bodies during operation. This probably can be explained by the fact that the authors saw the development of these issues in their subsequent studies.

In [5], the issue of improving the passenger car frame by using a beam with a corrugated wall as a profile for the execution of the girdle beam is highlighted. It is proven that such an implementation helps reduce the weight of the car frame while ensuring its strength. However, the use of such beams in the frame causes difficulties with the installation of the auto-coupling device; therefore, additional solutions are required to adapt the cantilever parts of the frame to interact with the auto-coupling stops. The cited paper set the task of justifying the feasibility of using beams with a corrugated wall in the frame structure. That is why the authors did not conduct research on the placement of automatic coupling devices on it.

The features of impact tests of a passenger car are highlighted in work [6]. The authors conducted research on a full-scale car. Based on the results of those studies, recommendations were compiled on safe operating conditions for passenger cars. However, no solutions were proposed to improve the most loaded components of the frame during operation. Perhaps the authors set themselves the task of identifying the areas of greatest stress concentration in the body and, subsequently, devising solutions aimed at improving its strength.

A similar drawback is inherent in work [7]. It presents the features of constructing a computer model that makes it possible to predict the strength indicators in collisions of passenger cars. The study was conducted using the finite element method. The results allowed the authors to derive recommendations for improving traffic safety. They did not consider the possibility of improving the car frame. They probably saw this as a further development of their study.

The features of the concept of designing bodies of railroad vehicles are highlighted in paper [8]. The authors proposed using standard thin-walled profiles in the structures of the frames. The feasibility of this idea was confirmed by the results of theoretical studies. At the same time, the authors

did not consider the possibility of applying this concept to passenger car bodies. This may be due to the fact that they focused their attention on freight vehicles, since they experience greater loads during operation.

Work [9] reports a study on the main quality indicators of modern passenger car structures. The smoothness of the car movement was chosen as the controlled parameter. The calculation of the parameters of the passenger car movement is presented using the example of the 61-920 model. The disadvantage of the work is that the authors did not propose solutions aimed at improving the safety of passenger car movement. This is due to the fact that the authors set themselves the task of assessing the smoothness of the car movement.

In [10], a solution was proposed to improve the strength of the passenger car frame by using energy-absorbing material in the girdle beam. The results of the theoretical calculations confirmed the feasibility of such a solution as the frame strength indicators have better values than those of a typical design. However, such an implementation requires significant capital investment, which hinders its serial implementation.

In [11], a study on the impact of the environment on the technical condition of passenger car bodies was reported. The main structural elements that are subject to the greatest corrosion impact were identified. The degree of corrosion of the car body components was studied. However, no solutions were proposed aimed at improving the bodies in order to reduce the corrosion impact. This may be due to the fact that the author set a goal – to determine the residual resource of the bodies, and in subsequent studies it was planned to devise appropriate measures to improve their structures.

Our review of the literature [4–11] allows us to conclude that up to now the issue of improving passenger car bodies in order to improve their strength indicators has not been given due attention. In this regard, there is a need to conduct appropriate research in this area.

3. The aim and objectives of the study

The purpose of our study is to identify patterns in the strength indicators of the passenger car body depending on the use of a C-shaped profile with perforation in the frame girdle beam. This will allow us to improve the strength of the passenger car body and, accordingly, reduce the cost of its operation.

This goal was achieved by solving the following tasks:

- to calculate the strength of the passenger car body with a girdle beam made of a C-shaped profile with perforation;
- to conduct a modal analysis of the passenger car body.

4. The study materials and methods

The object of our study is the processes of occurrence and acceptance of loads by the body of a passenger car with a girdle beam under operational modes.

The principal hypothesis of the study assumes that the use of a C-shaped profile with perforation as the profile of the girdle beam could contribute to the reduction of its tare while maintaining the conditions of operational strength.

To improve the strength of the passenger car frame, it is proposed to introduce a C-shaped profile with perforation as the profile of the girdle beam (Fig. 1).

The use of such a profile has a number of advantages compared to the typical one, namely, reducing the mass of the girdle beam and improving the moment of resistance of its cross section (Table 1).

