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Damping Composites from Materials with Different Elastic Hysteresis Properties for Sandwich Shock Absorbers of Railroad Transport

E. G. Kurzina[a, *], A. G. Kolmakov[b], V. N. Filippov[a], A. V. Semak[a], and A. M. Kurzina[a]

[a] *Russian University of Transport (MIIT), Moscow, 127994 Russia*

[b] *Baikov Institute of Metallurgy and Materials Science, Russian Academy of Sciences, Moscow, 119334 Russia*

**e-mail: kurzina_elena@mail.ru*

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Abstract—The damping composites from the materials with different elastic hysteresis properties have been studied at dynamic loads and temperatures of +23°C and –40°C. A sandwich shock absorber for a rail damping element that is 14 mm in thickness from fiber-reinforced rubber composite and thermoplastic elastomer, which combines the advantages of each material, has been developed. A procedure for the choice of elastic hysteresis characteristics of sandwich shock absorbers and a mathematical model of a wagon–track multiple-mass vibration system making it possible to evaluate the applicability and performance of such shock absorbers have been proposed.

Keywords: damping materials, fiber-reinforced rubber composition materials, elastomer composition materials, sandwich shock absorbers, damping elements, elastic hysteresis properties, multiple-mass vibration system

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INTRODUCTION

Shock absorbers made from materials with improved damping characteristics in a broad range of climatic temperatures are one of the most economically feasible approaches to decreasing the dynamic impact on the track superstructure and the elements of rolling stock.

At present, mathematical models of the interaction of wheel and rail have been developed and calculations of the parameters of the material have been performed abroad on the basis of the study of dynamic properties of rubber rail pads depending on the loading frequency and preloading [1]. In addition, a dynamic model of interaction of the composite sleeper with mating elements was developed and its dynamic characteristics were compared with the mass-produced concrete sleeper in order to decrease vertical dynamic loads of rolling stock and track systems in tunnels [2]. With the aim of vibration absorption of the elements of rolling stock (running gears and shock absorbers), resilient supporting structures made from elastomer and composition materials were developed, more specifically, rubber-metal springs and blocks, spring side stops, adapters, and liners [3, 4].

However, the damping materials employed in the constructions cannot fulfill all operating requirements.

For this reason, different reinforcement conditions of polymer matrices were attempted. In order to increase the frost resistance of mechanical gaskets from butadiene-nitrile rubber with the acrylonitrile content of 18% (BNKS-18), ultra-high-molecular-weight polyethylene (UHMWPE) and mechanoactivated natural zeolite were added upon rolling [5]. In this case, the use of mechanoactivated zeolite improved the interaction at the butadiene-nitrile rubber—ultra-high-molecular-weight polyethylene interface.

The design of the composite damping constructions from various materials, so-called sandwiches, is an alternative solution of this problem. Pandrol International Ltd and DuPont Engineering Polymers used a combined "studded" pad of rail fastenings for a high-load coal line, which consists of a liner (Hytrel 6358 thermoplast) and pad (Hytrel EP2 thermoplast) [6]. A prospective design of the center-coupler draft gear, which represents a set of resilient polymer blocks from polyester thermoplastic elastomers, was developed at the Bryansk Technical University [7].

It should be noted that sandwich shock absorbers based on similar materials are proposed in the mentioned works. However, optimal values of all characteristics cannot be achieved in a uniform blend of elastomers, because there are specific relationships between individual characteristics. Therefore, it is reasonable to investigate elastic hysteresis properties of

