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DETERMINATION OF THE STRESS–STRAIN STATE OF THE RIGID PAVEMENT STRUCTURE OF AN AIRFIELD ACCESS ROAD

[1]**Dubyk O.M.,** PhD, Associate Professor,
oleksandr.dubyk@npp.kai.edu.ua, ORCID: 0000-0001-8082-7603
[1]**Chernyshova O.S.,** PhD, Associate Professor,
oksana.chernyshova@npp.kai.edu.ua, ORCID: 0000-0002-8132-2153
[1]**Osovskyi I.M.,** postgraduate,
5177530@stud.kai.edu.ua, ORCID: 0009-0003-8294-6990
[1]**Kononenko D.Yu.,** student,
7437049@stud.kai.edu.ua, ORCID: 0009-0008-7425-5379
[1]*State University «Kyiv National Aviation University»*
1 Lyubomyr Huzar Ave., Kyiv, 03058, Ukraine

Abstract. The article presents a comprehensive study of the stress–strain state of a rigid pavement structure of an airport taxiway, taking into account the three-dimensional nature of aircraft wheel loading and the long-term operational conditions of the pavement system. The relevance of the research is driven by the growing need to ensure high durability and structural reliability of airfield pavements that operate under intensive cyclic loading from modern aircraft and must provide safe and uninterrupted functioning throughout the designated service life.

The study describes the material characteristics of the three-layer airfield pavement system and determines the load parameters applied by the main landing gear of the reference aircraft. Bending moments in the upper and lower concrete layers are calculated, and compliance with strength conditions is assessed for a 20-year operation period at an intensity of five aircraft movements per day. The geotechnical and hydrogeological conditions of the construction site are analyzed, including the classification of engineering-geological complexity and the potential impact of natural processes on pavement performance.

The bearing capacity of the pavement structure is evaluated using the FAARFIELD 2.1.1 software based on the method of aircraft and pavement classification parameters. To verify and refine the obtained results, a finite element model consisting of nine concrete slabs with expansion joints is developed in LIRA-SAPR. The model allows visualization of vertical and horizontal displacements and stress distribution under aircraft loading. The maximum vertical displacement of the structure is 0.941 mm, horizontal displacement is 0.216 mm, and peak vertical stresses reach 39.8 t/m², indicating that the structure operates within safe limits.

Based on the numerical calculations, recommended layer thicknesses for two aircraft mass scenarios –maximum takeoff weight and empty weight – are proposed. The optimal thickness of the upper concrete layer (C25/30) is 298 mm and 158 mm respectively, while the lower lean-concrete layer (C8/10) is optimized to 150 mm instead of previously accepted 300 mm. These results confirm sufficient bearing capacity and structural effectiveness of the designed pavement system.

The findings contribute to improving the design of rigid airfield pavements and support the selection of rational material and structural solutions. Future research should focus on assessing pavement behavior under varying climatic impacts, freeze–thaw effects, moisture sensitivity, and interaction with heterogeneous soil foundations, as well as modeling pavement response under increased traffic intensity from modern aircraft fleets.

Keywords: airfield pavement, taxiway, stress–strain state, finite element model.

Introduction. Modern airfield access pavements are operated under intensive and repeated cyclic loading, which results in increased requirements for strength, durability, and rigidity. Given the need to ensure safe aircraft operations, the relevance of research aimed at refining the stress–strain state of rigid pavement structures and optimizing their parameters is increasing.

In existing publications, considerable attention is paid to improving the physical and mechanical properties of concrete, optimizing material composition, increasing crack resistance, and promoting resource efficiency. However, the issue of comprehensive consideration of the spatial nature of aircraft wheel loads in stress–strain calculations of rigid airfield pavements requires further development.

The purpose of this work is to determine the stress–strain state of a rigid pavement structure of an airfield access road based on an integrated assessment of bearing capacity, verification of the strength of concrete layers, and spatial modeling of structural behavior under operational loads.

Analysis of Recent Research and Publications. The problem of determining the stress–strain state of rigid airfield and road pavements is one of the key issues in transportation construction, since the correctness of the adopted calculation model determines the reliability, durability, and economic efficiency of the structure throughout its entire service life [1–15].

Studies [1–4] investigate monitoring and numerical modeling of rigid airfield pavements considering interaction with the soil foundation. The main focus is on determining stresses in concrete slabs and assessing the influence of the physical and mechanical characteristics of the base on bending moment distribution. In particular, [3] applied the finite element method to analyze slab behavior when interacting with a weak soil foundation, which made it possible to establish the sensitivity of the stress state to changes in the modulus of subgrade reaction.

