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Comparative Analysis of the Work of Bridge Spherical Bearing at Different Antifriction Layer Locations

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Abstract: The novel results reported here present qualitative and quantitative regularities of the deformation behavior of a spherical bearing with a different location and inclination angle of the antifriction layer. A number of topical problems encountered during the assessment of the performance bearings are considered in the work. The spherical bearings of the bridge span are investigated. Structures are load-bearing elements of transport systems. They perceive thermal power loads from the bridge span. The temperature problem is not considered in this study. In this paper, a comparative analysis of the bridge spherical bearing operation at different antifriction layer locations was performed. Two bearing geometries are considered: the interlayer is pressed in a spherical segment (classical geometry); the interlayer is pressed into a recess located in the lower steel plate. The six modern antifriction materials considered proved suitable to some extent as contact unit sliding layers for various purposes. Additionally, the influence of the inclination angle of the antifriction layer end face on the structure operation for all sliding layer material variants was analyzed. It has been established that the bearing design with an interlayer in the lower steel plate has a more favorable deformation behavior. Changing of the inclination angle of the antifriction layer end face leads to a decrease in the maximum level of contact parameters and deformation characteristics for all the considered structures.

Keywords: polymers; composite materials; friction; contact; bridge bearing; sliding; modeling; geometry



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1. Introduction

1.1. Research Objectives

The study purposes: performance comparison of spherical bearing of bridges two geometries differing in the antifriction layer location; influence analysis of the antifriction layer materials and the inclination angle end face to work of design.

Research tasks:

1. The work of two variants of the spherical bearing geometry is compared in an axisymmetric formulation.
2. The antifriction layer material effect is evaluated.
3. Analysis of the influence of the inclination angle of the antifriction layer end face on the stress–strain state of structures.

1.2. Problem Context

The first metal bridge structure was built in 1779. This design and its elements have been studied from different angles over the course of all subsequent years. Bridge structures of various types can be found today [1]: adjustable and fixed; spacer, beam or combined; arched and suspended. Structural features of various types of bridges and their elements

are described by many authors [2,3]. The tasks of the structure durability, its economically profitable construction, and the increase in its load-bearing capacity are researched [4]. The issues of preventive maintenance of bridges and their elements are also relevant to ensure the safety and serviceability of existing structures [5]. Wear models are often built from regular records of the bridge condition based on visual inspections [4,6]. The bridge state is determined by the main elements: supports, bearings, spans, etc. Calvert et al. proposed to include defects in the main structural elements and the interaction between them in the analysis of the bridge life cycle [7]. The use of information and communication technologies and robots to assess the current state of bridges and their elements is promising [6,8].

Cost analysis for the restoration of deteriorating structures and optimization of their service life and reliability are topical tasks in bridge building [9,10]. Replacing load-bearing structures, such as bridge bearings, is labor-intensive and costly [11–13]. Loss of element stability, disconnection of carrier nodes, overload, etc., are the main causes of the critical state or the destruction of bridges [14–16]. The operability of structures is associated with a breakdown or bearing capacity loss of elements: expansion joints [17,18], bearing [19–22], spans [22,23], lifting structures of drawbridges [24], and others. The tasks of rationalization and optimization of the principal load bearing elements are constantly relevant. This is due to the constant growth of the car park and the increase in the load on transport systems [14,25]. Now, manufacturers are striving not for mass production, but for the selection of structural parts for the bridge structure work, e.g., the selection of the sliding layer material in the bearing for the bridge span maximum load. These tasks are resolved not only for construction bridges planned, but also for already built historical bridges [26,27].

Increasing the strength, load-bearing capacity, and maintenance-free service life of transport systems elements are the main areas of research in this industry. The list of current tasks is quite extensive, including the rationalization and optimization of the designs of critical elements and bridges in general [28,29], new technologies for the creation and restoration [29–32], introduction of new materials with improved physico-mechanical and operational properties [33,34], as well as changing the geometry and configuration of bearing elements [33]. It is also important to analyze the influence of materials on the unit functionality [35,36].

Significant progress can be noted in the field of creating new modern functional materials for various elements of bridge structures. Materials can show increased value in terms of reliability, durability, and wear resistance. They have improved physical-mechanical, frictional, and rheological properties. Factors that hinder the effective use of modern polymeric materials and composites based on them in many industrial areas and as thin antifriction layers in the bearing of bridge spans are noted in [37,38]. Modern materials can significantly increase the working life of the sliding layer bearings of bridges [39–41]: nanofilled and unfilled PTFE, ultrahigh molecular weight polyethylenes (UHMWPE), nanomodified polymeric materials and composites of various brands and production. The particular interest here applies to a comparative analysis of the influence of the antifriction layer materials of the bridge bearings on their deformation behavior. The study of geometric design various modifications of the bearings is also relevant.

1.3. Problem Description

The bearings geometry was flat due to the difficulty of producing a spherical structure initially. Many varieties of bearing geometries now exist. Most of them are considered in [19]. Rubber [42–44] and spherical [33,45–47] bearings are the most common. Spherical bearings are widely used in bridge structures in transportation systems around the world. This effect is due to the fact that the articular type is the best mechanism for mitigating shocks and ensuring smooth movements in nature. The spherical element in contact with the spherical deepening is an articular type construction [46]. There are many manufacturers of spherical bearings: MAGEBA (Bülach, Switzerland), MAURER (Munich, Germany), FIP MEC (Selvazzano Dentro, Italy), AlfaTech LLC (Perm, Russia), KO Lumi-ere Ltd. LLC

(Moscow, Russia), Mostotrest (Moscow, Russia), etc. The different manufacturers bearing differ in the elements design and the sliding layers materials. Constructions with a sliding layer deposited on a spherical segment are quite common, as noted in [19]. Many manufacturers implement structures with a spherical sliding layer pressed into the bottom steel plate. The question arose about comparing these configurations and identifying the features of their applicability. The interlayer between the contact pairs is used to ensure the structure longevity. The interlayer position, its thickness, the cutout geometric configuration for the interlayer, etc. have a great influence on the bearing deformation process [47].

Tasks related to the use of various polymers and composites in the bridge bearing remain just as relevant. PTFE is one of the most common materials used as a sliding layer in bearings. Its use in its pure form is not always effective, as noted in [48]. For example, the authors [49] noted a decrease in the wear rate of the material after exposure to irradiation on PTFE composites due to increased interfacial interactions of macromolecules. A large set of modern polymeric materials and composites based on them exists and they can be used as antifriction coatings and interlayers in friction units [50–52]. New polymeric and composite materials [50,51] can have improved physico-mechanical, frictional, thermomechanical, and rheological properties. UHMWPE and composite materials based on them [20,50,53], antifriction materials based on PTFE [20,50,54], and modified PTFE [52–55] are antifriction materials.

This work is aimed at comparing the deformation behavior of bridge bearings of different geometry. Spherical bearings are considered. The study also includes an analysis of the performance of interlayers from various modern materials in the bearings.

2. Materials and Methods

2.1. Model

Two variants for the bearing geometry are considered (Figure 1). Model A: an interlayer (3) fills a recess in the upper steel plate (1). Model B: an interlayer (3) fills a recess in the lower steel plate (2). The main overall dimensions of the structure and the load-bearing capacity do not depend on its configuration. Structure height is $h = h_1 + h_p + h_2 = 54$ mm, width is $B = 2b = 155$ mm, and standard vertical load is 1000 kN. The interlayer thickness is constant $h_p = 4$ mm. The antifriction layer end face S_{K_3} (3) is partially in contact with the steel elements. The initial contact surface is 50% of the interlayer thickness (2 mm). Standard inclination angle of the antifriction layer end face is $\alpha_p = 30^\circ$. The polymer layer is pressed into steel structural elements. Overall dimensions correspond to the minimum standard size of bearings manufactured by AlfaTech LLC.