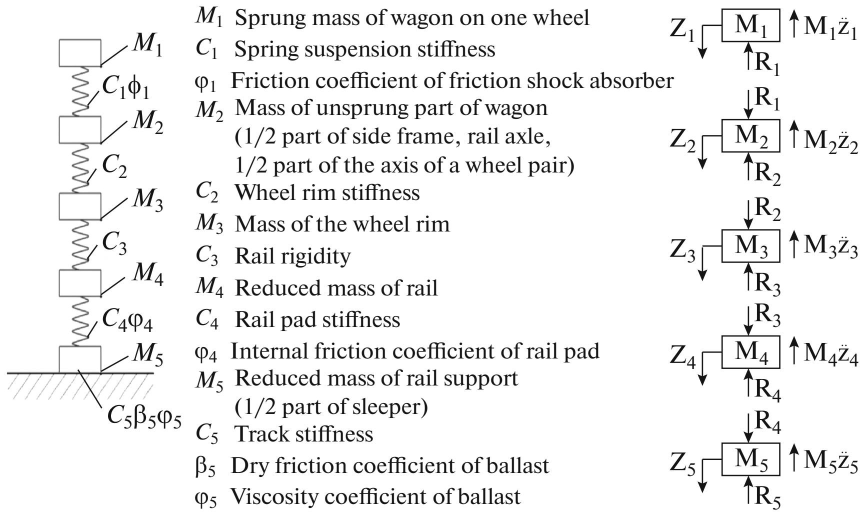

Fig. 1. General model and design model of interaction of rolling stock with the railway track superstructure.

various types of modern elastomer composition materials in a broad range of climatic temperatures and design multilayer damping compositions in order to develop sandwich shock absorbers.

In this work, a procedure for the choice of elastic hysteresis characteristics of sandwich shock absorbers and evaluation of their performance was proposed. A rail damping element was designed in the form of sandwich that is 14 mm in thickness and made from fiber-reinforced rubber components and thermoplastic elastomer, which combines the advantages of each material.

MATERIALS AND METHODS

Materials and Experimental Studies

The following materials were chosen as test elements for the design of sandwiches: unreinforced rubber composite (TPRK) based on SKI-3 rubber, 20% of reinforced rubber composite consisting of rubber matrix based on SKI-3 rubber and dispersed polyamide cork (RVK), and thermoplastic elastomer (TEP1nzh) (blend of polyurethane and poly(vinyl chloride) plasticized rubber).

Investigation of elastic hysteresis properties of damping specimens of composition polymer materials based on the rubber blend and thermoplastic elastomer at dynamic loads and temperatures of +23°C and –40°C was carried out according to the procedure described in [8, 9]. Features of the specimens of the materials under study were also described in these references. The data on dynamic hysteresis curves of the test specimens that are 14 mm in thickness from the TPRK, RVK, and TEP1nzh materials at test temperatures of +23°C and –40°C were obtained as the main result.

In order to determine the effect of the parameters of elastic hysteresis properties of the rail damping element C_4 and φ_4 (Fig. 1, pads) between the rail and rail support on other elements of the vibration system, preliminary multivariate calculations of the developed mathematical model were carried out using experimental data.

Modeling of Railroad–Rolling Stock Thermodynamic Vibration System

In order to choose the optimal dimensional parameters and elastic hysteresis characteristics of the damping element between rail and rail support (sleeper), a mathematical model describing a railroad–rolling stock thermodynamic vibration system was suggested. A general model and a design model of the multiple-mass vibration system are given in Fig. 1. According to the D'Alembert principle, a system of second-order differential equations was generated, which was integrated by numerical methods using a special program. Wheel impact on rail was modeled. Initial data (mass, stiffness, and friction and viscosity coefficients of the elements of the system) were determined from reference data for a high-sided wagon with the axial load of 25 tf, R65 rail, ferroconcrete sleeper, and stone ballast. One can vary the stiffness and internal friction of damping elements in each variant of calculation, which are chosen from particular experimental and calculated dynamic hysteresis curves for each type of composition material.

Results of the calculation of the program represent numerical values of reactive forces (constraint force R_i) and deflections (z_i) in each element.

Procedure of Choice of Elastic Hysteresis Characteristics of Sandwich Shock Absorbers and Evaluation of Their Performance

The performance of shock absorber was evaluated by the analysis of the distribution of reactive forces and deflections in a wagon–track general vibration system. To develop sandwich shock absorbers made from various materials, a special procedure was developed, which involves the following stages:

1. Choice of initial data:

(a) dimensional parameters of shock absorber (sizes) for mating with other structural elements;

(b) elastic hysteresis characteristics of test specimens obtained experimentally or taken from the formed library of elements based on accumulated experience.

2. Determination of the criteria of the limiting state of shock absorbers taken from standard documentation or the results of research works.