Study [5] considers the dynamic response of a concrete airfield pavement under impact loading. Numerical modeling incorporating inertial effects revealed an increase in peak stresses in the tire–pavement contact zone. The results confirmed the need to consider the dynamic component of loading in airfield pavement design.

Studies [6, 7] compared analytical solutions with finite element results. It was shown that analytical models provide high accuracy for simplified schemes (homogeneous foundation, symmetric loading), but have limitations when accounting for multilayer structures, complex boundary conditions, and localized load application. Numerical methods allow a more detailed representation of real stress distribution.

Papers [10–12] present three-dimensional finite element models of rigid pavements considering temperature gradients and moving load from aircrafts. The results indicate that temperature-induced stresses may be proportional to or even exceed stresses from operational loads, which require an integrated calculation approach.

Study [13] is devoted to the analysis of fatigue strength of concrete airfield pavements. The authors systematized existing fatigue failure prediction models and demonstrated the dependence of pavement durability on load intensity and tensile stress levels in the bottom zone of the slab.

Regulatory approaches to airfield pavement design are presented in ICAO documents [14, 15], which apply the ACR–PCR classification parameter method. This approach ensures coordination between aircraft characteristics and pavement bearing capacity, but does not provide detailed internal stress distribution within pavement layers, limiting local analysis of slab and joint performance.

Thus, analysis of recent research shows that:

– analytical methods provide a basic assessment of the stress state but have limitations for complex multilayer systems;

– numerical methods, particularly the finite element method, allow for the spatial nature of load application and material heterogeneity;

– the issue of a comprehensive combination of normative calculation of bearing capacity (ACR–PCR), analytical strength verification, and three-dimensional numerical modeling for specific hydrogeological conditions remains insufficiently covered.

Given this, it is relevant to conduct a comprehensive study that combines the calculation of bearing capacity according to regulatory methods with three-dimensional finite element modeling of a three-layer structure of a rigid airfield pavement, taking into account the real distribution of the load from the aircraft wheels and the engineering and geological conditions of the site.

Aim and Objectives. The purpose of this article is to determine the stress-strain state of the airfield hard pavement structure, taking into account the spatial nature of the load application.

The objectives of the study are:

– to determine the load-bearing capacity of the airfield approach road structure;

– to provide recommendations regarding structural solutions for the airfield access road;

– to determine stresses, displacements, and deformations in the airfield access road structure.

Materials and Research Methodology. The stress-strain state is calculated and the bearing capacity of the airfield access road structure is determined, shown in Fig. 1.

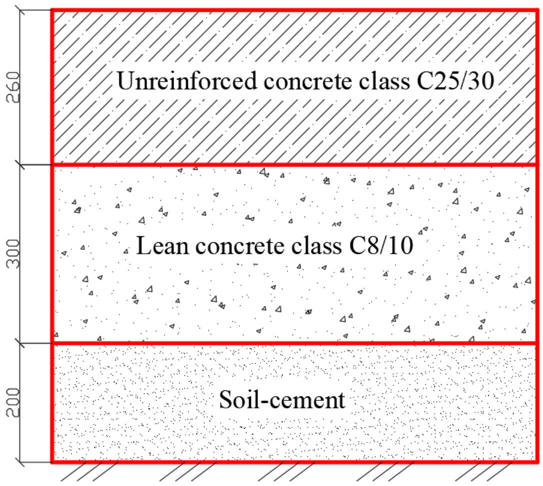


Fig. 1. Structure of the access road pavement

The characteristics of materials of the layers of airfield clothing are as follows:

– upper layer – concrete class C25/30: $E_{cd} = 25\ 000\ MPa,\ R = 3,4\ MPa$;

– lower layer – lean concrete class C8/10: $E_{cd} = 12\ 600\ MPa,\ R = 1,6\ MPa$.

– layer of artificial base– soil-cement: $E = 370\ MPa$.

The calculation is performed for a 20-year operation period of the reference aircraft, the geometric parameters of which are shown in Fig. 2.