The paper considered the contact between the steel bearing elements with an antifriction layer at a constant friction coefficient of 0.04 (according to the data of the bearings manufacturer AlfaTech LLC).

Earlier, the deformation behavior study was carried out with two variants of the bearing geometry [56]. The study was conducted on an example of the layer made from modified PTFE. The contact divergence in model A is observed at the standard angle of the end face. The zone of complete “no contact” on the mating surface, on which the spherical segment is possible rotation, is observed near the antifriction layer edge (model A— S_{K_2}). In the bearing of model B, the effect of “no contact” is not observed.

In [57], the authors studied the influence of the inclination angle of the antifriction layer end face (modified PTFE) on the deformation of structures of different geometries. End face angles from 0° to 45° have been investigated. The paper has established that a favorable distribution of the contact zone parameters and the deformation characteristics of the sliding layer is obtained at the inclination angles of the end face of 25° and 40° for model A and 0° for model B.

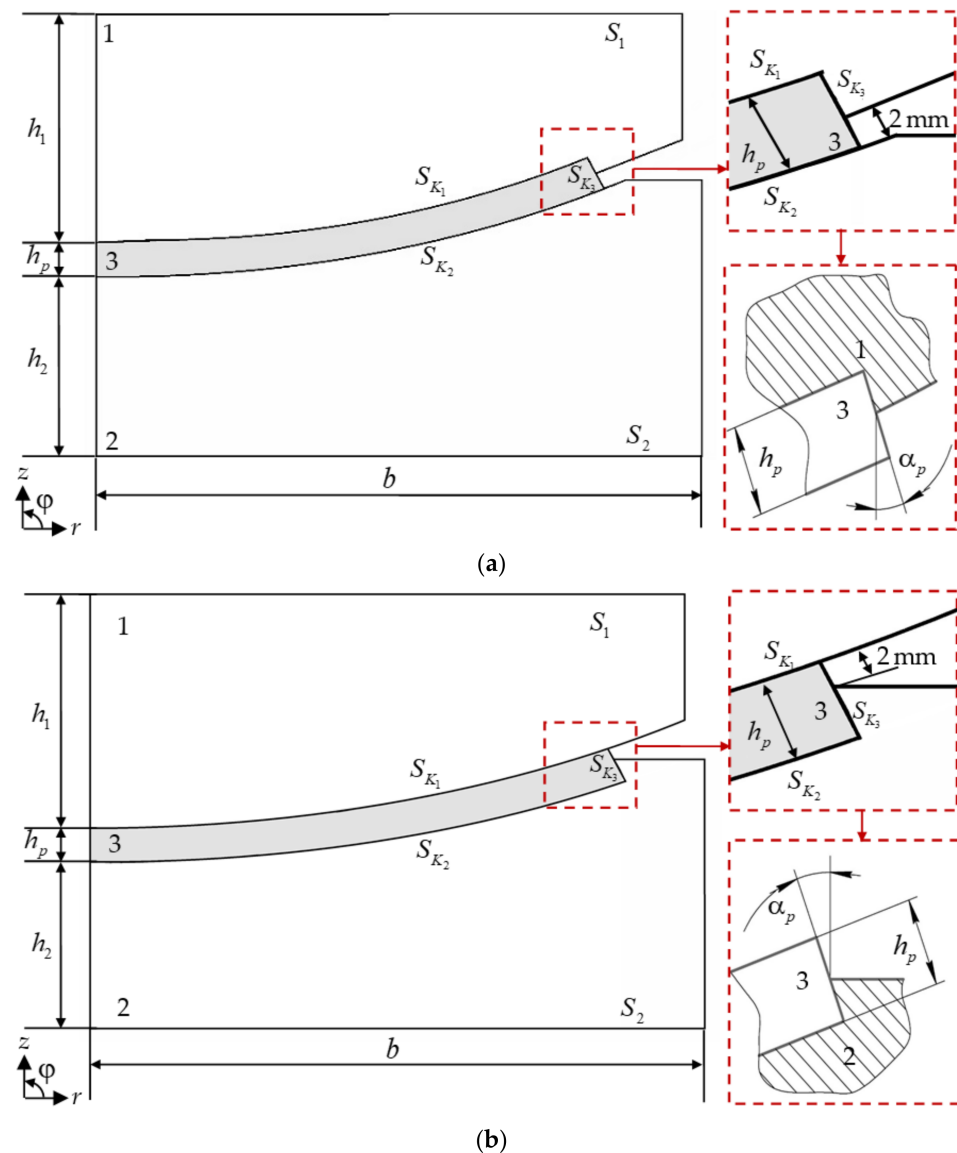


Figure 1. Calculation scheme of the spherical bearing: (a) is model A; (b) is model B.

The analysis of the influence layer material properties on the structure performance of different geometries is of interest. Studies include standard and “rational” α_p .

2.2. Materials

A series of experiments (Figure 2) to determine the antifriction polymer and composite mechanical properties for suitability as a bearing layer was previously carried out on the basis of the IMSS Ural Branch of the Russian Academy of Sciences (Perm, Russia). The research included more than 30 materials. Antifriction materials based on PTFE, ultrahigh molecular weight polyethylenes, and composites based on them with different fillers are researched. Research is aimed at the selection of new antifriction materials with improved performance properties. Optimization of the design performance of the bearing manufactured by AlfaTech LLC is the goal. The experiments are aimed at determining the physico-mechanical and operational characteristics of antifriction polymer and composite materials.

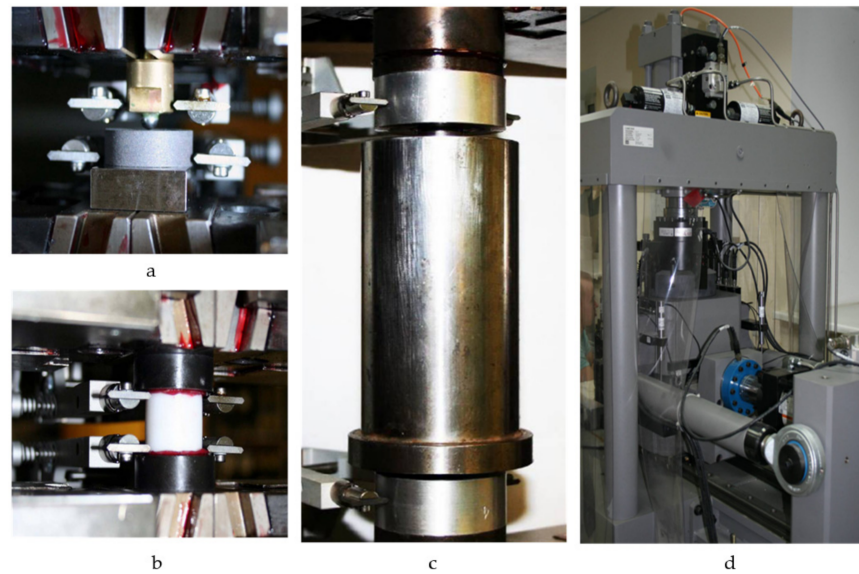


Figure 2. Experimental studies: (a) is Brinell hardness; (b) is free compression; (c) is cramped compression; (d) is friction studies on the MTS 316 test rig with original equipment.