3. Choice of the number of layers, possible thickness values, and their favorable alteration.

4. Calculation of characteristics of each component according to test specimens.

The static and dynamic stiffness of each chosen component of the sandwich at various test temperatures are determined according to the following equation [7]:

$$C_c = (\delta_t/\delta_c)C_t, \quad (1)$$

where C_t is the static (dynamic) stiffness of the material of the test specimen (kN/mm) with thickness δ_t (mm) and C_c is the static (dynamic) stiffness of the material of the component (kN/mm) with thickness δ_c (mm).

The relative elastic hysteresis values, such as the stiffness coefficients, mechanical loss coefficients, and effective resilience, are constant for a specific material and do not depend on thickness; therefore, they are considered equal to the test specimen [7]. The mechanical losses after one cycle, which are determined by the hysteresis loop area, are inversely proportional to the change in the thickness of material:

$$q_c = (\delta_c/\delta_t)q_t, \quad (2)$$

where q_c are the mechanical losses after one strain cycle of the material of the test specimen with thickness δ_t (mm) and q_c are the mechanical losses after one strain cycle of the material of component with thickness δ_c (mm).

5. Calculation of sandwich characteristics.

The static and dynamic stiffness of sandwich C_s are calculated for several components using the following equation:

$$\frac{1}{C_s} = \frac{1}{C_{c1}} + \frac{1}{C_{c2}} + \dots \frac{1}{C_{ci}}, \quad (3)$$

where C_{c1} is the static (dynamic) stiffness of the first component, kN/mm; C_{c2} is the static (dynamic) stiffness of the second component, kN/mm; and C_{ci} is the static (dynamic) stiffness of the *i*th component, kN/mm.

The coefficient of variation of static stiffness of the sandwich is determined according to the formula

$$K_s = C_{s(stat1)}/C_{s(stat0)}, \quad (4)$$

where $C_{s(stat1)}$ is the static stiffness of the sandwich at the chosen temperature, kN/mm, and $C_{s(stat0)}$ is the static stiffness of the sandwich at +23°C, kN/mm.

The stiffness coefficient of the sandwich at various temperatures is calculated as follows:

$$K_d = C_{s(din)}/C_{s(stat0)}, \quad (5)$$

where $C_{s(din)}$ is the dynamic stiffness of the sandwich at the chosen temperature, kN/mm.

6. Analysis of the obtained variant according to the criteria of limiting states in order to optimize elastic hysteresis properties of shock absorber and choose appropriate variants.

The calculated characteristics of the sandwiches made from different materials were highly convergent with the experimental data.

RESULTS AND DISCUSSION

The experimental results on the dynamic hysteresis curves of the test specimens that are 14 mm in thickness and made from TPRK, RVK, and TEP-1nzh materials at test temperatures of +23°C and –40°C are given in Fig. 2 and Table 1. It is clear that TPRK, which diffuses higher energy over one cycle of vibrations, possesses the lowest secant stiffness at +23°C among the composites based on the rubber blend (141.9 kN/mm). Reinforcement with the RVK cord of the rubber composite increases the stiffness (179.2 kN/mm), which is related to the lower volume of the resilient matrix of the material and a rapid compaction of the boundaries between the main matrix and cord filler at cyclic exposure. At –40°C, the difference between the stiffness parameters of the TPRK and RVK rubber composites almost disappears, which is related to the violation of additive effect of the RVK components, as well as the onset of crystallization of the rubber matrix, at which the stiffness values of the main matrix and cord filler become nearly comparable. Thus, an increase in the stiffness of rubber materials due to reinforcement with dispersed polyamide cord for the stabilization of dimensional parameters of a general vibration system is effective up to the onset temperatures of crystallization of rubber, while with a further decrease in temperatures the stiffness of the main rubber matrix in the design should be considered.