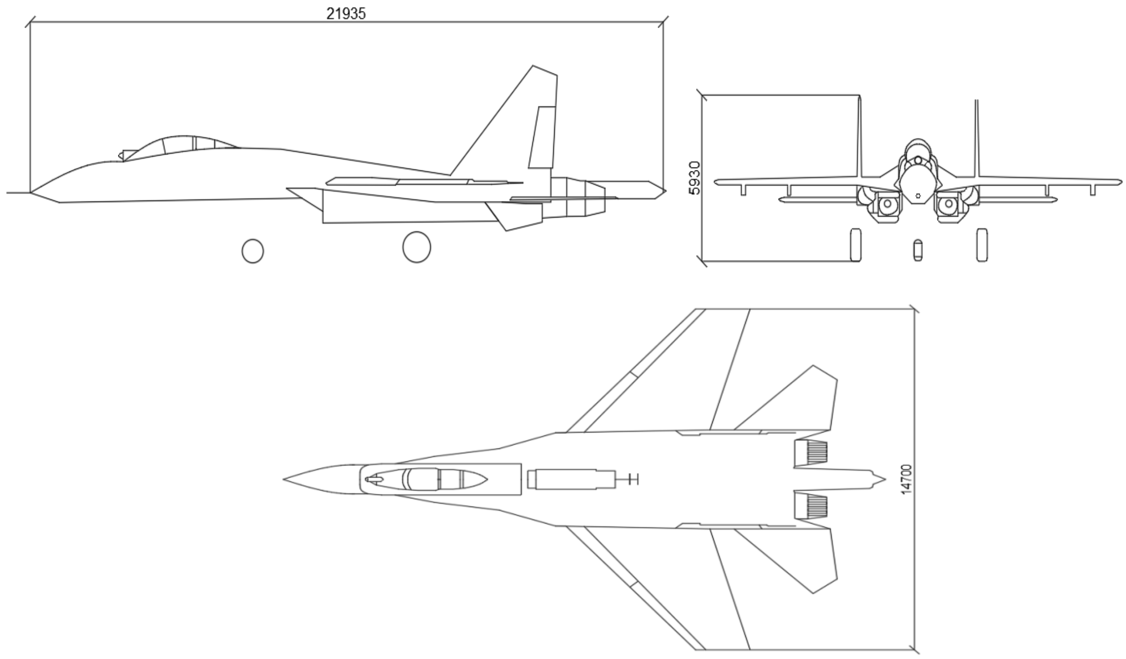


Fig. 2. Geometric parameters of the reference aircraft

The length of the reference aircraft is 21.935 m, the wingspan is 14.7 m, and the height is 5.93 m.

The load on the main support of the aircraft is determined:

$$F_n = \frac{0,95 \cdot m_{tot} \cdot g}{2} = \frac{0,95 \cdot 30090 \cdot 9,81}{2} = 140,2\ kN, \quad (1)$$

where $m_{tot} = 30090\ kg$ – is the total aircraft mass; $g = 9,81\ m/s^2$ – is acceleration of free fall.

The load on one wheel of the main landing gear is:

$$F_d = \frac{F_n}{n_k} \cdot k_d \cdot \gamma_f = \frac{140,2}{1} \cdot 1,15 \cdot 1 = 161,23\ kN, \quad (2)$$

where $F_n = 140,2\ kN$ – is the load on the main landing gear; $n_k = 1$ – is the number of wheels on the main landing gear; $k_d = 1,15$, $\gamma_f = 1$ – are the dynamic and unloading coefficients:

$$R_e = \sqrt{\frac{F_d}{\pi \cdot p_a}} = \sqrt{\frac{161,23 \cdot 10^3}{\pi \cdot 1,23 \cdot 10^6}} = 0,204\ m, \quad (3)$$

where $p_a = 1,23\ MPa$ – is the reference tire pressure.

The equivalent side length of the square wheel imprint is:

$$a = R_e \cdot \sqrt{\pi} = 0,204 \cdot \sqrt{\pi} = 0,361\ m. \quad (4)$$

The calculated bending moments in the slabs of the upper and lower layers are:

– bending moment in the upper layer is:

$$m_{d,\sup} = \frac{k' \cdot m_{c,\max}}{1 + \frac{B_{\inf}}{B_{\sup}}} = \frac{1,2 \cdot 34,34}{1 + \frac{2,89}{3,73}} = \frac{41,208}{1,775} = 23,216\ \frac{kN \cdot m}{m}; \quad (5)$$

– bending moment in the lower layer is:

$$m_{d,\inf} = k' \cdot m_{c,\max} - m_{d,\sup} = 1,2 \cdot 34,34 - 23,216 = 17,99\ \frac{kN \cdot m}{m}, \quad (6)$$

where $k' = 1,2$ – is the coefficient adopted for two-layer pavements with coincident joints when providing butt joints in the upper layer.