Regarding the study of physico-mechanical properties, the hardness of materials was assessed according to Brinell, with complicated loading of materials samples under free and constrained compression in the range of working deformations and stresses, etc. A number of materials were excluded from further study based on the experiments results. The main reasons for excluding materials from further consideration:

- materials cannot be produced in the required volume;
- materials have a very heterogeneous set of properties;
- significantly nonlinear compressibility of materials under constrained compression has been discovered;
- additional experimental studies with different histories of long-term multistage loading are required, etc.

The 6 materials with improved properties compared to pure PTFE were selected based on the research results. Pure PTFE is still the most common material for the antifriction layer of bearings [45,58,59]. Materials based on UHMWPE and modified PTFE have almost elastic behavior with weakly non-linear hardening. The rigidity of UHMWPE and modified PTFE is significantly (~1.5 times) higher than the other materials' rigidity at a pressure level of 50 MPa. Two composites based on PTFE are included in the selected set of materials. Materials are included in the study for comparison. Composites produced by AlfaTech LLC are considered. Materials under study (Table 1): 3 UHMWPE from different manufacturers (mat. 1–3), 2 composite materials based on PTFE with bronze inclusions of different geometry (mat. 4–5), and radiation-modified PTFE (mat. 6).

Table 1. Physical and mechanical properties of antifriction layer materials.

Parameter	Material 1 (UHMWPE with Carbon Additive)	Material 2 (UHMWPE Produced in Germany)	Material 3 (UHMWPE Produced in Russia)	Material 4 (MAK Composite with Dendritic Bronze Inclusions)	Material 5 (MAK Composite with Spherical Bronze Inclusions)	Material 6 (Modified PTFE)
E , MPa	1420	706	1050	903	860.52	863.8
ν	0.440	0.470	0.452	0.447	0.439	0.461

An additional series of experiments to refine the physical and mechanical properties is required for material 1, which was established in the framework of studies [60].

Materials can be described as a viscoplastic compressible body with non-linear volumetric compressibility and phase transitions. A complete description of the rheological features of materials is a complex and time-consuming task. Materials work under slowly changing loads and temperatures. In the first approximation the materials model may reflect the main features of their behavior without time factor. The use of the simplest elastoplastic models with material volumetric compressibility is preferable. Elastoplastic hardening MISO is selected as the sliding layer material model [47]. At the moment, the team is working on a mathematical description of the materials rheology. The search for modern antifriction materials and composites of Russian and foreign production with improved thermomechanical properties continues.

A series of experiments on frictional properties included a limited set of materials. The American Society of Lubrication Engineers (ASLE) classified 234 known test devices according to their geometry into 12 groups in 1976. "Plane on plane" (reciprocating or linear motion) is the 4th group. This method of determining the friction characteristics was used in the development of the test program. The friction of materials on steel chrome and polished sheet without and with lubrication at pressure in the range of $1.2 \div 60$ MPa was investigated. The dependences of the friction coefficients on the applied load are established. The friction coefficient steel-polymer does not exceed 0.04 according to the bearing manufacturer. The friction coefficients of polymers and composites under different conditions were found to be about 0.04 or less at a load of ~ 55.5 MPa (standard load L-100). It was decided to consider the materials work at the same constant friction coefficient of 0.04 within the first approximation.

2.3. Mathematical Setting, Boundary Conditions and Methods

The problem of mathematical formulation is described within the framework of the deformation theory of elastoplasticity [60]. The constitutive relations are supplemented by taking into account large deformations in the antifriction layer volume.

Boundary conditions:

$$\int_{S_1} P dS_1 = -Q_z, u_z(r, z_{S_1}) = U = \text{const}, \sigma_{rz} = 0, r \in S_1,$$

$$u_z = 0, \sigma_{rz} = 0, r \in S_2$$

where Q_z is the vertical force applied to S_1 , and U is an unknown constant value.

Figure 3 presents boundary conditions and finite element models of the spherical bearings.

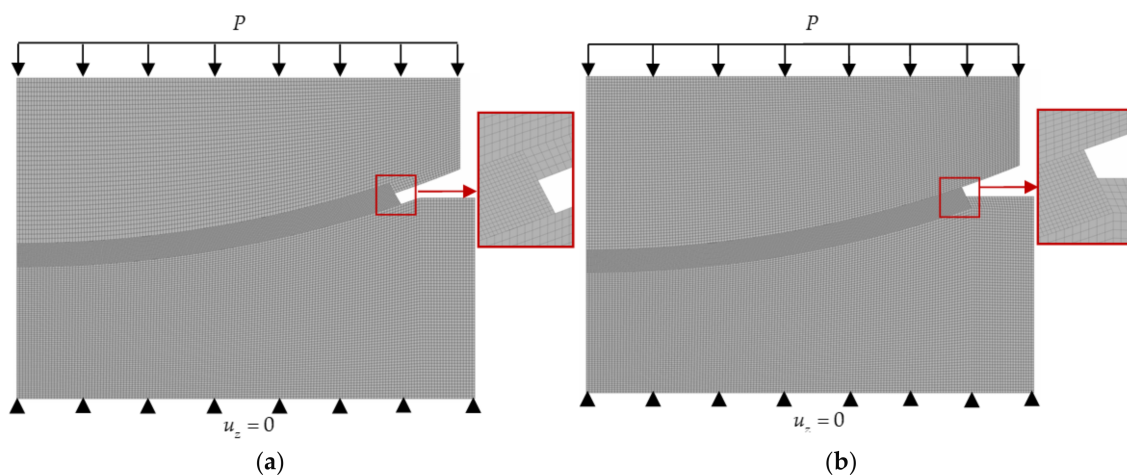


Figure 3. The boundary conditions and finite element models: (a) is model A; (b) is model B.

The problem is implemented in an axisymmetric formulation using the finite element method. An axisymmetric four-nodal finite element is used. Gradient condensation of elements to the contact areas is implemented. The antifriction layer is divided into 16 elements in thickness. The convergence analysis of the numerical solution on the degree of system discretization was performed earlier [20].

The commercial package of engineering analysis ANSYS Mechanical APDL (ANSYS Inc., Canonsburg, PA, USA) was used to implement the task.

Contact boundary conditions are described in [60]. The paper considered a surface-to-surface contact with an unknown pattern of the distribution of contact state statuses (adhesion, sliding, no contact). The contact interaction is implemented taking into account friction along the mating surfaces. The elements contact pair CONTA171 and TARGE169 is used. “Close gap” is the initial settings of contact elements. Augmented Lagrangian method is contact computation method.

The model parametrization process was carried out to automate numerical calculations. Parameterization parameters: interlayer thickness, inclination angle of the antifriction layer end face, position of the interlayer relative to the steel plate, etc.

The problem solution is based only on the operational requirements for structures. A number of studies aimed at solving the optimization problem are planned to be carried out in the future.

Comparison of the contact stress-strain state parameters of structures is carried out according to the formula (1), where the data of model A are chosen as the reference values:

$$\Delta X = |X_{\text{model A}} - X_{\text{model B}}| / X_{\text{model A}} \cdot 100\%, \quad (1)$$

where $X_{\text{model A}}$ and $X_{\text{model B}}$ are respectively the values of the compared parameters of models A and B. The comparison parameters: P_K is contact pressure; τ_K is contact tangential stress; u_n is normal displacements on S_{K3} ; $\Delta u_z|_{r \in S_1}$ is structure draft.

