Prediction of the Residual Resource of Pneumatic Tire Materials from Accumulation and Type of Damage

DMITRY DMITRIEV[1], SERHII CHURSOV[1], SERHII RUSANOV[2]
[1]Department of Automation, Robotics and Mechatronics, Faculty of Engineering and Transport,
Kherson National Technical University,
Instytutska 11 Street, 29016 Khmelnytskyi,
UKRAINE

[2]Department of Transport Systems and Technical Service, Faculty of Engineering and Transport,
Kherson National Technical University,
Instytutska 11 Street, 29016 Khmelnytskyi,
UKRAINE

Abstract: - The present paper examines the mechanical characteristics at the boundary of the distribution of rubber matrix and metal and fabric fibrous materials as a distinct area in the crack braking mechanism, and their impact on the durability of pneumatic tires in the event of damage accumulation during operation. Experimental studies were conducted on the delamination of the components of the tire material composition in samples obtained from diverse locations of the car tire. The strength of the rubber matrix fibers of the metal cord was determined, which makes it possible to assess the overall strength of the tire material as a composition of reinforcing elements and the matrix during the accumulation of damage created artificially during operation. The method of experimental research is reasonably stable. The nature and behavior of the sample rupture during the tests were evaluated.

Key-Words: - composite material, fibers, destruction, material strength, rubber matrix, tire materials, accumulation and type of damage.

Received: July 12, 2023. Revised: February 12, 2024. Accepted: March 4, 2024. Published: April 26, 2024.

1 Introduction

Modern research and approaches to the construction of rubber-elastic shells with a multi-component composition of materials of various origins as composites allow designers, technologists, marketers in various industries to understand and predict exactly what indicators should be expected from tires, [1], [2], [3], [4]. Tests of ready-made pneumatic tires are based on a set of important criteria, structural strength, quality of rubber compounds, homogeneity, stiffness and geometric characteristics of tires are checked. The development of a pneumatic tire design with a high operational level requires a series of experimental studies to determine stability and reliability. However, the vast majority of test and bench tests, including independent tests to ensure these parameters, are directed beyond the direct study of material properties, [5], [6], [7], [8], [9], [10]. In their own maneuvers, overcoming obstacles, braking, and critical operating situations, pneumatic tire materials perceive the most complex external influences and change their own properties during operation, which cannot be directly monitored as a vector of influences and loads and evaluated, but only based on a priori information on changes in material properties. Therefore, it is necessary to consider the determination of the strength of the rubber composition as a matrix reinforced with metal fibers and the influence of their ratio on resistance to damage, [3], [4], [11], [12], during the operation of automobile tires. An alternative to experimental testing is numerical modeling, [1], [3], [13], [14], using the finite element method, [5], [6], [7], [9], [10], thanks to which deformations, [3], [11], [13], and stress states, [11], are estimated, which arise in the structure of the tire, and introduce correlating changes in the design and composition of materials, [2], [3], [4], [8], [11], [12]. Predicting the tired resource of pneumatic tire materials shortens the development cycle and reduces the cost of pneumatic tires by increasing resource indicators, which is important for reducing the use of raw materials and reducing environmental pollution, [15]. The utilization of modeling is imperative for enhancing the parameters of tire design and minimizing defects during the process of tire production. The mechanical properties of elastic materials from various tire components are investigated using experiments with cyclic loading and unloading at different speeds and deformations, [11]. The deformation and stress of the rubber components, [11], [12], [14], [16], [17], [18], [19], [20] and the reinforcement of the cord during the manufacturing stage can be obtained using simulations, which provide data to evaluate the rationality of the tire design, [12]. In this regard, the task of researching the accumulation of damage in tire material is relevant. Attention is paid to the mechanical properties of the matrix, in which various types of damage accumulate, resulting in a redistribution of loads in fibrous fillers (metal cord, fabric) and their distribution boundaries, [14].