Limiting bending moments of the upper and lower layers for an intensity of 5 aircraft movements per day are calculated as follows:

– for upper-layer slabs:

$$m_{u,\sup} = \gamma_c \cdot R_{btb1} \cdot \frac{b \cdot t^2}{6} \cdot k_u = 0,9 \cdot 3,4 \cdot 10^6 \cdot \frac{1 \cdot 0,26^2}{6} \cdot 1,238 = 42,68\ kN \cdot m/m; \quad (7)$$

– for lower-layer slabs:

$$m_{u,\inf} = \gamma_c \cdot R_{btb2} \cdot \frac{b \cdot t^2}{6} \cdot k_u \cdot k_m = 0,9 \cdot 1,6 \cdot 10^6 \cdot \frac{1 \cdot 0,3^2}{6} \cdot 1,238 \cdot 1,27 = 33,96\ kN \cdot m/m, \quad (8)$$

where $\gamma_c = 0,9$ – is the working condition coefficient; $R_{btb} = 3,4\ MPa$ – is the design flexural tensile strength of concrete; $t = 0,26\ m$ – is the thickness of the top layer of the airfield pavement slab; k_u – is a coefficient that takes into account the number of applications of aircraft wheel loads over a design service life of *20 years*:

$$k_u = 2 - 0,167 \lg U_d = 2 - 0,167 \cdot \lg 36\ 500 = 1,238, \quad (9)$$

where U_d – is the average annual number of wheel load applications for the airfield:

$$U_d = n_a \cdot N_i = 1 \cdot 5 \cdot 365 \cdot 20 = 36\ 500. \quad (10)$$

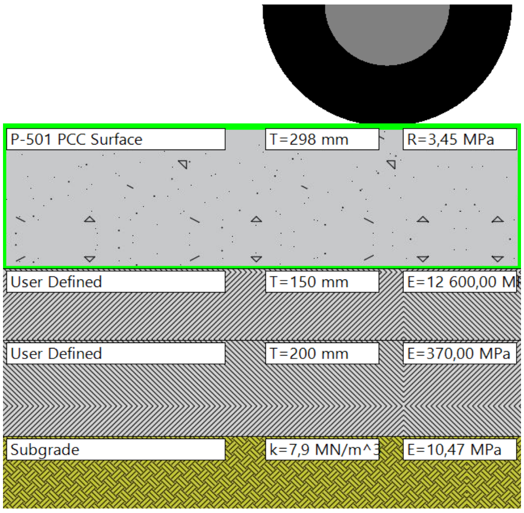
The strength conditions for the upper and lower layers are checked:

$$m_{d,\sup} = 23,216\ \frac{кН \cdot м}{м} < m_{u,\sup} = 42,68\ kN \cdot m/m; \quad (11)$$

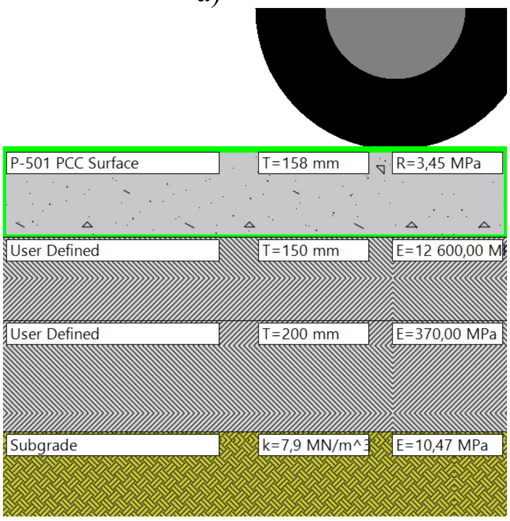
$$m_{d,\inf} = 33{,}96\frac{кН \cdot м}{м} < m_{u,\inf} = 33{,}96\, {kN \cdot m}/{m}. \qquad (12)$$

The strength conditions for the upper and lower layers are satisfied.