3. Results

The bridge bearing are friction units. Contact parameters of elements conjugation zones (contact pressure, contact tangential stress, contact states statuses) are the interest main characteristics. Let's introduce the notation:

- “pressed surface” is contact surface pressed into steel plates (S_{K1} in model A, S_{K2} in model B);
- “turning surface” is the contact surface along which the rotation of the spherical segment is possible (S_{K2} in model A, S_{K1} in model B);
- “end face surface” is relatively free end face of the interlayer (S_{K3} in model A and B);
- S_{adhesion} is area that is contact with full adhesion;
- $S_{\text{no contact}}$ is area of the zone of “no contact” (divergence) of mating surfaces.

Model A with an interlayer in the top steel plate is a classic bearing geometry [19]. Such a bearing geometry is currently quite often used in bridge structures. However, in the future, model B could show better results in the operation of the structure compared to model A. In this regard, the paper is of particular interest in the comparison of bearing performance with different positions of the interlayer relative to the structure steel plates.

The paper [47] presented the distribution pattern of contact parameters and deformation characteristics of the model B mating surfaces. Figures 4 and 5 present the distribution pattern of model A contact parameters. Figure 4 presents a “pressed surface” (S_{K1} of model A). Figure 5 shows a “turning surface” (S_{K2} of model A). The following contact parameters are shown in the figures: P_K , contact pressure; τ_K , contact tangential stress; r , radius of sliding layer.

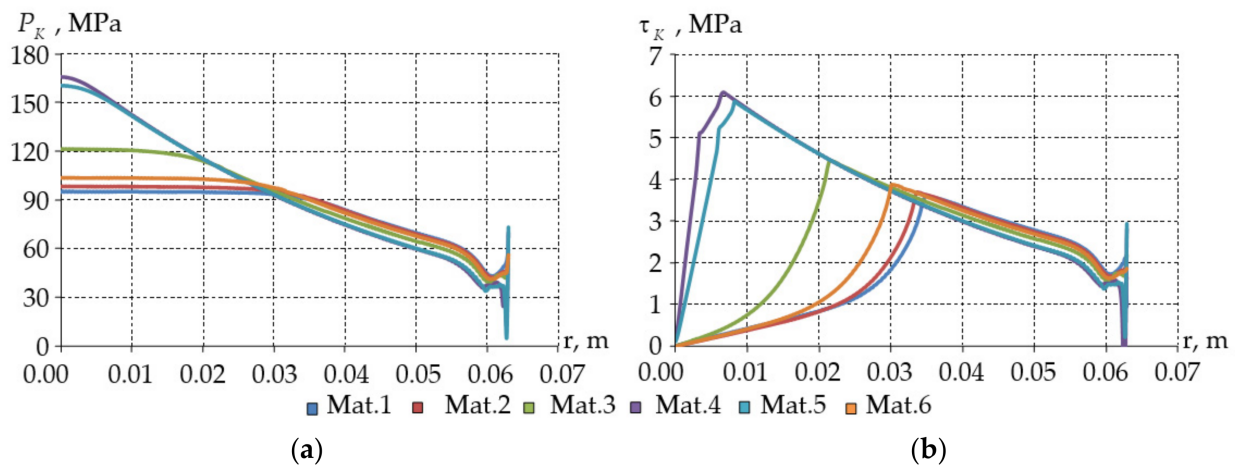


Figure 4. Contact pressure (a) and contact tangential stress (b) on “pressed surface” model A.

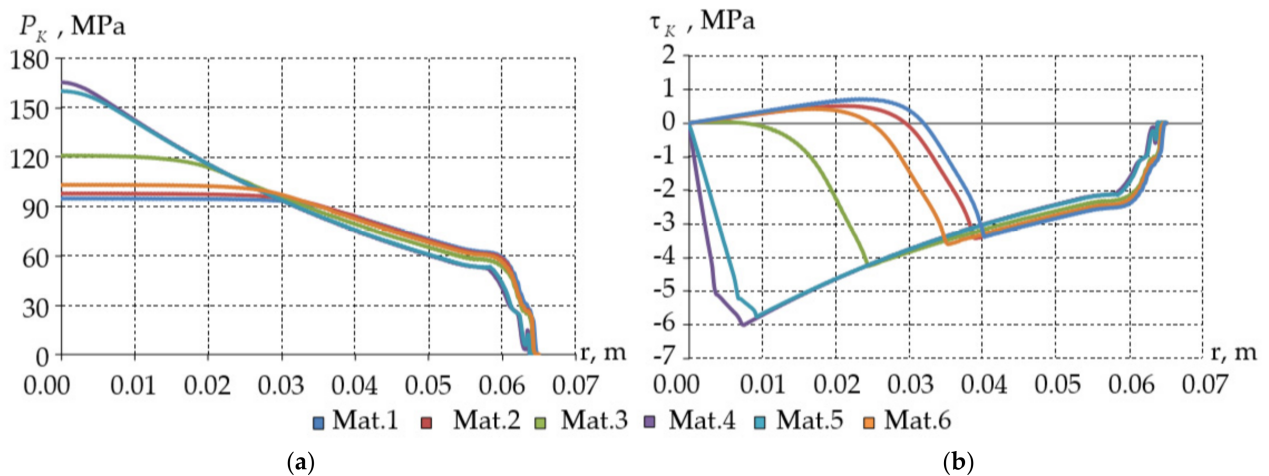


Figure 5. Contact pressure (a) and contact tangential stress (b) on “turning surface” model A.

The maximum level of contact pressure and contact tangential stress is observed in composite materials (mat. 4–5). The zone of contact surfaces complete “adhesion” is located in the bearing central part. The zone of contact status change from “adhesion” to “sliding” is located in the maximum level of contact tangential stress of polymer layers (mat. 1, 2, 3, 6). The distribution pattern of the contact states statuses is different for interlayers from composite materials (mat. 4–5). The zone of complete “adhesion” is minimal for composite materials (mat. 4–5). The zone of contact status change “adhesion”—“sliding” occurs at the points of change in the law of increase in the contact tangential stress. Such a difference is observed only in model A. Small differences in contact parameters are observed for interlayers of materials 1, 2, and 6: the percentage of the mating surface is in the “adhesion” state is maximum, i.e., materials work within the framework of the elasticity theory on a larger volume of the antifriction layer; the $\max P_K$ and $\max \tau_K$ is minimal.

Table 2 shows a comparison of the contact characteristics of the “pressed surface” for two variants of the structure geometry.

Table 2. Comparison of the maximum level of contact pressure and tangential stress on “pressed surface”.

Parameter	Material					
	1	2	3	4	5	6
Model A						
$\max P_K$, MPa	95.487	98.264	121.200	166.030	160.520	103.500
$\max \tau_K $, MPa	3.629	3.702	4.451	6.101	5.871	3.877
$\max P_K > \max \tau_K$	26.315	26.547	27.232	27.214	27.341	26.693
Model B						
$\max P_K$, MPa	90.559	92.095	110.39	148.32	135.44	96.193
$\max \tau_K $, MPa	3.060	3.166	3.810	5.276	4.717	3.291
$\max P_K > \max \tau_K$	29.599	29.093	28.971	28.111	28.716	29.228
Comparison Models A and B						
$\Delta \max P_K$, %	5.161	6.278	8.919	11.856	15.624	7.060
$\Delta \max \tau_K $, %	15.684	14.481	14.389	15.785	19.663	15.121

$\max \tau_K$ is lower than $\max P_K$ by an average of 27 and 29 times in models A and B, respectively. At the same time, the maximum level of contact parameters of model B is much lower than that of model A. The greatest influence of the interlayer position during the structure deformation is on the contact tangential stress. The maximum influence of the interlayer position on $\max P_K$ is observed in structures with a sliding layer from composite materials (mat. 5–6). The materials are subject to plastic flow, which affects the geometry of the end face.