To date, little has been studied about the different types of pneumatic tire failures, which include plastic, central burst, brittle, fatigue, twisting, corrosion, delamination, and seam failure. it is necessary to check the measured constants of the material by the methods of numerical modeling of the tire, comparing the results with the actual data of tests of mechanical properties contained in the technical documentation for the tire.

2 Experimental Process

Pneumatic tire materials represent a complex composite structure reinforced with both metallic and non-metallic fibers. Despite the rather wide application and established (stability) views regarding the mechanical characteristics of tire materials, different conditions of their operation directly affect the resource, passing capacity, and safety of car traffic, [1], [2], [5], [6], [7]. In this work, bench cyclic loads on special equipment were combined with tests for tension, delamination, and fracture analysis. The strength of the composition of rubber as a matrix reinforced with metal fibers and the influence of their ratio on resistance to damage during the operation of car tires was determined. The metal and fabric fibers were considered separately for the tensile test of the matrix and the matrix was separately removed while preserving the fibers. Today, it is necessary to describe in detail various types of component metal destruction in the form of a cord or side wire, as well as its mechanism in the form of both physical and morphological phenomena. This paper combines the relevance of each of these types of destruction with the improvement of technological processes for the production of metal cords, on-board wire, and the elimination of malfunctions in the operation of tires. To gain a more comprehensive comprehension and characterization of damage at locations of operational destruction of surfaces, it is imperative to examine the micro geometry, surface morphology, conditions of crack propagation, in the middle of materials and at the border of fractures, and conduct a comprehensive examination of the macro and microstructure of the material of pneumatic tires, [21].

The theoretical basis for solving the tasks was the works, [2], [3], [4], [11], [12], [15], [22], [23], [24], [25].

The relationship between pneumatic tire damage and the properties of the tire material in the process of accumulating damage was established using a phenomenological approach. The analysis of patterns of change in the properties of rubber-cord materials of pneumatic tires was performed, which is an important problem in the study of operational characteristics for vehicles.

Unlike most traditional rubber compound and tire composite tests, which are subject to tensile forces (tensile strength and pull-off strength) or compressive forces (indentation hardness), the dual-layer fatigue configuration stresses the rubber layer between the steel belts of the tire.

The aforementioned techniques were employed to investigate the mechanical characteristics at the boundary of the distribution of the rubber matrix and metal and fabric fibrous materials as a distinct area in the crack braking mechanism, and their impact on the durability of pneumatic tires during the accumulation of damage during operation.

3 Results and Discussion

Among the many methods of pneumatic tire research, [21], it is possible to single out the method of determining the connection in the elements of the pneumatic tire chamber, the essence of which is the layering of the tire elements on the power equipment with the fixation of the increase in force until the moment of destruction. Using this method, research was carried out on the forces and calculation of tire elements at the boundaries of the "rubber-metal fibers of the cord", "metal fibers of the cord" (between the fibers), and "rubber-fabric" joints. In Table 1, the delamination force at different sections of the car tire was determined.

Table 1. Measured explosion stress at the boundary of different tire material components

The border distribution	***Stratification effort, N***	***Width layering of material, mm***
«rubber-rubber»	40	15
«metal fibers»	60	
«rubber-metal fibers»	90	
"rubber-cloth"	80	

Figure 1 presents the results of the study of the mechanism and kinematics of the destruction of compositions of fibrous and metallic materials, as well as the mechanical properties at the boundary of the distribution of the rubber matrix and metallic and fibrous materials, as a separate area in the crack.

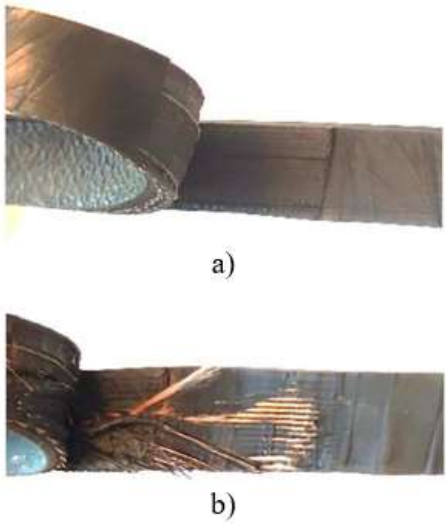


Fig. 1: Sample delamination and fracture surface at the "rubber-fiber metal cord" interface (a), between the cord fibers (b)