At –40°C, the secant stiffness of TEP1nzh thermoplastic elastomer significantly increases (868.3 kN/mm) as compared to the stiffness at normal temperature

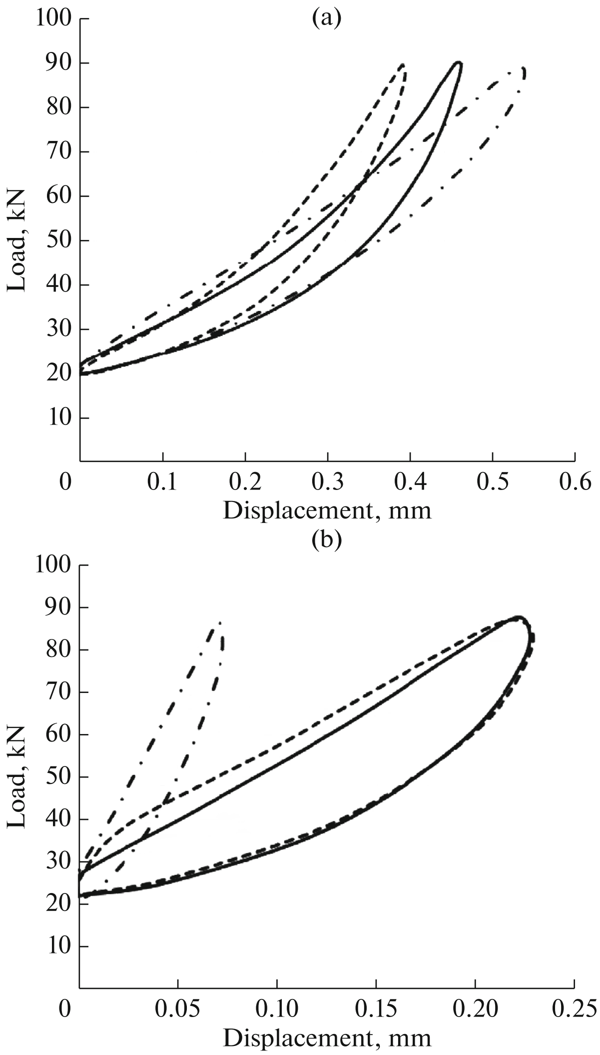

Fig. 2. Dependence of the compressive load on displacement in the case of dynamic loading at (a) +23°C and (b) –40°C for TPRK (bold line), RVK (dashed line), and TEP1nzh (dash-dotted line).

(134.2 kN/mm), because the material operates nearly in the vitreous state.

The materials from the "rubber" composites do not lose resilient properties at –40°C, while the composite from thermoplastic elastomer operates as a resilient solid. Consequently, more than a sixfold increase in the stiffness coefficient could represent a criterion of the limiting states of damping materials upon operation.

The results of multivariate calculations of a wagon–track multiple-mass system upon rolling of a wheel on a rail using dynamic hysteresis curves of the materials showed that the change in elastic hysteresis parameters of the damping rail element depending on the type of employed material affects marginally the spring part of wagon and rail support.

An increase in the dynamic stiffness of damping rail element of the TPRK and RVK rubber composites at –40°C (Fig. 3a) as compared to the stiffness at +23°C results in the decrease in reactive force on the rail by 24% owing to its lower deflection. In this case, reactive forces in other elements of the system (wheel, unsprung mass of wagon, and rail support) change marginally. Employment of RVK fiber-reinforced rubber composite at below-zero temperatures is more reasonable than TPRK rubber, because it decreases the load on the unsprung mass of the wagon by 8% and by the factor of 1.37 on the rail support.

The use of TEP1nzh thermoplastic elastomer as a damping rail element at –40°C as compared to normal temperature (Fig. 3a) results in the decrease in reactive force on the rail by 30% and an increase by 26 kN on the wheel (14%), which exceeds the maximum allowable axial load of 25 tf on one wheel by 8%.