The distribution pattern and comparison of the contact parameters of structures along the “turning surface” (Figure 5, Tables 3 and 4) are of great interest. P_K , τ_K , and areas of contact “adhesion” and “no contact” are considered. The results are presented on the example of model A (Figure 5).

Table 3. Comparison of the maximum level of contact pressure and tangential stress on “turning surface”.

Parameter	Material					
	1	2	3	4	5	6
Model A						
$\max P_K$, MPa	95.217	98.087	121.070	165.620	160.230	103.390
$\max \tau_K $, MPa	3.362	3.415	4.239	6.009	5.759	3.593
$\max P_K > \max \tau_K $	28.321	28.724	28.564	27.561	27.815	28.773
Model B						
$\max P_K$, MPa	90.803	92.216	110.390	148.460	135.570	96.268
$\max \tau_K $, MPa	3.421	3.475	4.085	5.396	4.852	3.621
$\max P_K > \max \tau_K $	26.540	26.539	27.024	27.514	27.944	26.587
Comparison Models A and B						
$\Delta \max P_K$, %	4.636	5.986	8.813	10.361	15.390	6.888
$\Delta \max \tau_K $, %	1.755	1.757	3.633	10.201	15.749	0.779

Table 4. Contact state on “turning surface” models.

Parameter	Material					
	1	2	3	4	5	6
Model A						
$S_{adhesion}, \%$	37.55	35.27	13.77	1.18	1.86	28.87
$S_{no\ contact}, \%$	1.49	2.97	2.97	4.73	4.44	2.23
Model B						
$S_{adhesion}, \%$	31.39	29.31	14.64	2.78	5.34	26.28
$S_{no\ contact}, \%$	0.00	0.00	0.00	5.17	4.44	0.00

The distribution pattern of the contact pressure over the “turning surface” is identical to the “pressed surface”. The interlayer position also does not affect the pattern of the contact pressure distribution. Ref. [26] considered comparison of the distribution pattern of contact parameters on the example of a layer from modified PTFE. Contact tangential stresses of structures with layers of composite materials (mat. 4–5) are negative over the entire “turning surface” area. The contact status change zone “adhesion”—“sliding” is located at the points of change in the law of increase in the contact tangential stress. This effect is not observed in structures with interlayers of polymeric materials. The “no contact” zone near the end face is observed in model A at $\alpha_p = 30^\circ$ for all variants of the interlayer material.

The maximum level of contact parameters on the “turning surface” is comparable in terms of values with the “pressed surface”. The maximum parameters level is observed in structures with layers of composite materials (mat. 4–5). $\max \tau_K$ is lower than $\max P_K$ by an average of 28 and 27 times in models A and B, respectively. The maximum level of contact parameters of model B is much lower than that of model A. The interlayer position on the “turning surface” has the greatest influence on the contact pressure. Differences $\max \tau_K$ on the “turning surface” are minimal in the design with a layer of modified PTFE (mat. 6), less than 1%.

Model A has more $S_{adhesion}$ than model B for half of the interlayer materials (mat. 1, 2, 6). The mating surfaces divergence is observed for all interlayer materials near the end face of the sliding layer. This effect is associated with deformation of the relatively free end face of the interlayer. The redistribution of contact pressure and contact tangential stress occurs when a zone of “no contact” appears. This leads to an increase in the contact parameters maximum level in the bearing center (model A). The “no contact” zones are not observed in model B for structures with interlayers of polymeric materials (mat. 1–3, 6). The “no contact” zone is observed in structures with interlayers of composite materials (mat. 4–5) on 4.44–5.17% of the mating surface.

The contact parameters of the main mating surfaces $S_{K_1} - S_{K_2}$ depend on the deformation relative to the free end face of the interlayer. Changing the contact parameters of the end face is not informative. Displacements along the surface normal are the main indicator of the structure performance (Figure 6).

The end face of the interlayer model A is more prone to deformation. The interlayer material flows out of the bearing steel part, which leads to a significant level of deformation. The possibility of cutting off the interlayer material part arises in this case. Normal displacements of less than 1 mm are observed in structures with interlayers of polymeric materials (mat 1–3, 6). Interlayers from composite materials are more susceptible to deformation. A similar pattern is also observed in model B: the level of displacement along the normal of the interlayers end face from composite materials is much greater than that of polymer interlayers. The interlayer material remains in 100% contact with the recess in the structure of the lower steel plate.

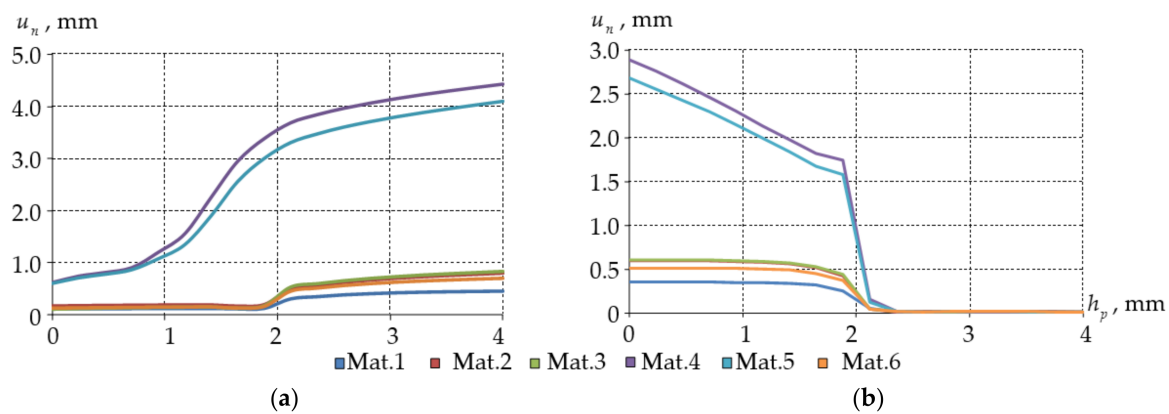


Figure 6. Normal displacements (b) on S_{K_3} : (a) is model A; (b) is model B.

Table 5 presents a comparison of the maximum level of displacement along the normal “end face surface”.

Table 5. Comparison of the maximum level normal displacement of the anti-friction layer end.

Parameter	Material					
	1	2	3	4	5	6
Model A						
$\max u_n$, mm	0.451	0.802	0.834	4.423	4.093	0.700
Model B						
$\max u_n$, mm	0.358	0.594	0.607	2.894	2.680	0.513
Comparison Models A and B						
$\Delta \max u_n$, %	20.621	25.935	27.218	34.569	34.522	26.714

The maximum displacements along the normal “end face surface” of model B are 20% or more lower than those of model A. The normal displacement “end face surface” interlayer from composite materials is more than 4 mm in model A, which is comparable to the antifriction layer thickness. The “no contact” zones on the contact surface S_{K_3} are observed in model A, which leads to a decrease in the structure performance.