The mechanical properties at the boundary of the distribution of the rubber matrix and metal and fabric fibrous materials, as a separate area in the crack braking mechanism, and its effect on the durability of pneumatic tires are considered when damage is accumulated during operation. Experimental studies were conducted on the delamination of the components of the tire material composition in samples obtained from diverse locations of the car tire. The strength at the interface of the rubber matrix fibers of the metal cord and between the fibers of the cord was determined. This makes it possible to assess the overall strength of the tire material as a composition of reinforcing elements and the matrix during the accumulation of damage created artificially.

Reinforcing fibers are intended to be used as a shearing mechanism for breaking cracks by the fibers themselves on the matrix adhesion surface. Experimental studies on the delamination of elements of the composition of the tire material in samples made from different places of the car tire and transitional layers that form connections between reinforcing fibers are shown in Figure 2. Mechanical damage during the operation of automobile tires can cause braking cracks.

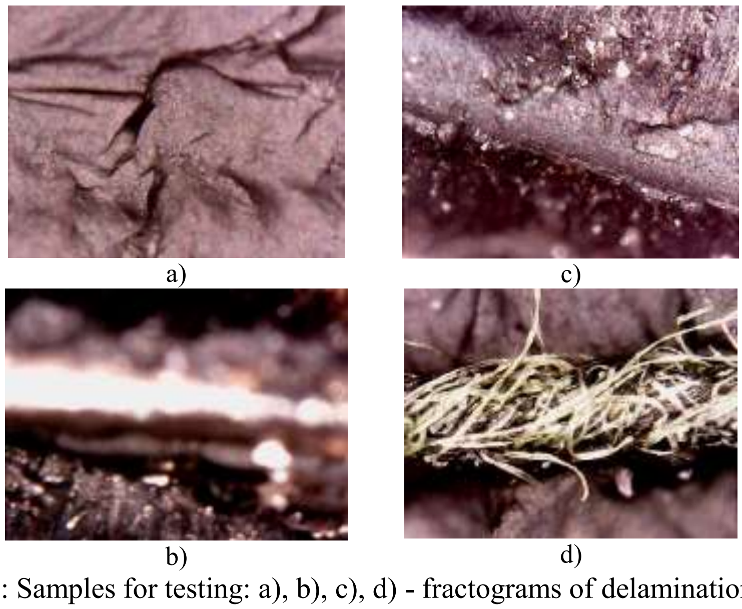
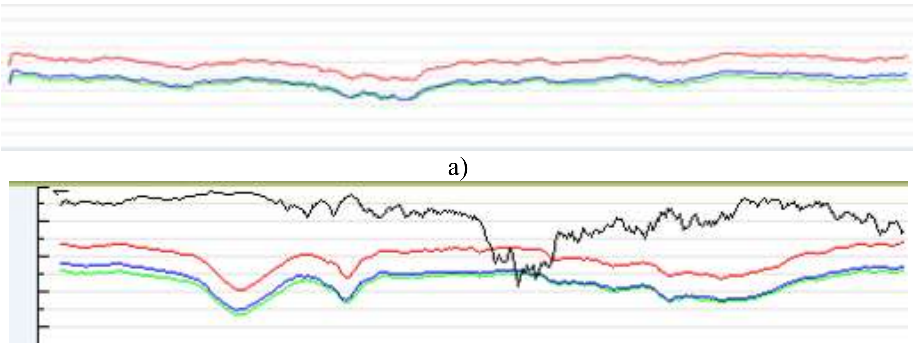


Fig. 2: Samples for testing: a), b), c), d) - fractograms of delamination sites "rubber", "metal fibers", "rubber-metal fibers", and "rubber-fabric", respectively



a)

b)

Fig. 3: Microgeometry of the delamination of the rubber matrix in two mutually perpendicular directions on the surface of the sample: along the horizontal axis (a), along the horizontal axis (b)

Fractographic studies are related to establishing the correspondence between the relief of the fracture surface and the type of force impact, as well as the load conditions. The criterion for the correct interpretation of information about the destruction process as a result of the analysis of an operational fracture is the reproduction of a similar topography of the fracture in laboratory conditions.