Analysis of the distribution of deflections (displacements from initial position) of the elements of the track–wagon multiple-mass system showed that deflections of wheel (0.24 mm in TPRK and 0.15 mm in the case of RVK) and unsprung mass of wagon (0.27 mm in TPRK and 0.16 mm in the case of RVK) decrease with an increase in the stiffness of the rubber composites at –40°C along with marginal changes in the deflections of the rail (Fig. 3b). However, deflections in the rail support increase (0.21 mm in TPRK and 0.25 mm in the case of RVK). When the TEP1nzh thermoplastic elastomer is used, there is also a decrease in the deflections of the wheel by 0.21 mm and unsprung mass of the wagon by 0.21 mm along with an increase in the deflections of the rail support by 0.34 mm with an increase in stiffness at –40°C as compared to the nor-

Table 1. Parameters of elastic hysteresis properties of test materials with thickness of 14 mm for the calculation of the components of sandwich shock absorber

Brand	Static stiffness at +23°C, kN/mm	Dynamic secant stiffness at +23°C, kN/mm	Static stiffness at –40°C, kN/mm	Dynamic secant stiffness at –40°C, kN/mm	Static stiffness coefficient	Stiffness coefficient at +23°C	Stiffness coefficient at –40°C
TPRK	83.2	141.9	90.0	288.9	1.08	1.71	3.47
RVK	84.7	179.2	85.0	297.9	1.00	2.12	3.52
TEP1nzh	66.2	134.2	346.3	868.3	5.23	2.03	13.12

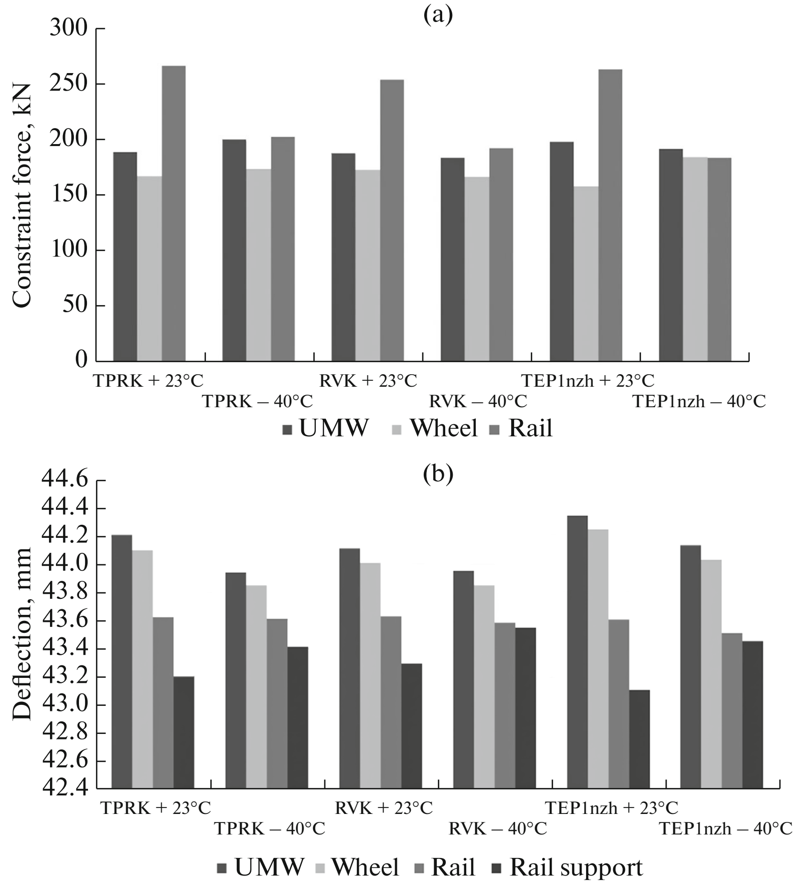

Fig. 3. (a) Distribution of reactive forces and (b) distribution of deflections in the elements of a wagon–track multiple-mass vibration system at +23°C and –40°C upon mounting TPRK and RVK rubber composites and TEP1nzh thermoplastic elastomer (UMW is unsprung mass of wagon).

mal temperature (Fig. 3b). It should be noted that the degree of deflections of the wheel and unsprung mass of the wagon at –40°C when using TEP1nzh thermoplastic elastomer is 1.6 times larger than that of the TPRK and RVK rubber composites, which is caused by a significant increase in stiffness owing to operation in the temperature range of the brittle state.

Derived from analysis of the results of the calculation of the wagon–track multiple-mass vibration system, as well as the operational requirements on the rail damping element, possible designs were calculated according to the procedure of design of sandwich shock absorbers.