AlfaTech LLC has developed an original experimental setting. The setting allows you to create conditions as close as possible to the structure stress-strain state in the bridge span. The scientists investigated the bearing with a layer of modified PTFE (mat. 6) located in the lower steel plate (model B). It is established that the numerical simulation error from the experiment on the structure draft ($u_z|_{r \in S_1}$) was 13.67%. The model draft is less than in the experiment. Table 6 shows an analysis of the influence of materials and the location of the interlayer on the bearing operation in terms of structural draft.

The model A draft is greater than that of model B. This effect is associated with a significant deformation of the “end face surface”. The maximum draft of structures is observed when using interlayers from composite materials (mat. 4–5).

The influence of the inclination angle “end face surface” on the structure operation will be considered further. The influence of the inclination angle of the end face on the contact parameters of the “turning surface” (Figure 6, Tables 7 and 8), displacement along the normal “end face surface” (Figure 7, Table 9), and the structure draft (Table 10) is of the greatest interest.

Table 6. Draft of bearing under different interlayer locations.

Parameter	Material					
	1	2	3	4	5	6
Model A						
$u_z _{r \in S_1}$, mm	0.120	0.190	0.147	0.318	0.312	0.142
Model B						
$u_z _{r \in S_1}$, mm	0.108	0.162	0.102	0.243	0.252	0.123
Comparison Models A and B						
$\Delta u_z _{r \in S_1}$, %	11.135	17.260	44.046	30.876	23.522	15.833

Table 7. Comparison of the maximum level of contact pressure and tangential stress under different α_p .

Parameter	$\alpha_p, ^\circ$	Material					
		1	2	3	4	5	6
Model A							
$\max P_K$, MPa	0	90.888	100.090	99.848	142.510	120.610	97.690
	30	95.217	98.087	121.070	165.620	160.230	103.390
$\max \tau_K $, MPa	0	3.173	3.493	3.494	5.080	4.257	3.393
	30	3.362	3.415	4.239	6.009	5.759	3.593
Model B							
$\max P_K$, MPa	25	87.417	94.860	93.021	124.540	114.140	92.495
	30	90.803	92.216	110.390	148.460	135.570	96.268
	40	87.878	94.400	93.434	126.870	115.650	92.886
$\max \tau_K $, MPa	25	3.306	3.532	3.493	4.563	4.204	3.483
	30	3.421	3.475	4.085	5.396	4.852	3.621
	40	3.322	3.520	3.514	4.658	4.286	3.487

Table 8. Contact state on “turning surface” models under different α_p .

Parameter	$\alpha_p, ^\circ$	Material					
		1	2	3	4	5	6
Model A							
$S_{adhesion}, \%$	0	42.81	28.87	30.10	4.83	12.94	33.07
	30	37.55	35.27	13.77	1.18	1.86	28.87
$S_{no\ contact}, \%$	0	0.00	0.00	0.00	3.71	2.97	0.00
	30	1.49	2.97	2.97	4.73	4.44	2.23
Model B							
$S_{adhesion}, \%$	25	38.36	29.80	27.21	9.39	14.17	33.10
	30	31.39	29.31	14.64	2.78	5.34	26.28
	40	35.69	27.21	27.97	7.59	12.11	29.51
$S_{no\ contact}, \%$	25	0.00	0.00	0.00	4.33	4.33	0.00
	30	0.00	0.00	0.00	5.17	4.44	0.00
	40	0.00	0.00	0.00	3.55	2.84	0.00

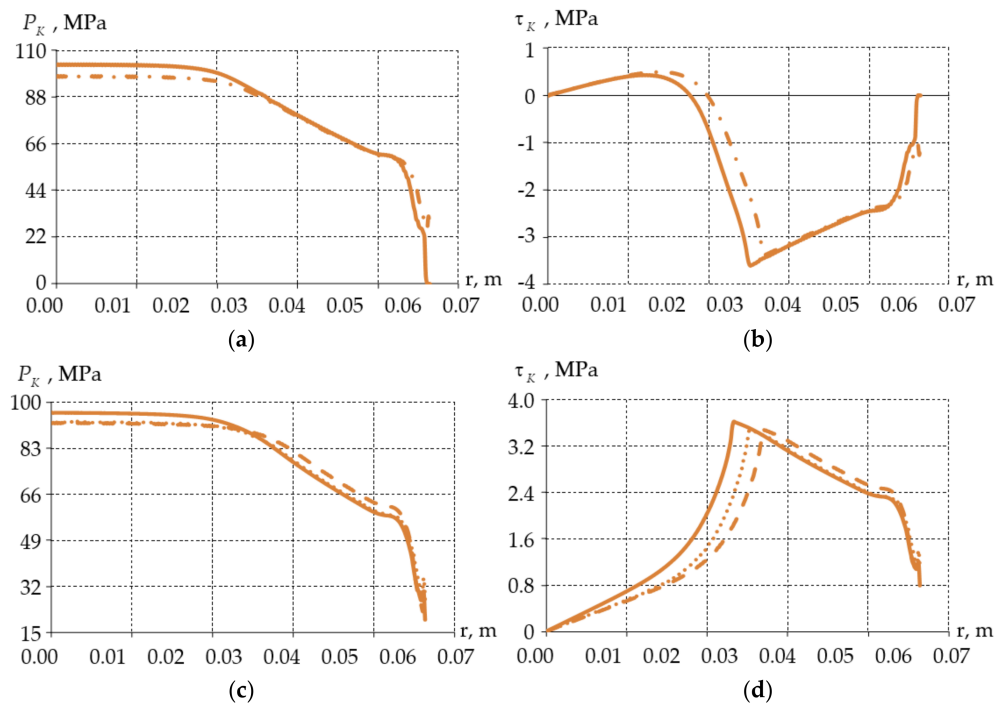


Figure 7. Contact pressure (a,c) and contact tangential stress (b,d) on turning surface: (a,b) is model A; (c,d) is model B; solid line is $\alpha_p = 30^\circ$; dash-dotted line is $\alpha_p = 0^\circ$; points is $\alpha_p = 25^\circ$; dotted line is $\alpha_p = 40^\circ$.

Table 9. Comparison of the maximum level displacements along the normal “end face surface” under different α_p .

Parameter	$\alpha_p, ^\circ$	Material					
		1	2	3	4	5	6
Model A							
$\max u_n, \text{ mm}$	0	0.400	0.688	0.679	2.596	2.200	0.560
	30	0.451	0.802	0.834	4.423	4.093	0.700
Model B							
$\max u_n, \text{ mm}$	25	0.353	0.585	0.569	2.224	2.066	0.480
	30	0.358	0.594	0.607	2.894	2.680	0.513
	40	0.334	0.553	0.536	2.550	2.262	0.454

Table 10. Draft of bearing under different α_p .

Parameter	$\alpha_{p'},^\circ$	Material					
		1	2	3	4	5	6
Model A							
$u_z _{r \in S_1}, \text{ mm}$	0	0.116	0.136	0.138	0.240	0.243	0.133
	30	0.120	0.190	0.147	0.318	0.312	0.142
Model B							
$u_z _{r \in S_1}, \text{ mm}$	25	0.100	0.114	0.116	0.218	0.217	0.113
	30	0.108	0.162	0.102	0.243	0.252	0.123
	40	0.112	0.130	0.130	0.224	0.233	0.127

Figure 7 presents the distribution pattern of contact pressure and contact tangential stress on the example of the layer from modified PTFE (mat. 6).

Changing the inclination angle of the end face of the interlayer made it possible to obtain a number of positive effects for most sliding layer materials:

- an increase in the area of full “adhesion” of mating surfaces;
- lowering the maximum level of contact parameters;
- absence of “no contact” zone near the end face of the model A layer.