The recommended access-road pavement structure designed for 5 aircraft movements per day is shown in Fig. 3, a and Fig. 3, b.



a)



b)

Fig. 3. Recommended layer thicknesses for 20 years of operation and 5 aircraft movements per day: a – maximum takeoff weight m = 30.090 kg; b – empty aircraft weight m = 16.400 kg

The bearing capacity of the access-road structure was calculated using FAARFIELD 2.1.1 software. The software is based on the aircraft–pavement classification parameter method, where ACN is the aircraft numerical value and PCN is the pavement numerical value. The calculation was performed for maximum takeoff mass of 30.090 kg and empty mass of 16.400 kg. According to the calculation results, the recommended thickness of the upper C25/30 concrete layer is:

– 298 mm for maximum takeoff mass *m = 30.090 kg;*

– 158 mm for empty aircraft mass *m = 16.400 kg.*

The recommended thickness of the lower layer made of lean concrete C8/10 is 150 mm instead 300 mm.

Hydrogeological conditions of the design area are determined by geological and tectonic structure and physical-geographical conditions. The first aquifer from the surface is associated with Quaternary deposits and is recharged by atmospheric precipitation and surface waters.

Considering modern geological and engineering–geological processes and phenomena (landslides, karst, mudflows, abrasion, erosion, mechanical or chemical suffusion, physical

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weathering, earthquakes, dynamic impacts, electromagnetic radiation, soil contamination), it can be stated that within the site they do not occur and there are no prerequisites for their manifestation.

Assessment of engineering–geological complexity of the site:

– geomorphological conditions − Category 1 (simple);

– geological–lithological factors in the interaction zone with the geological environment – Category 2 (moderate);

– hydrogeological conditions − Category 3 (complex);

– geological processes that negatively affect construction and operation conditions of buildings and structures − Category 1 (simple).

Physical and mechanical soil properties were determined considering possible changes of the geological environment (for which forecasting data are available).

Changes in physical and mechanical soil properties under natural factors are not expected.

The finite element model of the airfield pavement structure is shown in Fig. 4. The slab size is 3.75 × 3.75 m. Expansion joints are provided between slabs. Modeling was performed in LIRA-SAPR using 9 slabs. The natural subgrade was modeled using the Winkler elastic foundation model with modulus of subgrade reaction k_se = 7.9 MN/m³. This approach accounts for local foundation response without modeling the full soil mass. The modulus value was adopted based on engineering–geological investigations.

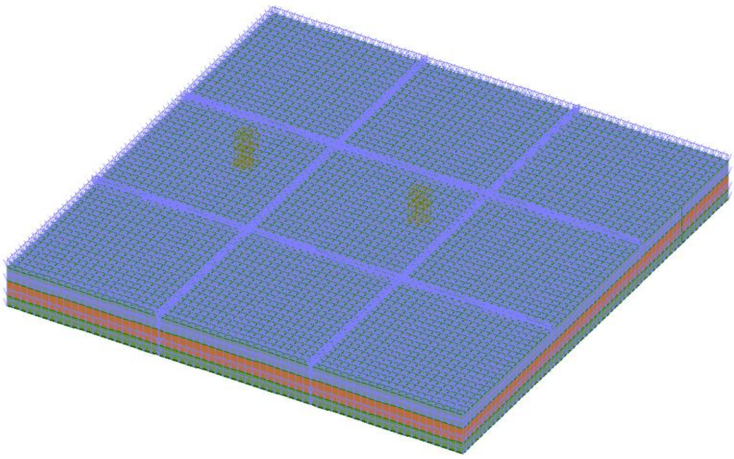

Fig. 4. Finite element model of the three-layer airfield pavement structure

Results of the stress-strain state calculation under self-weight and aircraft loading are presented in Figs. 5–7.

The isofields of vertical displacements of the finite element model of the airfield pavement slab are shown in Fig. 5.