Shock absorbing properties for the effective absorption of various impact loads and shock absorption, friction characteristics for the increase in the resistance to longitudinal forces on the rails, electrical insulating properties, resistance to climatic changes and exposure to aggressive media, and service life are main operational requirements on the rail pads. Therefore, the following principle laid the foundation of the design: the component from the rubber blend possessing high friction properties for the resistance to track displacement in the longitudinal direction is the upper layer of the sandwich, while the lower layer is composed of the thermoplastic elastomer component, which is resistant to an aggressive environment, as well as more processable and durable.

The results of the calculation of stiffness values of the sandwich shock absorbers for the pads of rail fastenings are given in Tables 2 and 3. The following designations of sandwiches were used: T is the TPRK material, R is the RVK material, and P is the TEP1nzh material; the number after letter corresponds to the thickness of the component. Analysis of the results showed that the T5-P9 and R5-P9 sandwiches with the thickness of thermoplastic elastomer component of 9 mm possess high stiffness coefficient values at –40°C (more than 6.0); consequently, they possess lower shock absorbing properties at below-zero temperatures. The lowest stiffness coefficient values at –40°C were obtained in the T9-P5 and R9-P5 sandwiches. In this case, the R9-P5 sandwich possessing a higher stiffness coefficient at +23°C is more favorable for the stabilization of the parameters of the track at heavy-duty motion. Consequently, the sandwiches that are

Table 2. Results of calculation of the parameters of elastic hysteresis characteristics of initial components of sandwich shock absorber

Brand	Static stiffness at +23°C, kN/mm	Dynamic secant stiffness at +23°C, kN/mm	Static stiffness at –40°C, kN/mm	Dynamic secant stiffness at –40°C, kN/mm	Static stiffness coefficient	Stiffness coefficient at +23 °C	Stiffness coefficient at –40 °C
T5	233.0	397.3	252.0	808.9	1.08	1.71	3.47
T7	166.4	283.8	180	577.8	1.08	1.71	3.47
T9	129.4	220.7	140.0	449.4	1.08	1.71	3.47
P5	185.4	375.8	969.6	2431.2	5.23	2.03	13.12
P7	132.4	268.4	692.6	1736.6	5.23	2.03	13.12
P9	103.0	208.8	538.7	1350.7	5.23	2.03	13.12
R5	237.2	501.8	238.0	834.1	1.00	2.12	3.52
R7	169.4	358.4	170	595.8	1.00	2.12	3.52
R9	131.8	278.8	132.2	463.4	1.00	2.12	3.52

Table 3. Results of calculation of the parameters of elastic hysteresis characteristics of designed sandwich shock absorbers with thickness of 14 mm

Brand	Static stiffness at +23°C, kN/mm	Dynamic secant stiffness at +23°C, kN/mm	Static stiffness at –40°C, kN/mm	Dynamic secant stiffness at –40°C, kN/mm	Static stiffness coefficient	Stiffness coefficient at +23 °C	Stiffness coefficient at –40 °C
T7-P7	73.7	137.9	142.9	433.5	1.94	1.87	5.88
R7-P7	74.3	153.5	136.5	443.6	1.84	2.07	5.97
T9-P5	76.2	139.1	122.3	379.3	1.61	1.82	4.98
T5-P9	71.4	136.9	171.7	505.9	2.40	1.92	**7.08***
R9-P5	77.0	160.0	116.4	389.2	1.51	2.08	5.05
R5-P9	71.8	147.4	165.1	515.7	2.30	2.05	**7.18***

* Values exceeding the standard stiffness variation limit.

