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Research Article

Reduction of stresses in a passenger car frame under operating modes by means of an intermediate adapter

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Abstract: The article highlights the results of determining the strength of the passenger car frame under operational loading modes. The most loaded components of the frame are determined. It is proposed to use an intermediate adapter between the passenger car frame and the body to reduce the load on the frame. The peculiarity of such an adapter is that it consists of two metal sheets with a layer of energy-absorbing material in-between. The thickness of the adapter's sheets is determined using the Bubnov-Galerkin method. The results of the strength calculation for the frame with an intermediate adapter are presented. They demonstrate that the design solutions proposed can reduce the stresses in the frame by 25% and displacements by 29% compared to those for a typical design. The research will contribute to the development of best practices for the design of modern passenger car structures with improved technical, economic and operational characteristics, and for the higher efficiency of passenger car operations.

Keywords: transport mechanics; passenger car frame; frame load; frame strength; intermediate adapter; passenger transportation

I. INTRODUCTION

Rail transport is one of the top priority components of the transport industry, which ensures the coordinated development of Eurasian economies [1]. At the same time, passenger transportation is an integral and important component of rail transport [2]. Railway transport has unquestionable advantages in comparison with other types of transport. When it is about the land transport, rail vehicles offer significant positive features, such as lower energy consumption and in case of electric vehicles also strongly environmentally friendly kind of transport [3, 4]. Further, drag is lower in case of trainsets at a comparable passenger's capacity [5]. This advantage also applies to freight railway transport [6]. Another advantage is lower rolling resistance of rail vehicles [7, 8], which comes from forces ration in the wheel/rail contact [9-11]. Railway transport requires a suitable infrastructure in a form of quality railway tracks, energy sources and ensuring safety [12-16].

The features of railway transport mentioned above show its significant prospects to the future. However, this requires the application of modern solutions and the introduction of modern technologies not only in railway transport management, but especially in the construction of the vehicles themselves [17]. The most modern methods of design, simulation, testing and examination of vehicles supported by computer modelling are applied [18]. Such an approach was also used in the design of an improved design of the passenger car body presented in this research. The main goal of the modification of the passenger car frame is a reduction of stresses, which arise during wagon operation. A special intermediate adapter is designed for this purpose.

Currently, the 1520 mm gauge railways mostly use passenger cars with a body length of 23.6 m along the end beams of the frame. The considerable length of the passenger car frame causes fatigue stresses in it during operation due to the cyclical nature of the alternating loads acting on it. This can result in damage to the frame, which not only necessitates unscheduled repairs, but also endangers traffic safety. In this regard, there is a need to create solutions aimed at reducing the load on the passenger car frame in operation. Therefore, research on improving the design of the passenger car frame is quite relevant.

II. Analysis of recent research and publications

A lot of research is devoted to improving the load-bearing structures of passenger cars. For example, scientific publication [19] presents an algorithm that allows optimizing the design of a passenger car body. The authors also propose the introduction of cellular vacuum panels. This solution will improve not only the technical and economic performance of the car, but also its operational characteristics. However, these solutions do not improve the strength of the passenger car frame under operating loads.

The issues of optimizing the passenger car body are also covered in [20]. The objective of the optimization was to reduce the weight of the car body. This was achieved by using the latest materials, including composites. The paper also provides a justification for the proposed solution. However, it affected the body directly and does not contribute to the frame strength.

In order to improve the strength of the passenger car frame, the authors in [21] proposed the introduction of an energy-absorbing material into the centre sill. The profile was made of rectangular pipes. The paper presents the results of determining the load on the improved passenger car frame. However, there was no design solution proposed to reduce the load on other components of the car frame.

In order to improve the strength of passenger car bodies, the use of materials with improved physical and mechanical properties is proposed in [22, 29]. The authors of these papers highlight not only the specifics of use of these materials in car building, but also the prospects for their further implementation. However, at the same time, the authors did not study the issue of using these materials in the construction of the passenger car frame to improve its durability in operation.

An improved passenger car body in terms of its technical and economic indicators is presented in [24]. The authors carried out the topological optimization using the minimum material consumption criterion. The justification of the proposed design solutions is provided. However, these structural solutions are related directly to the car body and do not contribute to the strength of the frame.

The analysis of literature sources has shown that the issues of improving the strength of the passenger car frame require further research. In this regard, the purpose of the article is to present the results of a study of the load on the passenger car frame under operating conditions. To achieve this purpose, the following objectives have been set:

- to calculate the strength of a typical passenger car frame; and
- to calculate the strength of the passenger car frame, considering the proposed measures for reducing its load in operation.