The idea of the similarity of destruction in a laboratory experiment and operating conditions is reliable only from the point of view of the similarity of the reaction of the material to the impact in experience and operation. The development of destruction with the formation of one or another fracture relief is a self-similar process that can be implemented under different load conditions.

A different picture is observed during the long-term operation of automobile tires and the accumulation of small damages (Figure 3) during repeated static and dynamic loading, therefore, fractographic analysis provides a real picture when studying the heterogeneous structure of defects arising as a result of fatigue and other causes of failure of automobile tires, [4].

The determination of the strength at the interface between the rubber matrix and the fibers of the cord was conducted. This enables the evaluation of the overall strength of the tire material as a combination of reinforcing elements and the matrix during the accumulation of damage created artificially during operation. The experimental research methodology employed is relatively stable, and the nature and behavior of the sample rupture during tests were evaluated. Additionally, the morphology of the fracture on the surface of the interaction between the reinforcing wire fibers and the rubber matrix was evaluated. Particular attention should be paid to the mechanical properties of the matrix, which can accumulate various types of damage. Particular attention should be paid to the mechanical properties of the matrix, [2], [3], [4], [11], in which various types of damage accumulate, [5], [6], [7], [8], [11], resulting in a redistribution of loads in fibrous fillers (metal cord, fabric) and their distribution boundaries. The most accessible evaluation method is a tensile test.

The strength of the rubber composition as a matrix reinforced with metal fibers and the effect of their ratio on resistance to damage during the operation of automobile tires were determined. Samples with R 15 and a service life of 20 thousand km were made for the study (Figure 4).

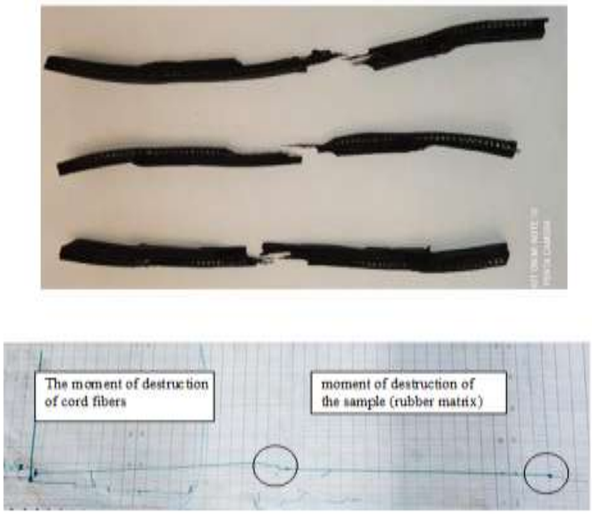


Fig. 4: Strength testing of rubber-cord material of a pneumatic tire: a) torn samples, b) tensile diagram

As a result of the accumulation of damage at the boundary of the distribution of a metal wire with a rubber matrix, [11], [16], there is a violation of the flat surface with the presence of wavy irregular cavities with a depth of 10 to 50 µm. The size and shape of the cavities increase for cyclic loads provided in the three directions x, y, and z, the largest violations of the perimeter are observed in the cross-section of the wire with increasing lateral load (Figure 5).