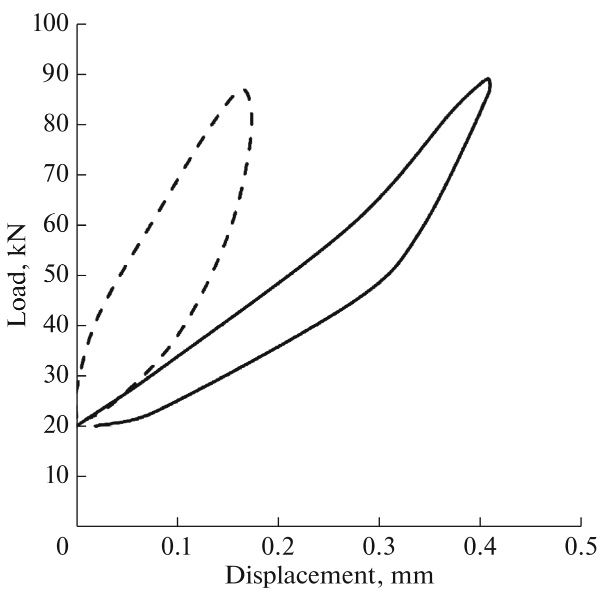

Fig. 4. Dependence of the compressive load on displacement in the case of dynamic loading at (a) +23°C and (b) –40°C for R9-P5 sandwich.

14 mm in thickness and consist of the rubber component (TPRK or RVK) and the thermoplastic elastomer component (TEP1nzh) with the thickness of at least 5 mm possess the highest damping characteristics.

Dynamic hysteresis curves of the R9-P5 sandwich shock absorber with the total thickness of 14 mm made from components of RVK with thickness of 9 mm and TEP1nzh with thickness of 5 mm at test temperatures of +23°C and –40°C are given in Fig. 4. To confirm the optimal variant of the R9-P5 sandwich consisting of the RVK fiber-reinforced rubber composite with thickness of 9 mm and TEP1nzh thermoplastic elastomer with thickness of 5 mm, the wagon–track multiple-mass vibration system was calculated and the results were compared with typical variants of the rail damping elements possessing the same thickness. The results of calculation are given in Figs. 5 and 6.

Analysis of the distribution of reactive forces when using the rail damping elements with the thickness of 14 mm (TPRK, RVK, TEP1nzh, and R9-P5 sandwich; Fig. 5a) at +23°C showed the optimal distribution of forces in the R9-P5 sandwich: the lowest con-

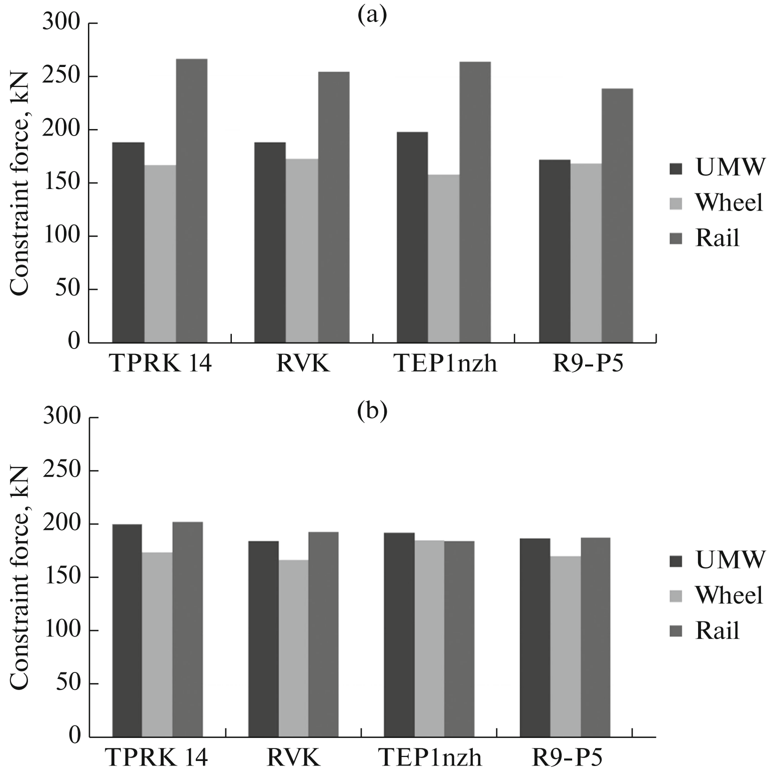

Fig. 5. Distribution of the constraint forces upon mounting similar damping rail elements and sandwich with thickness of 14 mm: temperature is (a) +23°C and (b) –40°C.