Table 1

Comparative analysis of girdle beam profiles

Weight of 1 linear meter, kg		Moment of resistance of the cross section, cm ³	
Channel No. 30	C-shaped profile with perforation	Channel No. 30	C-shaped profile with perforation
68.3	49.53	774	898.4

Analyzing the data given in Table 1, it can be concluded that the mass of the girdle beam using the proposed profile will decrease by more than 20%. At the same time, the moment of resistance of the cross-section of the girdle beam will increase by almost 14%.

To substantiate the proposed implementation, a spatial model of a rigid passenger car body was built (Fig. 2); corresponding strength calculations were performed. The spatial model was built in the SolidWorks software package (France). When building the spatial model of the passenger car body, welds between its components were not taken into account. This is the main simplification of this model. When building it, the nominal dimensions of the body components were taken into account.

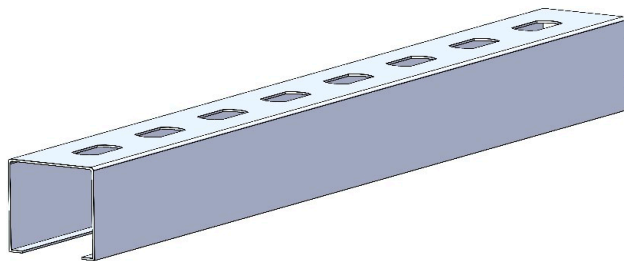


Fig. 1. C-shaped profile with perforation

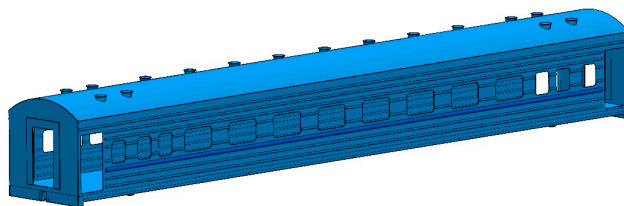


Fig. 2. Spatial model of a passenger car body

The strength calculation was performed in SolidWorks Simulation (France) using the finite element method [12, 13]. This choice of method can be justified by the fact that it is the most common not only in mechanical engineering [14, 15] but also in other transport industries [16, 17]. The mesh was constructed using tetrahedra (Fig. 3). The optimal number of mesh elements was determined graphically with a check of their sensitivity [18, 19]. Taking this into account, the model has 487921 elements and 169816 nodes. The largest element size in the mesh is 80 mm, and the smallest is 16 mm.

The body support on the bogies was modeled by setting rigid connections on the sliders. That is, the friction forces between the body sliders and the bogies were not taken into account. The body structure material is low-alloy steel, which has an allowable stress of 221 MPa in accordance with DSTU 7774:2015. Mainline locomotive traction passen-

ger cars. General technical standards for the calculation and design of mechanical parts of cars. The foreign analog of this document is EN 12663-2. Railroad applications – structural requirements of railroad vehicle bodies – Part 2: Freight cars.

When building the body design scheme, the effect of the vertical load P_v on its structure was taken into account (Fig. 4).

Longitudinal forces P_l were applied to the autocoupler stops on one side of the car, and on the other side, these forces were balanced by the corresponding reactions P_r .