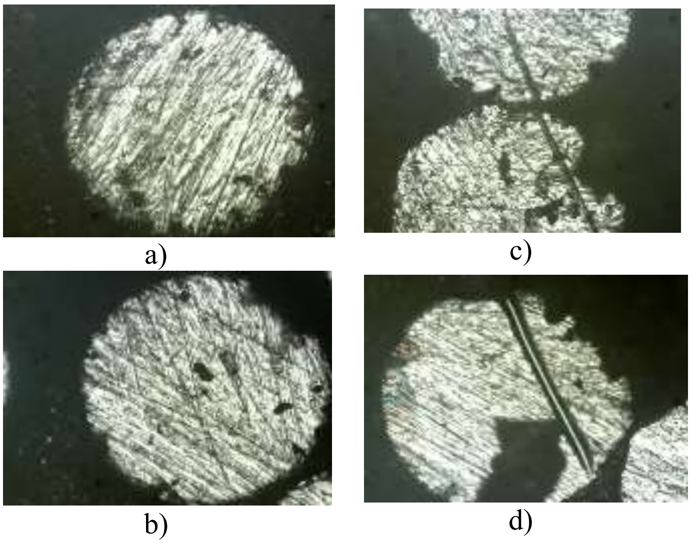


Fig. 5: Photomicrographs of a damaged metal cord in the macrostructure of a pneumatic tire from a set of bench loads: a) cyclic vertical loads N=1500; b) cyclic rotary cyclic movement of the wheel N=4500; c) cyclic horizontal in two coordinates N= 3000; d) combined rotary and linear in 5 coordinates N=7500

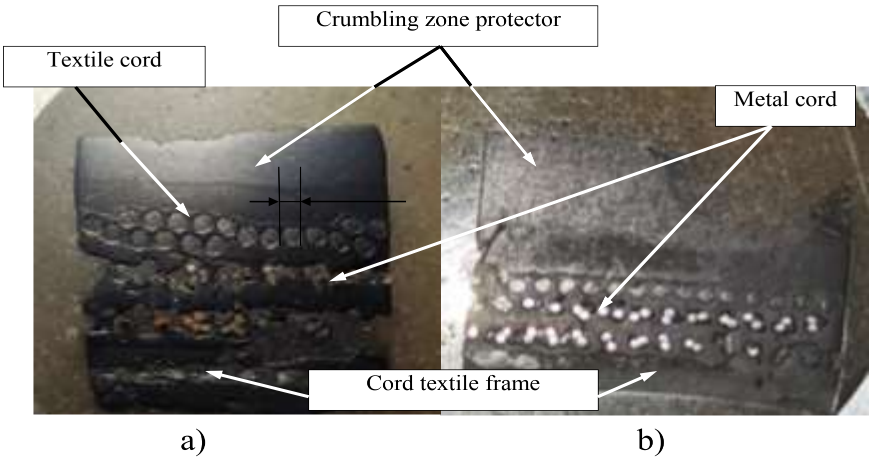


Fig. 6: Cross-section with deformations in the macrostructure after operation:
a) 50,000 km; b) 20,000 km

During the accumulation of damage, a change in the macrostructure in the cross-section is recorded as a degradation of the constituent elements of the rubber-cord composition and the boundaries of the elements, there is a deformation of the location line of the textile cord and the curvature of the tread zone with probable mechanical and thermal surface destruction (Figure 6).

Observations of wear according to the roughness criterion showed a 40% drop in the Ra parameter over a period of 24 hours of testing, with subsequent crushing of the outer surface and the formation of relatively large defects up to 50-100 microns. The destruction of the outer surface as a result of tribological interactions with an artificial obstacle and embrittlement of the surface layer, which has a light gray color to a depth of up to 1 mm in the tread, was recorded.

4 Conclusion

As a result of the defined processes of damage development of automobile tires, depending on various factors and obstacles, a change in mechanical characteristics was established, namely, a change in the limit values of the strength limit and the elasticity coefficient during the accumulation of damage. The results of fractographic analyses are related to the establishment of correspondence between the topography of the fracture surface and the type of force impact, as well as load conditions. By testing individual macrophases and distribution boundaries, specific numerical values of shear and axial loads, which the tire can withstand when overcoming various obstacles and braking, are determined.