Changing the inclination angle of the end face made it possible to reduce the maximum level of contact materials for most materials (except mat. 2). $\max P_K$ and $\max |\tau_K|$ decreased in model A by 4.5–24.7 and 5.6–26.1%, respectively. $\max P_K$ and $\max |\tau_K|$ decreased in model B on average by 3.5–15.5 and 3.1–14.6%, respectively. An end face angle of 25° allows to reduce the contact parameters maximum level more than an angle of 40° . This effect is not observed in structures with a UHMWPE interlayer made in Germany (mat 2). An increase in the contact parameters maximum level is observed in interlayers from mat. 2. $\max P_K$ and $\max |\tau_K|$ increased in model A by 2.04 and 2.28%, respectively. $\max P_K$ and $\max |\tau_K|$ increased in model B on average by 2.6 and 1.5%, respectively.

Changing the inclination angle of the end face made it possible to increase the “adhesion” area of mating surfaces for most materials (except mat. 2). A decrease in the mating surface percentage in status “adhesion” area is observed in interlayers from mat. 2. The “no contact” zones are not observed in structures with interlayers from polymeric materials (mat. 1–3, 6) in model A at $\alpha_p = 0^\circ$. The percentage of the “no contact” area of the mating surfaces has significantly decreased in structures with interlayers from composite materials at “rational” α_p .

Figure 8 shows displacements along the normal “end face surface” with a layer of modified PTFE as an example.

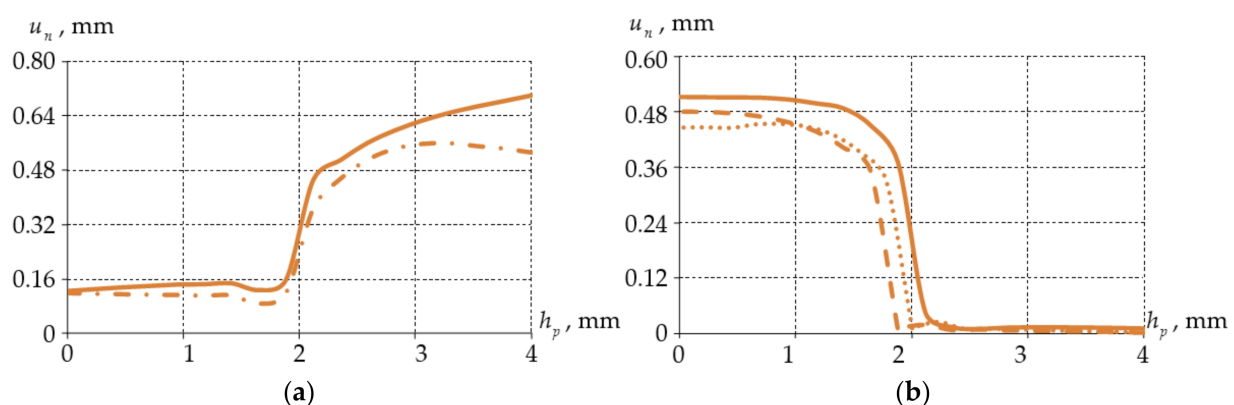


Figure 8. Normal displacements (u_n) on S_{K_3} : (a) is model A; (b) is model B; solid line is $\alpha_p = 30^\circ$; dash-dotted line is $\alpha_p = 0^\circ$; points is $\alpha_p = 25^\circ$; dotted line is $\alpha_p = 40^\circ$.

A decrease in the maximum level of displacements along the normal “end face surface” for “rational” α_p was observed.

The maximum decrease in $\max u_n$ is observed in model A with a layer from composite materials (mat. 4–5) and reaches more than 40% at an angle of 0° . The maximum decrease in $\max u_n$ is observed in model B at an angle of 25° with a sliding layer from composite materials and reaches more than 20%. The inclination angle of the end face has a minimal effect on the mat. 1 and 2 (UHMWPE). By an angle of 25° , $\max u_n$ became less than at a standard angle by less than 2%. The average decrease in the $\max u_n$ level compared to the interlayer with a standard end face angle is 10–25% in other cases.

A draft increase is observed in model B at an end face inclination angle of 40° in interlayers from mat. 1, 6 and reaches 3.3%. The draft level increasing in bearing with interlayers from mat. 3 is observed in model B when the standard inclination angle of the end face is changed. The maximum draft decrease is observed when changing the inclination angle of the end face in structures with layers from composite materials and

reaches more than 20% and 10% in models A and B, respectively. Structures with interlayers from polymeric materials (mat 1–3 and 6) showed a comparable draft with a change in the inclination angle of the end face, i.e., the materials of interlayer begin to work in the design with small differences.

4. Discussion

4.1. The Compared Results to PTFE Interlayer

Pure PTFE has not considered in the scientific group studies as a sliding layer of the bearing since 2013. The material was excluded from the most promising sliding layer materials set by the bearing manufacturer AlfaTech LLC. Paper [48] reflected the limitations of its use in friction units, too. However, articles [56–58] noted a number of modern scientific studies of the behavior of the bridges bearing with pure PTFE interlayers. Interest in the deformation of spherical bearings considered in this article has arisen, specifically pertaining to models with a layer of pure PTFE. Table 11 presents the study results.

Table 11. Deformation of pure PTFE interlayers.

Model	Parameter					
	$\max P_K _{\text{turning surface'}}$ MPa	$\max \tau_K _{\text{turning surface'}}$ MPa	$S_{\text{adhesion}} _{\text{turning surface'}}$ %	$S_{\text{no contact}} _{\text{turning surface'}}$ %	$\max u_n _{S_{K_3'}}$ mm	$u_z _{r \in S_1'}$ mm
A	168.95	6.02	3.59	7.05	5.77	0.41
B	156.58	5.05	14.59	5.72	3.90	0.27

The maximum levels of contact pressure and contact tangential stress of structures with a PTFE interlayer are much higher than those from modern sliding layer materials. With displacements along the normal of the end face of the sliding layer, the draft and the “no contact” area of “turning surface” of structure are also maximum. Plastic flow of material from the recess of lower plate is observed when using a layer of pure PTFE in Model B. The authors [48] obtained confirmation of data on the limited use of PTFE.

The behavior of composite materials is closest to pure PTFE. Thus, the insertion of reinforcing elements into the PTFE matrix slightly improved the physical and mechanical properties of the material. The question of the influence of the reinforcing elements on the structure steel elements is interesting. Bronze inclusions can act as an abrasive when the interlayer is deformed, which will lead to defects in polished mating surfaces.

The results presented in this article have an important place in the development of bridge building. They reflect the work comparison of different spherical bearing geometries of bridges. Information about bearings with different interlayer locations in steel plates of structures was presented by Eggert et al. as early as 1974 [41]. However, a work comparison of such structures as performed by the authors of this article was not found in open sources. The current study results showed that bearings with an interlayer pressed into the lower steel plate (Model B) better absorb the vertical loads from the bridge span.

The authors implemented the work comparison of a modern polymer and composite set as an antifriction layer of bearing, too. The data are of practical importance. The research is aimed at collecting a database on the interlayers from different material deformations. The conclusion made is based on the work results and studies performed earlier [33,47,49,56–58], namely that at the moment the most promising materials as an interlayer are mat. 2 and 6. Material 1 is not considered as more promising due to the lack of the possibility of its production on an industrial scale. The technological process development has led to the permanent creation of new antifrictional materials and composites [50,61]. LLC “AlfaTech” is constantly searching and undertaking experimental analyses of new materials suitable as sliding layers of bearings.