III. Strength calculation of a typical passenger car frame structure

To determine the strength of a typical passenger car frame structure, a spatial model of it was built. A non-compartment passenger car of the 61-821 model was used as a prototype. The frame of this car includes centre sill 1 (**Fig. 1**), bolster beams 2, end beams 3, cross bearers 4, stiffeners 5, reinforcement sheets 6.

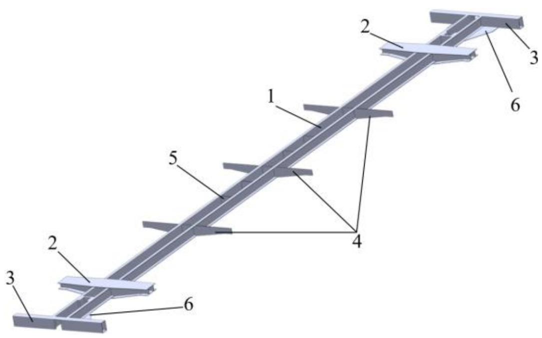

Figure 1. *A passenger car frame*

Graphic work on the building of a spatial model of the frame was carried out in SolidWorks. The strength was calculated using the finite element method in the built-in SolidWorks Simulation module. The strength of the frame under the vertical loads P_V, which included a vertical static component P_V^{St} and a vertical dynamic component P_V^D, was studied (**Fig. 2**).

For preliminary calculations, the value of the vertical dynamic load on the elements of the wagon from vibrations during movement in the train is determined by multiplying the gross gravitational force acting on the calculated node by the coefficient of vertical dynamics k_{VD}.

The vertical dynamic load was determined according to the methodology described in [25]. In accordance with this regulatory document:

$$P_V^D = P_V^{St} \cdot k_{DV} \quad (1)$$

where k_{DV} is the vertical dynamics coefficient.

The vertical dynamics coefficient k_{DV} is taken as a random function with a probabilistic distribution of the form:

$$P(k_{DV}) = 1 - \exp\left(-\frac{\pi}{4} \cdot \frac{k_{DV}^2}{\overline{k_{DV}^2}} \cdot \beta^2\right), \qquad (2)$$

where $\overline{k_{DV}^2}$ is the average probable value of the vertical dynamics coefficient, β is the distribution parameter.

The coefficient k_{DV} is defined as the quantile of expression (2) under the calculated one-sided probability $P(k_{DV})$:

$$k_{DV} = \frac{\overline{k_{DV}}}{\beta} \cdot \sqrt{\frac{\pi}{4} \cdot ln \cdot \frac{1}{1 - P(k_{DV})}}. \qquad (3)$$

It was assumed in the calculation, that rigid connections were used to the areas where the model (**Fig. 2**) rested on the bogies [26, 27]. Thus, frictional forces were not considered. The construction material was Steel 09G2S.

The finite element model was formed by isoparametric tetrahedra and included 39,105 elements (a maximum size of 95 mm and a minimum size of 19 mm) and 13,793 nodes. It is important to note that the graph-analytical method [28, 29] was used to create a finite-element model, which allowed us to determine the optimal number of elements.

The calculation results are shown in **Fig. 3** to **Fig. 5**. It is established that the maximum equivalent