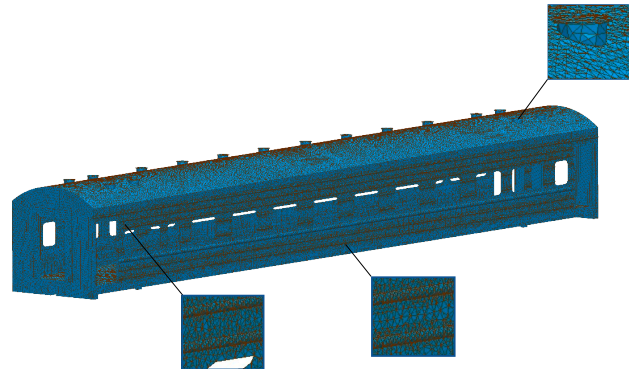


Fig. 3. Finite element model of a passenger car body

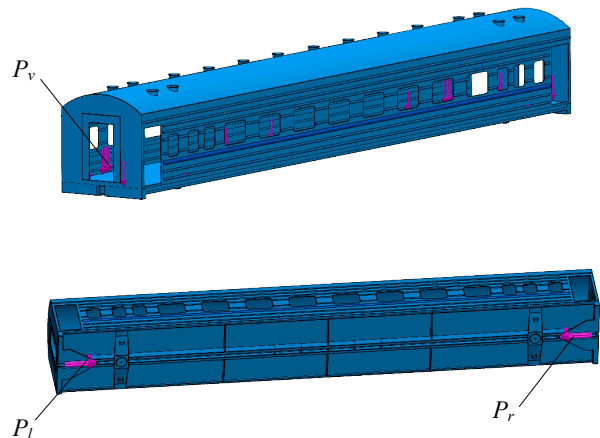


Fig. 4. Calculation diagram of the passenger car body: a – action of vertical loads; b – action of longitudinal loads

5. Results of identifying patterns in the strength indicators of the passenger car body

5.1. Results of calculating the strength of a passenger car body

The results of our strength calculations showed that the maximum stresses when modeling the “impact” (the effect on the rear stop of the autocoupler is a force of 2.5 MN), the maximum stresses arise in the girdle beam. The zones of concentration of these stresses are shown in blue in Fig. 5.

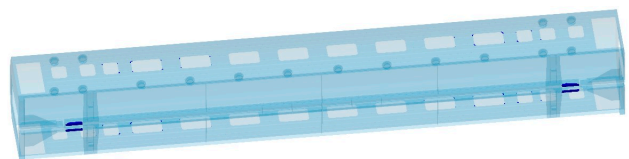


Fig. 5. Areas of greatest stress concentration in the body of a passenger car

The values of these stresses were 175.8 MPa (Fig. 6). They do not exceed the permissible ones and are lower than them by 20.5%.

The distribution of stresses along the length of the girdle beam is described in Fig. 7. This dependence was obtained using the “probe” option, which is built into the calculation software. It makes it possible to determine the controlled parameter at a given point. So, in the cantilever parts of the girdle beam, the stresses have maximum values. Then, towards the center of the girdle beam, they decrease slightly and in the center, they increase again and amount to about 140 MPa.

This stress distribution is described by an equation of the form

$$y = -7 \cdot 10^{-5} \cdot x^6 + 0.007 \cdot x^5 - 0.2832 \cdot x^4 + 5.5525 \cdot x^3 - 53.382 \cdot x^2 + 224.45 \cdot x - 177.62.$$

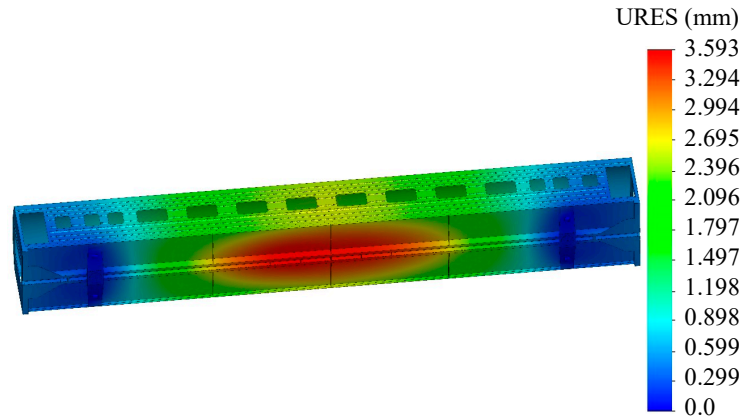


Fig. 8. Maximum displacements in the nodes of the passenger car body

The distribution of displacements is described by an equation in the following form

$$y = -6 \cdot 10^{-7} \cdot x^6 + 6 \cdot 10^{-5} \cdot x^5 - 0.0024 \cdot x^4 + 0.0433 \cdot x^3 - 0.3841 \cdot x^2 + 1.6989 \cdot x - 1.5611. \quad (2)$$