4.2. About Materials

Polytetrafluoroethylene (PTFE) or Teflon has been discovered in 1938 by R. J. Plunkett [62]. The material is widely used as protective and antifriction coatings and interlayers [45,50,51,58,59]. The characteristics and properties of PTFE are improved in composite forms of material with various fillers according to Dhanumalayan et al. [48] and Wang et al. [63]. Bronze inclusions and molybdenum disulphide have been used to improve the properties of PTFE and produce a ground surface with a low friction coefficient [48].

PTFE composites with various bronze inclusions and molybdenum disulphide have a free compression modulus 58–65% higher than that of pure PTFE which was established in our work. The constrained compression modulus of composites with dendritic inclusions is lower by 3.4%, with spherical ones it is higher by 7.45%. Poisson's ratios are 4–6% lower. Elastic-plastic strain of 10% occurs in composites with dendritic and spherical bronze inclusions at stresses 37% and 44.6% higher than in pure PTFE, respectively.

Radiation-modified PTFE has also shown improved mechanical properties in experiments. The free compression modulus was 58.5% higher, the constrained compression modulus was 3.75% higher, the Poisson's ratio was 1.07% lower, and the stresses at 10% strain were 114.3% higher compared to pure PTFE.

The properties of PTFE and materials derived from them are being investigated quite extensively [63–66]. The insufficient properties of PTFE and materials based on it for the creation of viscoelastic behavior models were noted in [67]. Pure PTFE, modified PTFE, and PTFE composition with glassfiber and molybdenum disulphide were investigated Tan et al. The mechanical and viscoelastic properties of the materials were obtained. We can only make a qualitative comparison of materials deformation patterns. This is due to the research of materials different in terms of composition and manufacturers. The materials viscoelastic characteristics were also obtained by our scientific group. The deformation qualitative patterns and the value ranges of the mechanical characteristics obtained by us are similar to the results of Tan et al. The dependences of the deformation and mechanical characteristics obtained in the framework of the work visually correlate with the results of other authors [64–66]. Now, our group is engaged in the description of the materials viscoelastic behavior using the Prony rows. The material viscoelastic model will become an addition to the elastic-plastic model in further studies of the bearings when simulating dynamic, cyclic, and temperature loads.

The improved characteristics of PTFE composites and their modifications were also confirmed during the antifriction layer deformation of the bearings for all variants of its geometric configuration.

A large set of modern polymers and composites that can be used in friction units exists at present [50,54,61,68]. These are polyether ether ketone (PEEK), polymethylmethacrylate (PMMA), polyurethane (PU), polyamide (PA), UHMWPE, and composites based on them [69]. UHMWPE ROBO®SLIDE [70] and MSM [71] are used as sliding layers by MAGEBA and MAURER, respectively. These materials have improved properties compared to PTFE according to the data of manufacturers. The UHMWPE improved properties compared to other polymers have been confirmed by studies [72]. Research was conducted on a limited number of characteristics. Studies also could not include the entire volume of modern polymers. In our case, pure UHMWPE showed deformation and contact characteristics having little difference from the modified PTFE according to the results of experiments and numerical studies. Alfatech LLC and our research team singled out and modified PTFE as the most promising material for antifriction layers of bearings.

The search for modern antifriction materials and composites of Russian and foreign production with improved thermomechanical properties continues. It is necessary to analyze the available mechanical properties of PEEK, PMMA, PU, and PA in order to assess the possibility of their use in bearings. PEEK in its pure form has sufficiently high wear rates and friction coefficients according to [68,69,73]. At the same time, compositions based on it have improved characteristics [68]. This fact is very similar to the data for PTFE. Conclusions can be drawn that affirm the study of modern, including in real structures.

5. Conclusions

The influence of the antifriction layer location in the spherical bearings of six materials of the sliding layer was considered in this study. It has been established that the bearing with a layer pressed into the spherical segment (model A, the bearing classical geometry) has a number of disadvantages compared to the design with a layer placed in lower steel plate (model B):

- a higher level of maximum parameters on all interfaces of steel plates of structure with an interlayer;
- the “no contact” zones on the “turning surface”;
- the maximum level of displacements along the normal to the “end face surface” is greater;
- the plastic flow of interlayer materials from the steel plate recess, material shearing during the structure operation is possible;
- the draft level of the structure is greater.

The deformation behavior features of model A are observed for all variants of the interlayer material. Interlayers from composite materials (mat. 4–5) are subject to the greatest deformation.

Improvement in the structure operation regardless of the sliding layer location is observed when the standard inclination angle of the end face is changed to “rational”:

- the reduction of the maximum level of contact and deformation characteristics;
- the increase in the “adhesion” area of mating surfaces: the volume of the interlayer material working within the framework of the elasticity theory increases;
- the absence of a “no contact” zone in interlayer from polymeric materials (mat. 1–3, 6) or a decrease in % of the “no contact” area in interlayer from composites (mat. 4–5).

Moreover, the following could be distinguished from the data obtained:

- The construction with a layer placed in lower steel plate shows better performance compared to model A.
- Interlayers from materials 1, 2, and 6 show a better distribution of contact parameters compared to other materials.
- The constructions that have an inclination angle of the end face of 0° for model A and 25° for model B have more distributed contact parameters and lower draft values. Thus, it may be concluded that structures with these angles perform better than those with standard angles.

Future studies ought to assess the influence of the position and geometry bearing, taking into account the technological recesses in the sliding layer as well the horizontal and cyclic loads.

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Nomenclature

α_p	inclination angle of the antifriction layer end face;
h_p	antifriction layer thickness;
h_1	central section height of the upper steel plate;
h_2	central section height of the lower steel plate;
h	structure height;
b	maximum length of bearing half;
B	maximum length of bearing;
S_1	upper surface of the steel plate;
S_2	lower surface of the steel plate;
Q_z	vertical force applied to S_1 ;
P	pressure;
S_{K_1}	upper contact surface;
S_{K_2}	lower contact surface;
S_{K_3}	antifriction layer end face;
P_K	contact pressure;
$\max P_K$	maximum contact pressure;
$\max P_K _{\text{turning surface}}$	maximum contact pressure for the “turning surface”;
$\Delta \max P_K$	relative difference of contact pressure of models A and B;
τ_K	contact tangential stress;
$\max \tau_K $	maximum modulo contact tangential stress;
$\max \tau_K _{\text{turning surface}}$	maximum modulo contact tangential stress for the “turning surface”;
$\Delta \max \tau_K $	relative difference of maximum modulo contact tangential stress of models A and B;
u_n	normal displacements on S_{K_3} ;
$\max u_n$	maximum normal displacements on S_{K_3} ;
$\max u_n _{S_{K_3}}$	maximum normal displacements on S_{K_3} ;
$\Delta \max u_n$	relative difference of maximum normal displacements on S_{K_3} of models A and B;
$u_z _{r \in S_1}$	structure draft;
$\Delta u_z _{r \in S_1}$	relative difference of structure draft of models A and B;
S_{adhesion}	area that is contact with full adhesion;
$S_{\text{adhesion}} _{\text{turning surface}}$	area that is contact with full adhesion for the “turning surface”;
$S_{\text{no contact}}$	area of the zone of “no contact” (divergence) of mating surfaces;
$S_{\text{no contact}} _{\text{turning surface}}$	area of the zone of “no contact” (divergence) of mating surfaces for the “turning surface”.

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