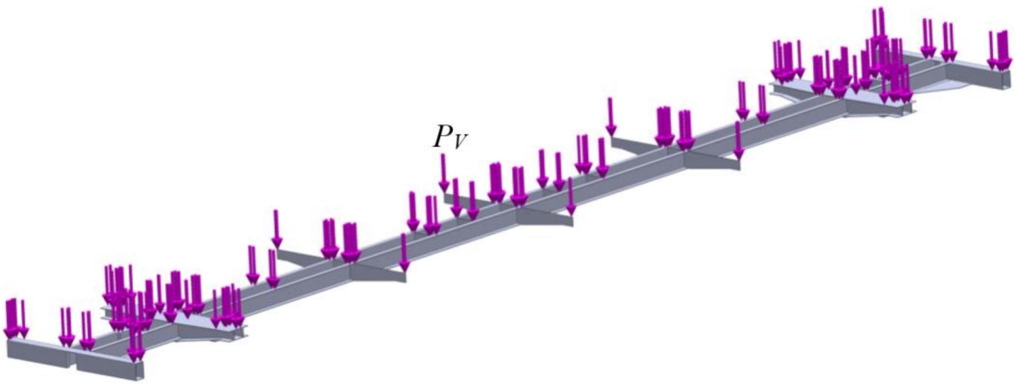

Figure 2. *A design diagram of the passenger car frame*

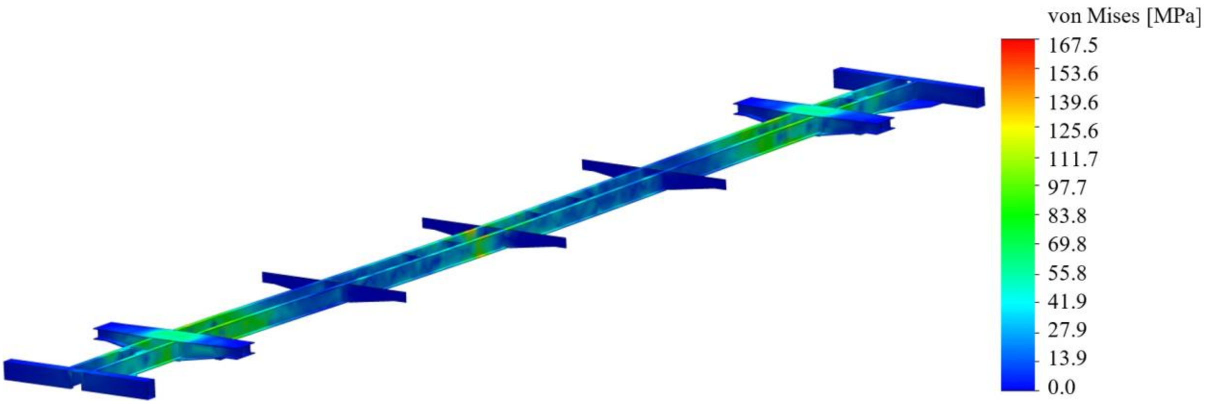

Figure 3. *A stress state of the passenger car frame*

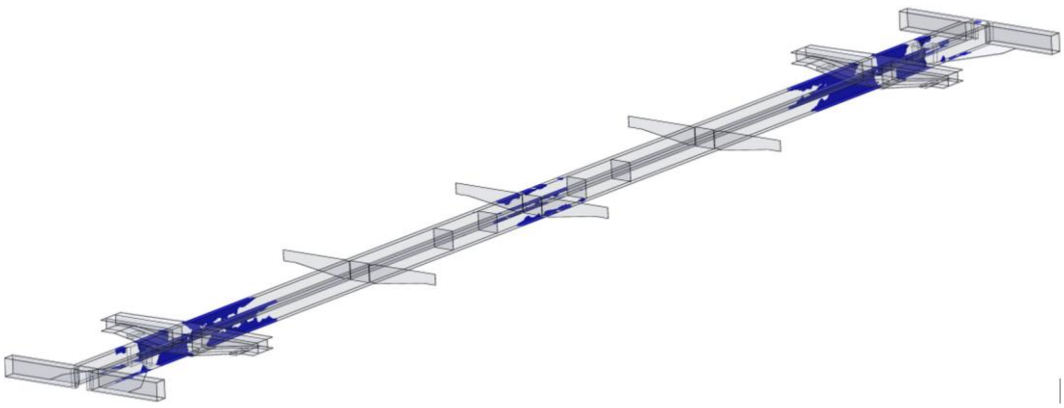

Figure 4. *The most loaded areas of the passenger car frame*

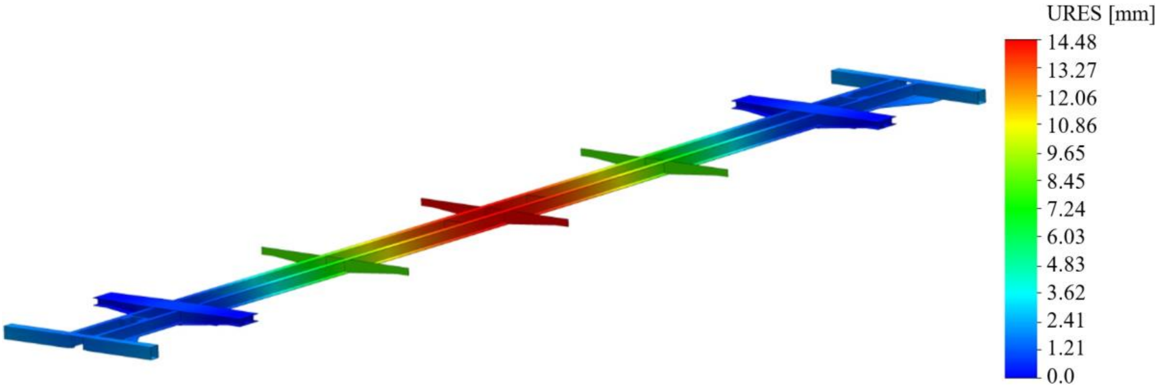

Figure 5. *Displacements in the passenger car frame units*

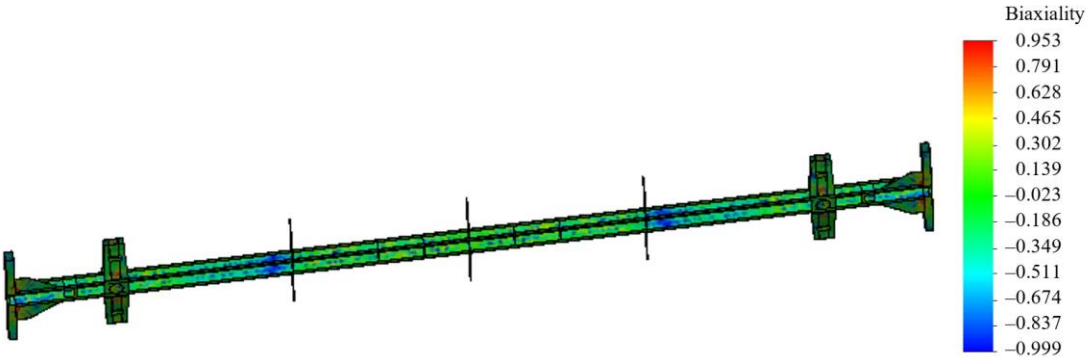

Figure 6. *The passenger car frame biaxiality indicator*

stresses occur in the zones of interaction of the bolster beams and the centre sill and are 167.5 MPa (**Fig. 3**). These stresses are lower than permissible (190 MPa [25]), but, under cyclic action, they accumulate in the most loaded areas of the frame (**Fig. 4**), which can lead to fatigue failure under operating conditions. The maximum displacements occur in the middle part of the frame and are 14.48 mm (**Fig. 5**). Based on the results of the static analysis, the biaxiality indicator of the passenger car frame was determined (**Fig. 6**).

It is established that the highest value of this indicator is in the areas of the centre sill, which are located close to the intermediate beams. This can be explained by the fact that the middle part of the frame has the greatest pliability.