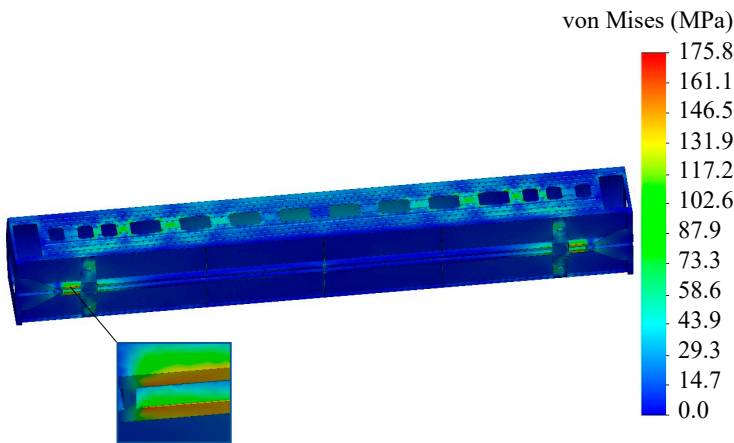


Fig. 6. Stressed state of the passenger car body

The resulting distribution of displacements can be explained in the same way as the distribution of stresses: the body is fixed by the sliders, and the middle part is free from fixing and loaded by vertical forces. Therefore, it is here that the maximum displacements occur.

The results of our calculation prove that with this loading scheme of the body, the strength of its structure is maintained. As part of the study, the strength of the passenger car body was determined for other calculation schemes in accordance with calculation modes I and III. The results of our calculations established that the strength of the passenger car body is maintained.

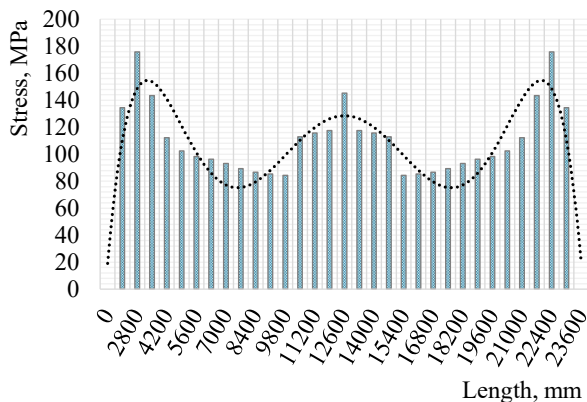


Fig. 7. Stress distribution along the length of the girdle beam

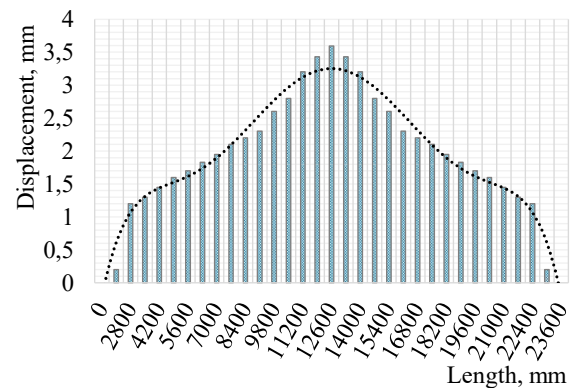


Fig. 9. Distribution of displacements along the length of the girdle beam

This distribution of stresses can be explained by the scheme of fastening and application of loads to the body. The maximum displacements occur in the middle part of the girdle beam and are about 3.6 mm (Fig. 8).

The distribution of displacements along the length of the girdle beam is described in Fig. 9.

In the cantilever parts of the girdle beam, the displacements have a minimal value. Towards the center of the girdle beam, they increase and amount to 3.593 mm.

5. 2. Results of modal analysis of the passenger car body

To ensure the safety of the passenger car movement, a modal analysis of its design was also carried out. The options from the SolidWorks Simulation software package were used. The calculation was carried out according to the calculation scheme shown in Fig. 4. The calculation results allowed us to identify the forms (Fig. 10) and frequencies of natural vibrations of the car body (Table 2).