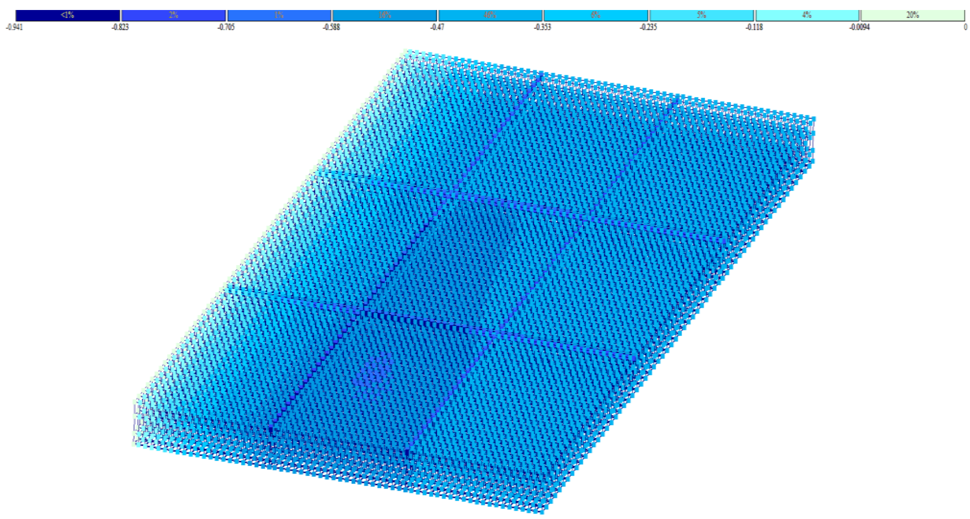

Fig. 5. Contours of vertical displacements of the slab finite element model, mm

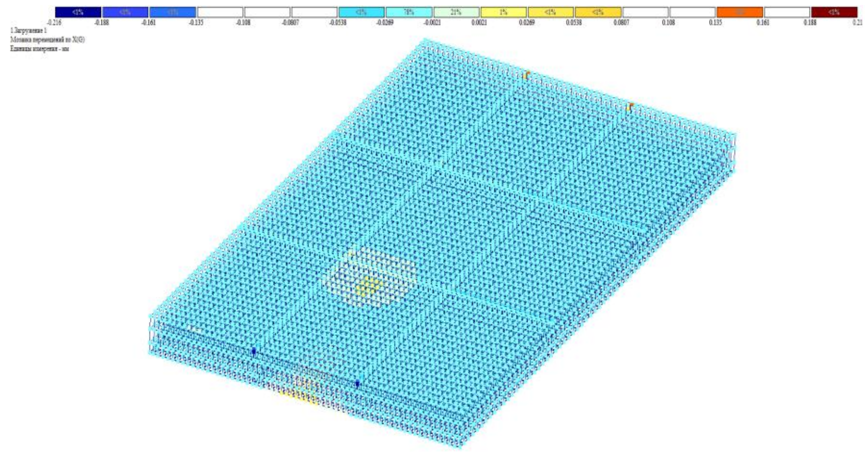

Fig. 6. Contours of horizontal displacements of the slab finite element model, mm

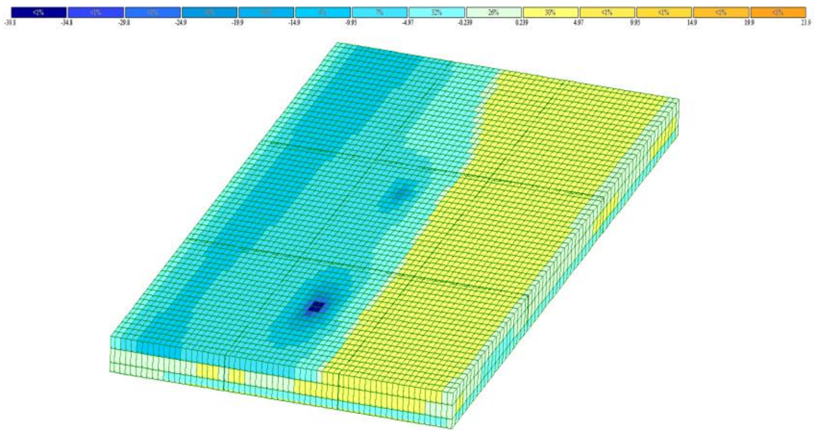

Fig. 7. Contours of vertical stresses of the finite element model

The maximum vertical displacements of the finite element model are 0.941 mm and are localized in the expansion joints and under the center of the wheel imprint. The maximum horizontal displacements are 0.216 mm.

The maximum vertical stresses of the finite element model are 39.8 t/m² and are localized under the center of the aircraft wheel tire imprint.

Comparison of the results obtained in FAARFIELD 2.1.1 and LIRA-SAPR showed consistency of the determined layer thicknesses and the stress distribution pattern. The deviation of calculated bending moments does not exceed 5–8%, confirming the correctness of the adopted calculation schemes. Accuracy was assessed by comparing limiting moments and maximum stresses in characteristic sections.