IV. CALCULATION OF THE STRENGTH OF THE PASSENGER CAR FRAME CONSIDERING THE PROPOSED MEASURES FOR REDUCING ITS LOAD IN OPERATION

To ensure the strength of the passenger car frame, it is proposed to use an intermediate adapter between the frame and the body (**Fig. 7**).

A feature of this adapter is that it consists of two metal sheets (Steel 09G2S). The gap between these sheets is filled with an energy-absorbing material such as aluminium foam. Thus, the design of this adapter is similar to a sandwich panel.

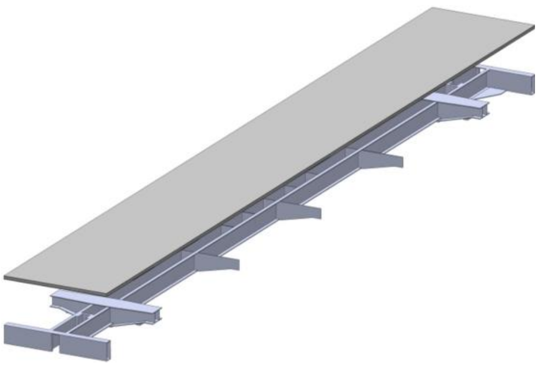

Figure 7. *A passenger car frame adapter*

The Bubnov-Galerkin method was used to determine the thickness of the sheets that formed the adapter. In accordance with this method, the thickness of a sheet (plate), given the known physical and mechanical properties of the structural material, can be calculated by the formula:

$$\delta = \sqrt{\frac{P \cdot \frac{96}{\pi^4} \cdot (b^2 + \mu \cdot a^2) \cdot a^2 \cdot b^2}{\sigma \cdot (a^2 + b^2)}}, \qquad (4)$$

where P is the load acting on the sheet, a, b are the width and the height of the sheet, respectively, μ is Poisson's ratio, σ is the permissible stresses of the sheet material.

The calculations at a = 3.105 m and b = 24.537 m demonstrate that the thickness of the sheet, provided that its strength is ensured, is about 5.4 mm.