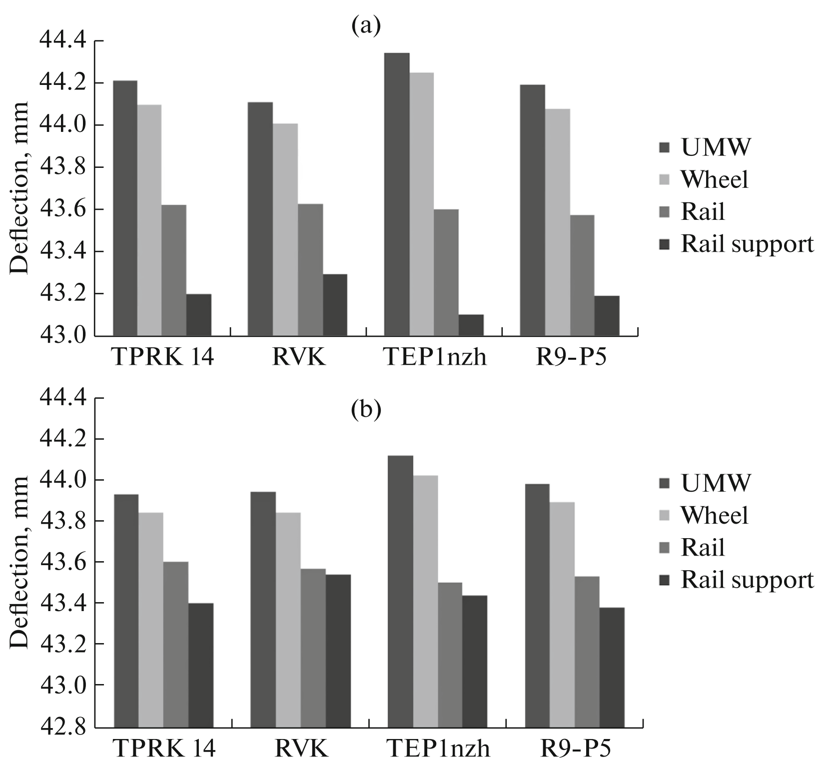

Fig. 6. Distribution of deflections upon mounting similar damping rail elements and sandwich with thickness of 14 mm: temperature is (a) +23°C and (b) –40°C.

straint force on the unsprung mass of the wagon and rail at nearly identical values with other variants on the wheel. At –40°C (Fig. 5b), the R9-P5 sandwich decreases the constraint force on the wheel and unsprung mass of the wagon to the degree of the RVK fiber-reinforced rubber composite and to the degree of TEP1nzh thermoplastic elastomer on the rail, which are minimal among the considered variants of shock absorber materials.

The distribution of deflections in the elements of the multiple-mass vibration system also showed the effectiveness of the R9-P5 sandwich, because the deflections of the wheel and unsprung mass of the wagon decreased to the level of rubber composites with a simultaneous decrease in deflection of the rail to the degree of TEP1nzh thermoplastic elastomer at above-zero and below-zero temperatures (Fig. 6). Deflections of the rail support of the sandwich decreased by 0.2 mm as compared to the deflections of the major RVK component.

The calculated characteristics of the sandwiches from various materials demonstrated high convergence with the experimental data.

CONCLUSIONS

Sandwich shock absorbers for rail transport from different damping materials possessing different dependences of elastic hysteresis characteristics on temperature and period of exposures are more effective than sandwich shock absorbers from similar materials. The highest operational characteristics have been determined for the rail damping element in the form of a sandwich made from the RVK fiber-reinforced rubber component 9 mm in thickness and the TEP1nzh thermoplastic elastomer 5 mm in thickness, which combines the advantage of each material at this ratio. This element provides a higher balance of the wagon–track vibration system, improves soft riding, and reduces the risk of resonance phenomena.

The developed procedure of the choice of elastic hysteresis characteristics of sandwich shock absorbers provides a sufficiently rapid design of their construction derived from the data of the test specimens with minimum expenditures.

The proposed mathematical model of the wagon–track multiple-mass vibration system makes it possible to evaluate the applicability and performance of the design of sandwich shock absorbers from the chosen materials for various operational conditions.

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