Conclusions. As a result of the performed theoretical and numerical studies, the stress–strain state of the rigid pavement structure of the airfield access road was determined taking into account real loading parameters of the reference aircraft and material characteristics of the pavement layers.

The stress–strain calculations and verification of strength conditions confirmed sufficient bearing capacity of the three-layer pavement structure for an intensity of 5 aircraft movements per day over 20 years.

Zones of maximum displacements and stresses caused by loading in the wheel imprint area at slab boundaries with expansion joints were identified. Maximum values of displacements and stresses do not exceed permissible limits, confirming the effectiveness of the adopted design solutions. Recommended thicknesses of the upper and lower layers were determined to ensure an optimal balance between strength and material consumption.

Future research should focus on refining pavement performance parameters under varying climatic impacts, accounting for freeze–thaw deterioration and moisture saturation processes, and modeling interaction with weak or heterogeneous subgrades. An additional direction of development is the analysis of the behavior of the coating when changing the intensity and spectrum of loads from modern aircraft, which will increase the reliability of airfield infrastructure facilities.

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ВИЗНАЧЕННЯ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ КОНСТРУКЦІЇ ЖОРСТКОГО ПОКРИТТЯ ПІД'ЇЗНОГО ШЛЯХУ АЕРОДРОМУ

[1]**Дубик О.М.,** к.т.н., доцент,
oleksandr.dubyk@npp.kai.edu.ua, ORCID: 0000-0001-8082-7603
[1]**Чернишова О.С.,** к.т.н., доцент,
oksana.chernyshova@npp.kai.edu.ua, ORCID: 0000-0002-8132-2153
[1]**Осовський І.М.,** аспірант,
5177530@stud.kai.edu.ua, ORCID: 0009-0003-8294-6990
[1]**Кононенко Д.Ю.,** студент,
7437049@stud.kai.edu.ua, ORCID: 0009-0008-7425-5379
[1]*Державний університет «Київський авіаційний інститут»*
просп. Любомира Гузара, 1, м. Київ, 03058, Україна

Анотація. У статті розглянуто питання визначення напружено-деформованого стану конструкції жорсткого покриття під'їзного шляху аеродрому з урахуванням просторових умов розподілу навантаження від розрахункового повітряного судна. Актуальність дослідження обумовлена необхідністю підвищення довговічності та надійності аеродромних покриттів, які зазнають циклічних навантажень і повинні забезпечувати безпечну експлуатацію повітряних суден упродовж нормативного терміну служби.

У роботі наведено характеристику матеріалів тришарової конструкції аеродромного одягу, визначено параметри навантаження від колісної основної опори літака та отримано згинальні моменти у плитах верхнього та нижнього шарів покриття. Розглянуто умови міцності конструкції за критеріями граничних згинальних моментів для різних режимів роботи та інтенсивності експлуатації покриття – 5 літако-виїздів на добу протягом 20 років. Окремо проаналізовано гідрогеологічні умови ділянки, категорії складності ґрунтових умов та їх потенційний вплив на роботу конструкції покриття.

Розрахунок несучої спроможності конструкції виконано в програмному комплексі FAARFIELD 2.1.1, що базується на методі класифікаційних параметрів, та підтверджено скінченно-елементним моделюванням у ПК ЛІРА САПР. Побудована модель включає дев'ять плит аеродромного покриття розміром 3,75×3,75 м з улаштованими деформаційними швами. Отримано значення вертикальних та горизонтальних переміщень і напружень, що дозволяють встановити характер розподілу напружень під дією власної ваги та навантаження від повітряного судна. Максимальні вертикальні переміщення конструкції становлять 0,941 мм, горизонтальні – 0,216 мм, а пікові вертикальні напруження досягають 39,8 т/м².

На основі комплексного аналізу визначено рекомендовані товщини шарів покриття для двох варіантів мас повітряного судна – максимальної злітної маси та маси порожнього літака. Зокрема, рекомендована товщина верхнього шару із бетону С25/30 становить 298 мм та 158 мм відповідно, тоді як товщину нижнього шару з пісного бетону С8/10 оптимізовано до 150 мм. Отримані результати підтверджують достатню несучу спроможність конструкції та забезпечують виконання умов міцності для заданих експлуатаційних параметрів.

У висновку сформульовано рекомендації щодо підвищення ефективності конструктивних рішень аеродромних покриттів і окреслено напрями подальших досліджень.

Ключові слова: аеродромне покриття, під'їзний шлях, напружено-деформований стан, скінченно-елементна модель.

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