A calculation was carried out to determine the strength of the car frame with an intermediate adapter. The design diagram of the frame with an adapter is shown in **Fig. 8**. The forces and connections used in the design diagram were identical to those used in the calculation of a typical frame design.

The finite element model of the frame with an adapter had 226,357 elements and 58,616 nodes. The maximum element size was 80 mm, and the minimum was 16 mm. The calculations show that the maximum stresses occur in the adapter, that is, in the areas of its interaction with the bolster beams; they amount to 124.2 MPa (**Fig. 9**), which is 25% lower than in a typical frame structure.

The maximum displacements occur in the middle part of the adapter and are 10.18 mm (**Fig. 10**). The resulting displacements are 29% lower than those in a typical design. The biaxiality indicator of the passenger car frame with an adapter is shown in **Fig. 11**. Its greatest value is in the bolster beams because the model was fixed by the side bearers.

The results of the calculations show that the use of an intermediate adapter helps to reduce the load on the passenger car frame under the action of operational loads. This can be used for increasing the efficiency of passenger cars, as well as developing appropriate recommendations for the modern designs with improved performance characteristics. The future research in this field will be focused on investigation of other properties of a wagon equipped with the designed body structure. There is mainly an influence of the structure on ride comfort for passenger. It will be assessed by means on MBS