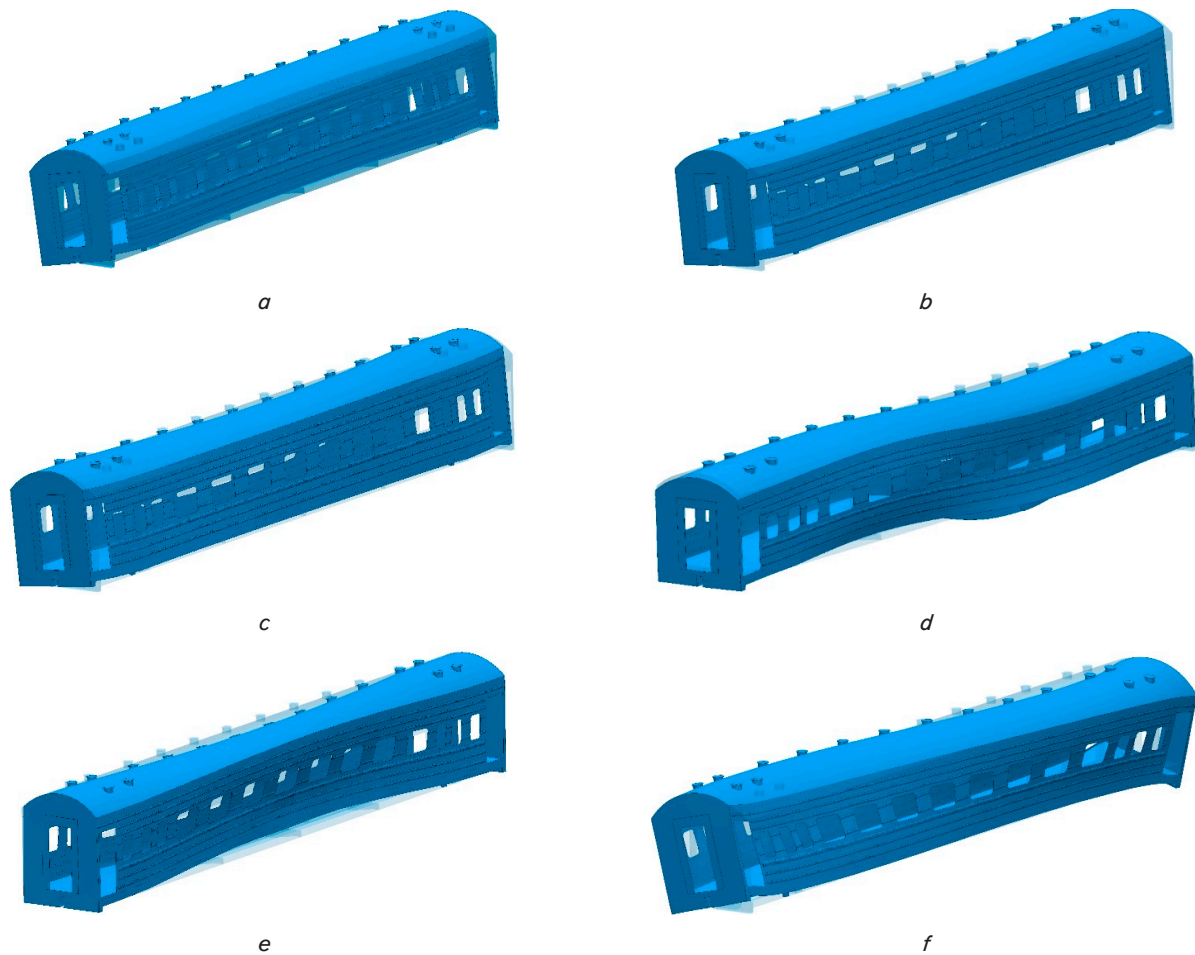


Fig. 10. Vibration forms of the passenger car body: *a* – mode I; *b* – mode II; *c* – mode III; *d* – mode IV; *e* – mode V; *f* – mode VI

Table 2

Vibration frequencies of the passenger car body

Mode No.	Frequency, Hz
Mode I	17.1
Mode II	19.8
Mode III	30.9
Mode IV	33.9
Mode V	35.9
Mode VI	41.0

Analyzing the results of our modal analysis, we can conclude that the safety of the car movement from the point of view of the obtained frequencies is ensured. The first natural frequency exceeds the threshold of 8 Hz and is 17.1 Hz.