References:

[1] He, H., Li, R., Yang, Q., Pei, J., & Guo, F. Analysis of the tire-pavement contact stress characteristics during vehicle maneuvering. *KSCE Journal of Civil Engineering*, Vol.25, 2021, pp. 2451–2463, https://doi.org/10.1007/s12205-021-1306-0.

[2] Gent, A. N., & Walter, J. D. (2006). *Pneumatic tire*. Mechanical Engineering Faculty Research, 854, Acron, [Online]. https://ideaexchange.uakron.edu/mechanical_ideas/854 (Accessed Date: February 2, 2024).

[3] Baranovski, P., Bogusz, P., Gotowicki, B., & Malachnowski, J. Assessment of mechanical properties of offroad vehicle tire: Coupons testing and FE model development. *Acta Mechanica et Automatica,* Vol.6, No.2, 2012, pp. 17-22, [Online]. https://www.researchgate.net/publication/268293803_Assessment_of_mechanical_properties_of_offroad_vehicle_tire_Coupons_testing_and_FE_model_development (Accessed Date: February 2, 2024).

[4] Shilavant, R., Samui, B. K., Chanda, J., Ghosh, P., Mukhopadhyay, R., & Banerjee, S. S. A critical review on fractographic studies of steel cord and bead wire used in tyre reinforcement. *Progress in Rubber, Plastics and Recycling Technology*, Vol.40, No.1, 2024, pp. 98-117, https://doi.org/10.1177/14777606231201866.

[5] Chen, L., Gao, Z., Shengkang, H., Guolin, W., Kwaku Asafo-Duho, B. M., & Ren, J. A fatigue evaluation method for radial tire based on strain energy density gradient. *Advances in Materials Science and Engineering*, Vol.2021, No.5, 2021, pp. 01-12, https://doi.org/10.1155/2021/8534954.

[6] Minrui, G., & Zhou, X. Tire-pavement contact stress characteristics and critical slip ratio at multiple working conditions. *Advances in Materials Science and Engineering*, Vol.2021, No.8, 2019, pp. 1-11. https://doi.org/10.1155/2019/5178516.

[7] Miao, Y., Guoxiong, W., Kong, L., & Tang, Y. Tire-pavement friction characteristics with elastic properties of asphalt pavements. *Applied Sciences,* Vol.7, No.11, 2017, paper 1123, https://doi.org/10.3390/app7111123.

[8] Korunovic, N., Fragassa, C., Marinkovic, D., Vitkovic, N., & Trajanovic, M. Performance evaluation of cord material models applied to structural analysis of tires. *Composite Structures,* Vol.224, 2019, pp. 111006-111028, https://doi.org/10.1016/j.compstruct.2019.111006.

[9] Korunovic, N., Trajanovic, M., Stojkovic, M., Misic, D., & Stojković Ex Milovanović, J. R. Finite element analysis of a tire steady rolling on the drum and comparison with experiment. *Strojniški vestnik – Journal of Mechanical Engineering*, Vol.57, No.12, 2011, pp. 888-897, https://doi.org/10.5545/sv-jme.2011.124.

[10] Korunovic, N., Trajanovic, M., Stojkovic, M., Victovic, N., Trifunovic, M., & Stojković Ex Milovanović, J. R. Detailed vs. Simplified tread tire model for steady-state rolling analysis. *Strojarstvo: Journal for Theory and Application in Mechanical Engineering*, Vol.54, No.2, 2012, pp. 153-160, [Online]. https://www.researchgate.net/publication/242330740_Detailed_vs_Simplified_Tread_Tire_Model_for_Steady-State_Rolling_Analysis (Accessed Date: February 3, 2024).

[11] Krmela, J., Beneš, L., & Krmelová, V. Statical experiments of tire as complex long-fibre composite for obtaining material parameters and deformation characteristics. *Materials Engineering*, Vol.19, No.3, 2012, pp. 124-135, [Online]. https://www.researchgate.net/publication/268061916_Statical_Experiments_of_Tire_as_Complex_Long-Fibre_Composite_for_Obtaining_Material_Parameters_and_Deformation_Characteristics (Accessed Date: February 2, 2024).