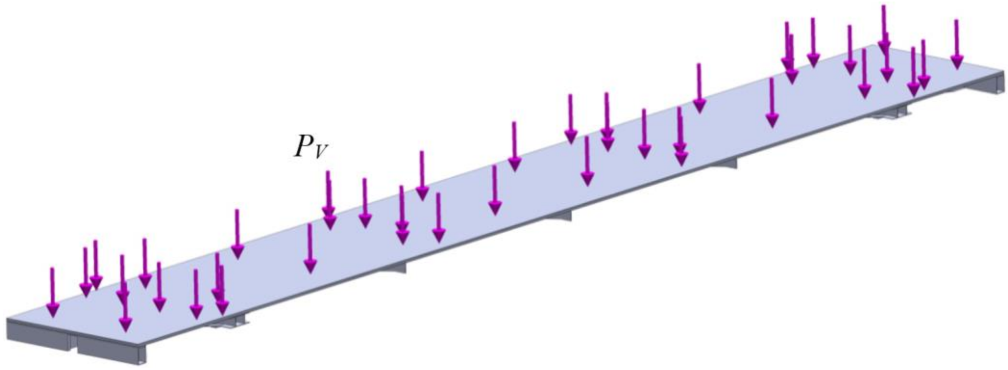

Figure 8. *A design diagram of the passenger car frame with the adapter*

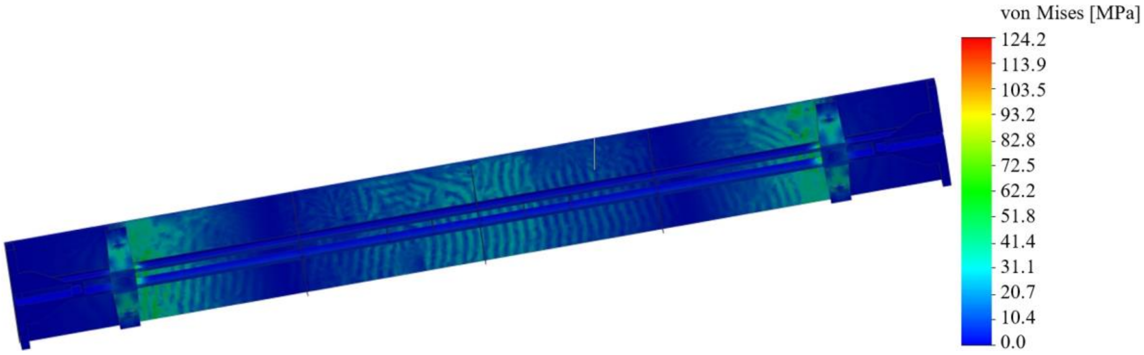

Figure 9. *A stress state of the passenger car frame with the adapter*

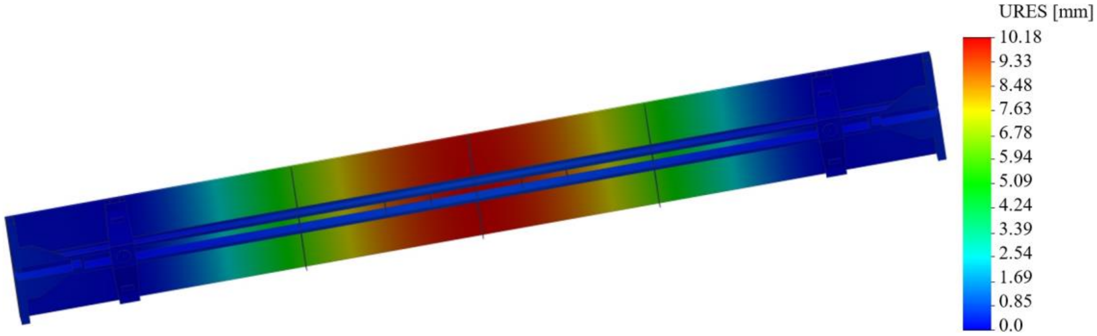

Figure 10. *Displacements in the assemblies of the passenger car frame with the adapter*

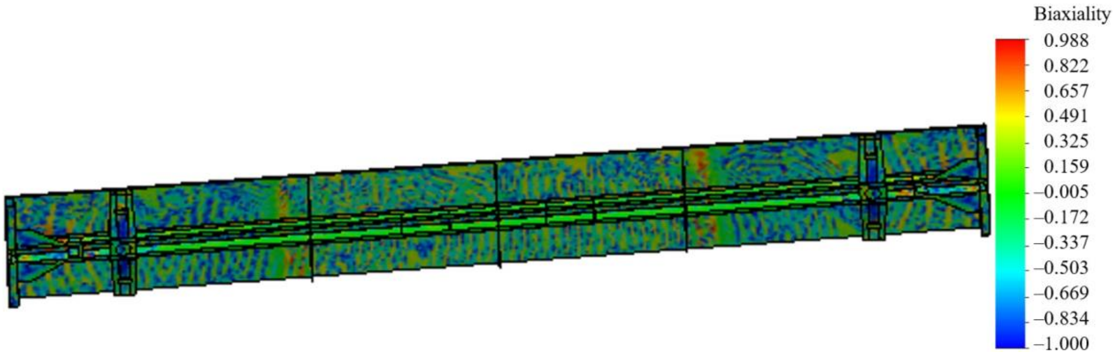

***Figure 11.** The biaxiality indicator of the passenger car frame with the adapter*

simulation computation in including a flexible wagon body to a model [30-33]. Further, efforts for assessment of passive safety of the structure will be made regarding to impact absorption. This is important from protection of passengers as well as other transport users [34, 35]. Finally, fatigue analyses will help to reveal reliability and integrity of the wagon body structure [36, 37].

It is important to note that the results of this study can also be applied to 1435 mm gauge wagons. The same algorithm presented in this research and implemented for a 1520 mm gauge wagon can be used. However, the load values specified in the regulatory document [38] will be used. The authors plan to pay attention to this issue in subsequent work.

Conclusion

1. The strength of a typical passenger car frame structure is calculated. The maximum equivalent stresses are recorded in the areas of interaction between the bolster beams and the centre sill; they amount to 167.5 MPa. It should be noted that these stresses are lower than permissible, but they accumulate in the most stressed areas of the frame during cyclic operation. Under certain operating conditions, this can lead to fatigue failure. The maximum displacements occur in the middle of the frame and are 14.48 mm. The greatest value of the biaxiality indicator is observed in the areas of the centre sill, which are located closer to the intermediate beams.

2. The strength of the passenger car frame is calculated, considering the measures for reducing the load in operation. The maximum stresses occur in the adapter and amount to 124.2 MPa. It should be noted that the proposed structural solutions help reduce stresses in the frame by 25% compared to those in a typical design.

The maximum displacements occur in the middle of the adapter and are 10.18 mm. The resulting displacements are 29% lower than those in a typical design. The highest value of the biaxiality indicator is in the bolster beams.

The research will contribute to the development of best practices for the design of modern passenger car structures with improved technical, economic and operational characteristics, and for the higher efficiency of passenger car operations.

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AUTHOR CONTRIBUTIONS

A. Lovska: Conceptualization, Software, Formal Analysis, Investigation, Data curation, Visualisation, Writing – original draft preparation, Project Administration.

J. Dižo: Methodology, Validation, Investigation, Data curation, Writing – review and editing, Project Administration.

V. Ravlyuk: Software, Validation, Sources, Project Administration.

D. Skurikhin: Graphical outputs, Supervision, Project administration.

A. Rybin: Calculation, Graphical outputs, Project administration, Review and editing.

DISCLOSURE STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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