6. Discussion of results based on identifying patterns in the strength indicators of the passenger car body

To improve the strength of the girdle beam of the passenger car body, it is proposed to use a C-shaped profile with perforation as its manufacturing profile (Fig. 1). The mass of the girdle beam using the proposed profile will decrease by more than 20% (Table 1), and the moment of resistance of the cross section will increase by almost 14%.

To substantiate this solution, a calculation was performed for the strength of the passenger car body. It was

established that under the most unfavorable loading mode of the body, the maximum stresses arise in the girdle beam (Fig. 5) and are 175.8 MPa (Fig. 6). It is important to note that these stresses do not exceed the permissible ones and are 20.5% lower than them. In the central part of the girdle beam, the maximum stresses are about 140 MPa (Fig. 7).

The maximum displacements in the frame were recorded in the middle part of the girdle beam. These displacements amounted to 3.593 mm (Fig. 8). Towards the cantilever parts, the displacements in the nodes decrease and amount to 1 mm (Fig. 9).

To ensure the safety of the passenger car in the train, a modal analysis of its design was carried out. The safety of the movement was assessed by the first natural frequency of oscillations, which should not be less than 8 Hz. The calculations showed that the first natural frequency of oscillations is 17.1 Hz (Table 2). That is, the safety of the movement from the point of view of modal analysis is observed.

This study has certain advantages compared to the known ones. For example, unlike works [4, 6–8, 11], we proposed solutions that could help improve the strength of passenger car bodies during operation. Unlike the solution specified in work [5], our improvement will not cause difficulties with the installation of automatic coupling devices on the girdle beam. The proposed improvement will help improve the safety of passenger car movement, unlike the studies reported in [9]. Unlike the solution provided in [10], our improvement does not require significant capital invest-

ments and also does not complicate the maintenance and repair of the car using the existing base.

The condition for using the results of the study is compliance with periodic maintenance of the passenger car body during operation.

As the main limitation of the study, it can be noted that this implementation can be carried out at the stage of manufacturing a new car design.

Our study has certain drawbacks. The main one is that when building a spatial model of the passenger car body, welds between its components were not taken into account.

Future advances in our research involve determining the dynamics of the car, taking into account the proposed improvement of its design [20–22]. It is also planned to consider the feasibility of using a floor made of sandwich panels to reduce the vertical load on the passenger car body during operation.

Our research will contribute to the formation of recommendations for the design of new passenger car structures with improved technical and economic indicators.

7. Conclusions

1. The strength of the passenger car body with a C-shaped profile with perforations has been calculated. It was found that the maximum stresses arise in the girdle beam, namely, in the area between the rear stops of the auto coupler and the heel and are 175.8 MPa. The resulting stresses do not exceed the permissible ones and are 20.5% lower than them. The maximum displacements in the body nodes are recorded in the middle part of the girdle beam and are about 3.6 mm. Under other design loading modes of the body, the strength of its structure is also observed.

2. A modal analysis of the passenger car body was performed. The safety of movement was assessed by the first natural frequency of oscillations. The calculations showed that the first natural frequency of oscillations is 17.1 Hz. Therefore, the safety of movement from the point of view of modal analysis is observed.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Sergii Panchenko: Funding acquisition, Investigation, Validation, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Alyona Lovska:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Data curation, Resources, Validation, Software, Supervision, Visualization, Writing – review & editing. **Iraida Stanovska:** Data curation, Resources, Validation, Software, Supervision, Visualization, Writing – original draft. **Arsen Muradian:** Formal analysis, Funding acquisition, Investigation, Funding acquisition, Investigation, Writing – review & editing. **Ihor Voloshyn:** Formal analysis, Funding acquisition, Visualization, Writing – review & editing.

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