[12] Pelc, J. Material modelling in cord-rubber structures. *KGK Kautschuk Gummi Kunststoffe*, Vol.53, No.10, 2000, pp. 561-565, [Online]. https://www.researchgate.net/publication/236983980_Material_modelling_in_cord-rubber_structures (Accessed Date: February 2, 2024).

[13] Koishi, M. Tire cornering simulation using an explicit finite element analysis code. *Tire Science and Technology*, Vol.26, No.2, 1998, pp. 100-119, [Online]. https://www.researchgate.net/publication/245552338_Tire_Cornering_Simulation_Using_an_Explicit_Finite_Element_Analysis_Code (Accessed Date: February 3, 2024).

[14] Shida, Z., Koishi, M., Kogure, T., & Kabe, K. A rolling resistance simulation of tires using static finite element analysis. *Tire Science and Technology*, Vol.27, No.2, 1999, pp. 84-105, https://doi.org/10.2346/1.2135980.

[15] Hodgkinson, J. (2000). *Mechanical testing of advanced fibre composites*. Woodhead Publishing, Cambridge.

[16] Jeong, K., Kee-Woon, K., & Jang, K. Global-Local finite element analysis for predicting separation in cord-rubber composites of radial truck tires. *Open Journal of Modelling and Simulation,* Vol.07, No.4, 2019, pp. 190-202, https://doi.org/10.4236/ojmsi.2019.74011.

[17] Zahir, K. A., Faizan, M., Azam, F., & Faheem, A. Hardness assessment of novel waste tire rubber-polypropylene composite. *Materials Today: Proceedings,* 2023, https://doi.org/10.1016/j.matpr.2023.03.445.

[18] Koishi, M., Shiratori, M., Miyoshi, T., & Kabe, K. Homogenization method for dynamic viscoelastic analysis of composite materials. *JSME International Journal Series A Solid Mechanics and Material Engineering*, Vol.40, No.3, 1997, pp. 306-312, https://doi.org/10.1299/jsmea.40.306.

[19] Koishi, M., & Kabe, K. Development of homogenization analysis system based on general-purpose FEM code. *JSME International Journal Series a Solid Mechanics and Material Engineering*, Vol.38, No.2, 1995, pp. 171-176, https://doi.org/10.1299/kikaia.59.1395.

[20] Akasaka, T., Kabe, K., Koishi, M., & Kuwashima, M. Analysis of the contact deformation of tread blocks. *Tire Science and Technology*, Vol.20, No.4, 1992, pp. 230-253, https://doi.org/10.2346/1.2139518.

[21] Chursov, S. O. Bond strength in elements of pneumatic tires as a composite material. Materials of the scientific and technical conference *"Progressive technique, technology and engineering education: Modern problems of mechanics of deformable solids"*, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, 2021, pp. 45-47.

[22] Pelc, J. An attempt to improve the axisymmetric model of a pneumatic tire. *Technical Sciences*, Vol.13, No.1, 2010, pp. 233-239, https://doi.org/10.2478/v10022-010-0022-7.

[23] Pelc, J. Bias truck tire deformation analysis with finite element modeling. *Applied Sciences*, Vol.10, No.12, 2020, pp. 1-12, https://doi.org/10.3390/app10124326.

[24] Pelc, J. Parametric study of a pneumatic tire under inflation using the FEM approach. *Journal of Theoretical and Applied Mechanic,* Vol.36, No.1, 1998, pp. 109-120, [Online]. https://www.researchgate.net/publication/256081164_Parametric_study_of_a_pneumatic_tire_under_inflation_using_the_FEM_approach (Accessed Date: February 2, 2024).

[25] Larin, O. Experimental estimation of fatigue resistance of rubber-cord composite under orthogonal to reinforcement deformation before and after artificial aging. *Bulletin of the National Technical University "Kharkiv Polytechnic Institute"*, Vol.26, 2016, pp. 63-68, https://doi.org/10.20998/2078-9130.2016.26.79931.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare.