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Calculation of strip foundations in complex conditions of its operation based on digital technologies

Abstract. The study aimed to develop a methodology for calculating strip foundations with due regard for difficult operating conditions. For this, the peculiarities of foundations on weak and subsiding soils were considered, the effect of incomplete contact with the foundation was investigated, as well as the influence of longitudinal forces arising from pretensioning of reinforcement and temperature changes. The calculation methodology was based on modelling the foundation as a finite beam resting on a two-parameter elastic foundation. The study analysed the effect of incomplete contact between the base and the foundation, which occurs in the case of localised dips or soil weakness, as well as longitudinal forces caused by external loads. A calculation program was developed for numerical modelling and implemented in Delphi. The study determined that the absence of full contact between the foundation and the substrate leads to stress redistribution, which can cause localised deformation concentrations. Longitudinal forces have

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different effects on the performance of the foundation: tensile reduce deflections and compressive – increase them. Analytical and numerical calculations have confirmed the need to incorporate these factors during design, as ignoring them can lead to significant deviations in the stress-strain state of the structure. The developed mathematical model incorporates these effects and identifies critical areas requiring adjustment of design parameters. The data obtained can be used in the design of strip foundations in difficult ground conditions, increasing their reliability and efficiency, as well as minimising the risk of cracking and uneven settlements. The proposed methodology can be used to calculate the foundations of buildings and structures operating in heterogeneous soils

Keywords: soil foundation model; Heaviside function; bending stiffness; generalised soil characteristics; bedding coefficient; elastic modulus; moment of inertia

INTRODUCTION

In modern construction, the reliability and cost-effectiveness of the designed structures are essential, especially when designing strip foundations operating in difficult ground conditions. To ensure the safety and durability of such foundations, several factors must be incorporated: the heterogeneity of the soil base, the possibility of subsidence, the impact of temperature and mechanical loads, as well as the specifics of the interaction between the foundation and the soil. Traditional calculation methods do not always provide an accurate estimation of the behaviour of such structures, which often causes errors at the design stage and increases the cost of building construction and operation. A.T. Marufiy *et al.* (2021) developed a methodology for calculating strip foundations with consideration of incomplete contact with the ground and the action of longitudinal forces. The study determined that incomplete contact led to a redistribution of loads and an increase in deflections, while tensile forces reduced deflections by 10-5%, and compressive – forces increased them by 5-10%. The implemented methodology improved the accuracy of prediction of the stress-strain state of foundations and increased the reliability of design solutions.

The development of digital technologies can analyse complex engineering problems related to the calculation of building structures, including strip foundations, in more detail. Modern software systems implementing numerical methods made it possible to consider various factors affecting the behaviour of the foundation and improve the accuracy of predicting its performance. For instance, M. Alabi (2024) considered the effectiveness of computational methods in the design of responsible building systems, and H.F. Schweiger *et al.* (2018) described approaches to the correct formulation of numerical modelling for complex interactions “structure-soil”.

One of the key factors affecting the behaviour of foundations is incomplete contact with the subgrade. This situation often occurs on weak and subsiding soils, where there is a loss of bearing capacity in individual sections, which leads to a redistribution of loads and a change in the stress state of the structure. This effect was analysed by Q. Liu (2023) in an assessment of the capabilities of modern algorithms in evaluating deformed beam structures on elastic foundations. In addition, M. Ertz *et al.* (2024) highlighted that the local absence of support can provoke

significant deformations that require mandatory consideration in design models.

Another significant aspect was the impact of longitudinal forces caused by temperature fluctuations, pre-tensioning of reinforcement or uneven load distribution. These factors could affect the strength and stability of the structure, adjusting the design characteristics. For instance, the study by M. Clement (2025) analysed the features of compressive effects and their impact on the stress distribution in the elements, and A.N. Hoshyar *et al.* (2019) demonstrated that the consideration of longitudinal forces improved the accuracy of prediction of the risk of localised loss of stability.

To solve this problem, the method of modelling a strip foundation in the form of a finite beam on a two-parameter elastic foundation was used. This approach incorporated both local disturbances in contact with the ground and the influence of longitudinal forces, bringing the design conditions as close as possible to actual operation. This was confirmed by the findings of Y. Fisssha *et al.* (2024), which emphasised the importance of a correct assessment of the load distribution and stress state of structures in the context of soil heterogeneity. The importance of architectural software tools was demonstrated by I. Zgoda (2023), who highlighted the speed and convenience of performing complex calculation operations with subsequent graphical interpretation.

Analysis of existing research determined that previously published works did not fully consider the combination of incomplete contact between the strip foundation and the subgrade and longitudinal tensile or compressive forces, especially in conditions of significant soil heterogeneity and its subsidence properties. In several cases, possible temperature effects and dynamic factors were not incorporated, which distorted the real picture of the stress-strain state of the structure. In this regard, it became necessary to determine the influence of the combined action of incomplete contact and longitudinal forces on the distribution of deflections, bending moments and critical stress zones. The study aimed to develop a methodology for calculating strip foundations with consideration of incomplete contact and longitudinal forces, which ensured a more accurate prediction of the stress-strain state of the structure under difficult operating conditions.



MATERIALS AND METHODS

Since the method for calculating strip foundations was based on universal modelling principles, no attention was initially paid to possible regional characteristics. In real-life conditions, specific geotechnical factors were observed to have an impact. The research established that the soils of the Fergana Valley had several characteristic properties, including high heterogeneity, pronounced subsidence, the presence of loess layers, and significant fluctuations in the groundwater level. These features significantly influenced the behaviour of the foundations, requiring adjustments to the standard calculation models. In this regard, it was appropriate to account for the properties of the soils of the Fergana Valley to improve the accuracy of the calculations.

A rectangular beam (width $b = 1.25$ m, height $h = 1.5$ m) was used as the initial modelling object, which operates as a strip foundation with a length of $l = 18$ m. The beam material was characterised by a density of $\rho = 2,500$ kg/m³ and an elastic modulus of $E = 21 \cdot 10^3$ MPa. The external forces considered were the dead weight of the structure, a concentrated load in the centre of the span $P = 100$ kN, and longitudinal tensile or compressive forces $N_x = 200$ t/m acting in the midplane of the beam. The initial data of the beam with a rectangular cross-section are shown in Figure 1.

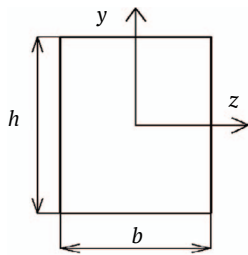


Figure 1. Rectangular beam section

Source: compiled by the authors

The incomplete contact is represented by a trench of size $2a$ located in the centre of the end beam and subjected to longitudinal forces (Fig. 2). The beam is subjected to the beam's weight q_0 and a concentrated force $P = 100$ kN applied in the centre of the beam.

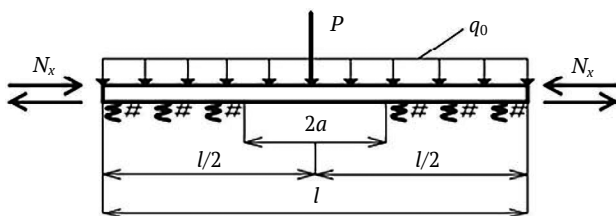


Figure 2. Design diagram of the end beam

Source: compiled by the authors

The subgrade was modelled using a two-parameter model that considers not only vertical elastic displacements (bedding coefficient k_0) but also shear deformations (additional stiffness parameter). The complexity of the problem

is due to the incomplete contact in width $2a$ located in the central zone of the beam. Three variants of $2a$ were considered: 3 m, 4.5 m and 6 m, reflecting different scenarios of weakening or absence of support under the foundation. To improve the accuracy of the calculations, it is necessary to incorporate the soil properties of the Ferghana Valley, characterised by high heterogeneity, the presence of subsidence and loess soils, and significant fluctuations in the groundwater level.

To describe the bending of a finite beam on an elastic base with incomplete contact, a fourth-order differential equation was adopted, supplemented by terms that consider longitudinal forces and the Heaviside function to model the “interruption” of contact in section $2a$. In general, it will be presented as follows (1, 2):

$$EJ \frac{d^4 w(x)}{dx^4} - 2r^2 \frac{d^2 w(x)}{dx^2} + s^4 w(x) \theta(x-a) - N_x \frac{d^2 w(x)}{dx^2} = q(x), \quad (1)$$

where $w(x)$ – deflection function of the beam; $\theta(x-a)$ – Heaviside function reflecting the absence of soil support in the area $[a, l-a]$; N_x – intensity of longitudinal forces (tensile or compressive); EJ – bending stiffness; r and s – parameters characterising the elastic properties of the foundation; $q(x)$ – external load.

$$E = 21 \cdot 10^3 \text{ MPa} \cdot r, \quad (2)$$

where E – modulus of elasticity characterises the resistance of a material to deformation in tension or compression; r – dimensionless coefficient equal to 10.19716, which is used to convert the modulus of elasticity from megapascals to the required system of units.

The analytical transformations performed obtained solutions for various combinations of parameters $2a$ and N_x . The influence of the coefficient α , which relates the longitudinal forces and stiffness characteristics of the beam, is notable (3):

$$\alpha = \frac{N_x l^2}{EJ_z}. \quad (3)$$

By introducing correction terms in the differential equation, both the effect of the “hanging section” and deformations caused by longitudinal forces are incorporated. As part of the calculations, the dead weight of the beam was determined using the following formula:

$$q_0 = \rho \cdot b \cdot h, \quad (4)$$

where q_0 – evenly distributed load produced by the dead weight of the beam (in kg/m or t/m); ρ – density of the beam material, measured in kilograms per cubic centimetre (kg/cm³); b – beam (base) width, measured in metres (m) or centimetres (cm); h – beam height, measured in metres (m) or centimetres (cm).

To verify the analytical solutions and their subsequent engineering application, the developed algorithm was implemented in the Delphi environment. This platform was chosen due to the convenience of creating a user interface, as well as the high speed of processing data arrays, which



is critical for numerical experiments. The numerical experiment consisted of several stages. In the first stage, the initial geometric and mechanical parameters were set, including cross-sectional dimensions, beam length, physical properties of the material and the magnitude of loads such as dead weight and concentrated force P . Next, the variants of incomplete contact were considered, where the program sequentially calculated the cases of $2a = 3$ m, 4.5 m and 6 m, while all other parameters remained unchanged.

At the next stage, longitudinal forces were modelled, with N_x values entered as both positive (tension) and negative (compression) at a fixed angle of inclination $\alpha \approx 0.102$. Then, calculation iterations and convergence analysis were performed: for each combination $\{2a, N_x\}$, the program calculated deflections, bending moments, and base reaction diagrams. Convergence was verified by comparing the results of the iterations and comparing them with analytical expressions, which confirmed the correctness of the algorithm.

The graphical dependencies demonstrated how an increase in the partial contact zone or a change in the sign and value of N_x affects the deflection shape and the nature of the moment distribution. Thus, a comprehensive methodology combining an analytical approach and numerical modelling was used for a detailed analysis of the effect of both incomplete contact and tensile/compressive longitudinal forces on the behaviour of strip foundations.

RESULTS

The study provided the analytical solution to the problem of bending a finite beam on a two-parameter elastic foundation with consideration of incomplete contact with the soil foundation and the action of tensile and compressive longitudinal forces applied in the midplane of the beam. This calculation is based on the analytical solution of the problem of bending a finite beam resting on a two-parameter elastic foundation, considering two key factors. The first factor is the incomplete contact between the foundation and the subgrade, which occurs in width $2a$ (trench) located in the central part of the beam. This phenomenon can significantly affect the distribution of stresses and strains, changing the traditional patterns of interaction between the beam and the foundation.

The second factor is the longitudinal forces that occur in the centre plane of the beam. These forces can be either tensile or compressive, and their occurrence is caused by various external influences, such as pre-tensioning of reinforcement, temperature fluctuations or other operating conditions. Their inclusion in the design model improves the accuracy of description of the behaviour of the beam in real-world conditions.

The modulus of elasticity of the beam material is equal:

$$E = 21 \cdot 10^5 \text{ MPa} = 21 \cdot 10^5 \cdot 10.19716 \frac{\text{kg}}{\text{cm}^2 \cdot \text{t}} = 214.14 \cdot 10^5 = 214,140 \frac{\text{kg}}{\text{cm}^2} = 2,141,400 \frac{\text{t}}{\text{m}^2}.$$

The dead weight of the beam is calculated using formula (4):

$$q_0 = 2,500 \frac{\text{kg}}{\text{cm}^3} \cdot 1.25 \text{ m} \cdot 1.5 \text{ m} = 2,500 \frac{\text{kg}}{\text{cm}^3} \cdot 125 \text{ cm} \cdot 150 \text{ cm} = 4,687.50 \frac{\text{kg}}{\text{m}} = 4,687.5 \text{ t/m}.$$

To determine the total load acting on the beam, the dead weight of the beam was converted into a concentrated force:

$$P_{\text{general}} = P + q_0 \cdot l = 100 \text{ kN} + 4,687.50 \frac{\text{kg}}{\text{m}} \cdot 18 \text{ m} = 100 \text{ kN} + 84,375 \text{ kg} = 100 \text{ kN} + 84,375 \text{ kg} + 9.80665 \text{ N} = 100 \text{ kN} + 827,436 \text{ N} = 927.436 \text{ kN},$$

where P_{general} – total load acting on the beam (in kN); P – concentrated load applied to the beam (in kN); q_0 – uniformly distributed load from the beam's weight (in kg/m); l – beam length (in m).

The Fergana Valley is characterised by complex soil conditions, predominantly loess and loess-like soils, which often have subsidence properties and high layer heterogeneity. According to geotechnical surveys by M. Alabi (2024), deformation modules can vary within the range of 10–25 MPa, cohesion (c) from 10 to 30 kPa, and internal friction angle (φ) from 18 to 26°. In addition, such soils are sensitive to changes in moisture content and can lose part of their bearing capacity when moistened. All this significantly affects the performance of strip foundations and requires correct consideration in the design model.

An additional complicating factor in the region is seismic activity: The Ferghana Valley is classified as an area with seismicity levels of 7–9 on the MSK-64 scale. When designing foundations, it is necessary to incorporate dynamic effects that cause vibrations of the structure and additional load on the “hanging” sections of the foundation (if there are areas of incomplete contact). In this study, the seismic load was modelled by introducing a horizontal component proportional to the beam mass and the site seismicity factor. This can be used to estimate the increase in deflections and stresses, especially in weak or subsiding soil conditions.

Digital technologies were used to verify and improve analytical solutions. A software module was developed in the Delphi environment that accounted for all key factors affecting the object under study. The numerical experiment included solving a system of equations (finite difference method or finite element method) for various combinations of $\{k_0, 2a, N_x\}$ and variations in seismic load. The results of the deflection and bending moment diagrams along the beam were compared with analytical expressions. With correct parameter settings, the discrepancies between the results of the analytical and numerical methods did not exceed 5–10%.

Thus, the integration of real geotechnical data from the Fergana Valley, consideration of the seismicity of the site and the use of digital technologies for numerical modelling provides a comprehensive and accurate approach to the design of strip foundations. In practice, this can be used to optimise cross-sectional and reinforcement dimensions, as well as to provide timely reinforcement measures in potentially dangerous areas with increased deflections or stresses.



To incorporate the effect of longitudinal forces, it is necessary to determine the value of the proportionality coefficient of the intensity of longitudinal forces. The intensity of longitudinal forces was assumed to be $N_x = 200 \text{ t/m} = 2,000 \text{ kg/cm}$.

The beam's mass was calculated by multiplying the volumetric mass by the cross-section and length, and, if necessary, the forces were converted into concentrated equivalents. To account for longitudinal forces, a dimensionless value α was introduced into the problem, characterising their relative value concerning the stiffness of the beam and the base. The value of α is defined as (5):

$$l = \sqrt[4]{\frac{E \cdot J_z}{k_0}}, \quad (5)$$

where l – characteristic length of the beam (in metres); E – modulus of elasticity of the beam material (in Pa, MPa or kN/m^2); J_z – moment of inertia of the beam cross-section relative to the z -axis (in m^4 or cm^4); k_0 – bedding coefficient, which characterises the elasticity of the subgrade (in N/m^3 or kN/m^3).

Where:

$$k_0 = 5 \frac{\text{MN}}{\text{m}^3} = 5 \cdot 10^6 \frac{\text{H}}{\text{m}^3} = 5 \cdot 0.10197162 \cdot 10^6 \frac{\text{kg}}{\text{cm}^3} = 5.1 \cdot 10^5 \frac{\text{kg}}{\text{cm}^3} = 0.51 \frac{\text{kg}}{\text{cm}^3} = 510 \frac{\text{t}}{\text{m}^3},$$

where k_0 – bed coefficient, characterising the stiffness of the ground base (in various units of measurement); 5 MN/m^3 – initial value of the bedding factor in meganewtons per cubic metre; $5 \cdot 10^6 \text{ N/m}^3$ – conversion to Newtons per cubic metre.

According to the above initial data, the value of the axial moment of inertia for a rectangular section (Fig. 1) was determined by the formula (6):

$$J_z = \frac{b \cdot h^3}{12} = \frac{1.25 \cdot 1.5^3}{12} = \frac{125 \cdot 150^3}{12} = 35,156,250 \text{ cm}^4 = 0.3515625 \text{ m}^4, \quad (6)$$

where J_z – axial moment of inertia of the beam cross-section relative to the axis; b – beam width (in m or cm); h – beam height (in m or cm); $\frac{b \cdot h^3}{12}$ – formula for calculating the moment of inertia of a rectangular section relative to its central axis; 1.25 m – beam width in metres; 1.5 m – beam height in metres; 12 – coefficient in the formula for the moment of inertia for a rectangular section.

The bending stiffness was determined:

$$E \cdot J_z = 21 \cdot 10^3 \text{ MPa} \cdot J_z = 214,140 \frac{\text{kg}}{\text{cm}^2} \cdot 35,156,250 \text{ cm}^4 = 2,141,400 \text{ t} \frac{\text{t}}{\text{m}^2} \cdot 0.3515625 \text{ m}^4 = 752,835.94 \text{ tm}^2,$$

where $E \cdot J_z$ – bending stiffness of the beam (bending stiffness); E – modulus of elasticity of the beam material (in Pa, MPa, kg/cm^2 or t/m^2); J_z – moment of inertia of the beam cross-section relative to the axis z (in m^4 or cm^4); $21 \cdot 10^3 \text{ MPa}$ – value of the elastic modulus in megapascals.

Substituting the values of $E \cdot J_z$ and k_0 in (3), the value of l was determined:

$$l^2 = \sqrt{\frac{E \cdot J_z}{k_0}} = \sqrt{\frac{752,835.94 \text{ tm}^2}{510 \frac{\text{t}}{\text{m}^3}}} = \sqrt{1,476.15} \approx 38.42.$$

$$\alpha = \frac{N_x \cdot l^2}{E \cdot J_z} = 2,000 \cdot \frac{38.42}{752,835.94} = \frac{76,840}{752,835.94} \approx 0.102.$$

The absence of beam support in this area leads to a redistribution of loads and, as a result, to changes in deflections and stresses. Table 1 shows the calculation results for each of the above cases.

Table 1. Calculated deflections of a foundation beam on a two-parameter elastic foundation under tensile longitudinal forces

No.	x	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	α	N_x , t/m	W excluding tensile stress
1 st row	W^p	-0.0053	-0.0052	-0.0049	-0.0043	-0.0037	-0.0031	-0.0023	-0.0014	-0.0007	0.00	0.0102	200	0.0059
2 nd row	W^p	-0.0067	-0.0066	-0.0061	-0.0055	-0.0047	-0.0038	-0.0028	-0.0018	-0.0008	0.00	0.0102	200	0.0074
3 rd row	W^p	-0.0077	-0.0075	-0.0070	-0.0063	-0.0053	-0.0043	-0.0032	-0.0021	-0.0009	0.00	0.0102	200	0.0085
4 th row	W^p	-0.0088	-0.0085	-0.0080	-0.0072	-0.0061	-0.0050	-0.0036	-0.0023	-0.0011	0.00	0.0102	200	0.0098

Source: compiled by the authors

One of the most important factors affecting the performance of strip foundations is the heterogeneity of the soil, as well as the probability of localised failures or subsidence. In this study, the incomplete contact was modelled as a $2a$ -wide trench located in the central part of the beam. Three options were considered:

- row 1 – when the beam is in full contact with the subgrade;
- row 2 – with incomplete contact in an area of trench width: $2a = (1/6) \cdot l = (1/6) \cdot 18 = 3 \text{ m}$;
- row 3 – with incomplete contact in an area of trench width: $2a = (1/4) \cdot l = (1/4) \cdot 18 = 4.5 \text{ m}$;



● row 4 – with incomplete contact in an area of trench width: $2a = (1/3) \cdot l = (1/3) \cdot 18 = 6 \text{ m}$.

The analysis of beam bending on a two-parameter elastic foundation, considering incomplete contact, revealed several key trends. First, an increase in deflection is observed with an increase in trench width. As parameter $2a$ increases, the bearing area of the beam on the foundation decreases, which leads to increased displacements in the central zone. This is due to a decrease in the stiffness of the beam-foundation system and an increase in the free section without support.

Secondly, there is a redistribution of forces along the beam. The areas immediately adjacent to the trench zone experience increased bending moments, since they have to take an additional part of the load, which would be distributed more evenly under full contact conditions. Thus, an increase in internal forces is observed in these zones, which should be incorporated when calculating the strength of the structure. Third, the shape of the deflection diagram changes. With full contact, the deflection is distributed smoothly, providing a uniform change in bending moments. However, in the case of incomplete contact, a sharp increase in deflection occurs in the “hanging” zone, which leads to localised deformations and a potential change in the stress-strain state of the beam.

The data obtained suggests that even a relatively small “break” in contact leads to a noticeable increase in displacements and stresses near the trench edges. Thus, when designing, it is necessary to carefully assess the probability of ground subsidence and possible local failures. Ignoring these factors can lead to an underestimation of the stresses in the foundation, which in real life can mean an increased risk of cracking and reduced bearing capacity. The calculations (Table 1) demonstrated that, without factoring in longitudinal forces, the maximum deflections could increase to -0.0098 m when the area of incomplete contact increased by $2a = 6 \text{ m}$, which is approximately 6,670% more than in the case of a smaller trench area ($2a = 3 \text{ m}$). This indicates that the structures are highly sensitive to the length of the section where there is no support on the ground. Based on the results shown in Table 1, graphs of the deflections of the end beam on a two-parameter elastic foundation were constructed, incorporating the incomplete contact of the beam with the soil settlement in the form of a single trench $2a$ wide, located in the centre of the beam, and the action of longitudinal tensile forces applied in the median plane of the beam. Figure 3 demonstrates the deflection graph of the end beam on a two-parameter elastic foundation, incorporating the parameters that ensure the approximation of the design conditions to the actual operation of the structure.

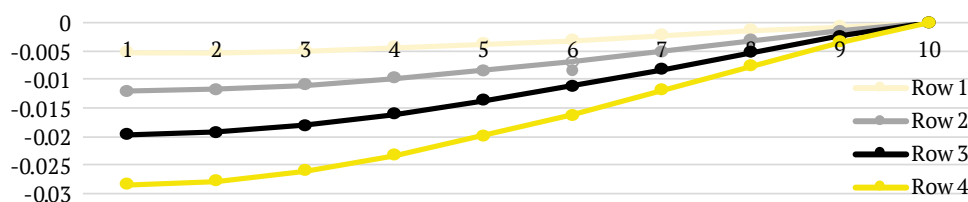


Figure 3. Deflection diagram of a finite beam on a two-parameter elastic base with consideration of the parameters providing conditions close to its actual operation

Source: compiled by the authors

Incomplete contact between the foundation (beam) and the subgrade was modelled as a central trench with a width of $2a$, which redistributed loads and locally increased deflections and stresses. Four scenarios were considered in the study: full contact (control case) and three variants of the trench with width $2a = 3 \text{ m}$, 4.5 m and 6 m . The study determined that an increase in the “hanging” area caused a significant increase in deflections and internal forces in the trench adjacent to the trench. The calculations demonstrated that with a trench width of $2a = 6 \text{ m}$, deflections in the central part of the beam increased by 66-70% compared to the $2a = 3 \text{ m}$ variant, which emphasised the high sensitivity of the structure to the unsupported zone.

The analysis of the results demonstrated that incomplete contact significantly increased deflections in the area of the “hanging” section. The distribution of internal forces became uneven, and the extreme sections of the trench experienced increased bending moments. With the increase in the width of the trench, the probability of deformation concentration and cracking significantly increased. The

study established that the weakened contact zones should be taken into account at the design stage to prevent the underestimation of stresses and increase the reliability of the foundation. In real-life conditions, strip foundations are often subjected to tensile longitudinal forces caused by preliminary tensioning of reinforcement, uneven heating or cooling of structures (temperature gradients), as well as design schemes that assume external influences creating tensile effects (Baida *et al.*, 2024). In the presented calculations, the intensity of tensile forces N_x was taken to be equal to 200 t/m with a coefficient $a \approx 0.102$. Comparative data for beam deflections with and without tensile stress are given in Table 1 (rows marked W_p).

The main conclusions on the effect of tensile forces demonstrated that the beam works somewhat more rigidly under tension, which leads to a reduction in deflections. The analysis of analytical and numerical data shows that, on average, deflections are reduced by about 10-11%. In addition, a levelling of the stress-strain diagram is observed, as tensile forces counteract the local loss of stability and



increase in deflections. In addition, the redistribution of forces near the edge of the trench becomes less sharp when in incomplete contact with the ground, which reduces the probability of excessive moments and concentrated deformations.

For instance, when the beam was in full contact with the substrate without longitudinal forces, the maximum deflection was -0.0059 m, while when tension was considered, it reached -0.0053 m. Although the difference in absolute values seems insignificant, in real-world construction, a 10-15% reduction in deformation can mean a significant safety margin and a reduction in the probability of damage. For the variants with incomplete contact, a similar pattern is observed: with a trench zone of 3 m in length, the deflection decreases on average from -0.0074 m to -0.0067 m, which confirms the favourable effect of tensile forces on the overall stiffness of the foundation-soil system. When the width of the incomplete contact is increased to 6 m, the tensile effect also results in a reduction of the ultimate deflection values by approximately 10-11%. Thus, the incorporation of tensile longitudinal forces improves the accuracy of determination of the actual stiffness of the foundation and predicting its behaviour under real loads.

In the presence of tensile longitudinal forces ($N_x > 0$), the beam demonstrated stiffer operation, which was reflected in a reduction of deflections and a smoother distribution of the stress-strain state. Calculations demonstrated that at an intensity of $N_x = 200$ t/m and a coefficient of $\alpha \approx 0.102$, deflections decreased by an average of 10-11%. This effect was observed both in the case of full contact of the beam with the base and various variants of incomplete contact (different values of $2a$). Even with large areas of incomplete contact ($2a = 6$ m), the tensile force remained a stabilising factor, reducing the risk of local deformation.

The analysis of the results confirmed that tensile longitudinal forces contributed to a reduction in deflections and an increase in the overall stiffness of the foundation-soil

system. The reduction in maximum deflections reached 10-15%, which significantly increased the safety margin of the structure in real construction conditions. Stress diagrams in the trench zone became smoother, reducing the risk of excessive deformation concentrations. These results enabled the use of prestressed reinforcement in strip foundations as an effective technique for stabilising the structure and increasing its reliability.

In addition to tensile forces, compressive forces can be substantial in the operation of strip foundations, which arise under various operating conditions. For instance, temperature exposure leads to linear expansion of the structure, as a result of which the foundation can rest against rigid elements, creating significant longitudinal compressive forces. In addition, the transfer of loads from overlying structures under specific support patterns can also contribute to compression, especially in places of concentration of forces. The peculiarities of installation and operation, such as the overstretching of supports or the presence of expansion joints, which can change the nature of the distribution of compressive stresses in the foundation, are also substantial.

In this study, compressive forces were modelled with the same intensity ($N_x = 200$ t/m), but with the opposite sign. The calculation results are shown in Table 2 (rows W_{cp}). The analysis demonstrated that compression can increase beam deflections, but the magnitude of this increase is usually less than the reduction effect from tension. The reason lies in the fact that a compressed beam is more prone to losing stability in the transverse direction, especially if there is weak or no contact with the ground in section 2a. Figure 4 demonstrates a deflection distribution graph of the final beam calculated on a two-parameter elastic basis with the above parameters. The graph showed the change in deflections along the length of the beam, and their maximum values were recorded, to assess the impact of the selected parameters on the behaviour of the structure under conditions close to real ones.

Table 2. Comparison of response times and computing costs

No.	x	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	α	N_x , t/m	W without compression
1 st row	W_p	-0.0063	-0.0061	-0.0057	-0.0051	-0.0043	-0.0036	-0.0027	-0.0017	-0.0009	0.00	0.0102	200	0.0059
2 nd row	W_p	-0.0078	-0.0077	-0.0072	-0.0065	-0.0055	-0.0045	-0.0033	-0.0020	-0.0010	0.00	0.0102	200	0.0074
3 rd row	W_p	-0.0009	-0.0088	-0.0083	-0.0074	-0.0063	-0.0051	-0.0037	-0.0024	-0.0011	0.00	0.0102	200	0.0085
4 th row	W_p	-0.0104	-0.0100	-0.0094	-0.0085	-0.0072	-0.0058	-0.0042	-0.0028	-0.0013	0.00	0.0102	200	0.0098

Source: compiled by the authors



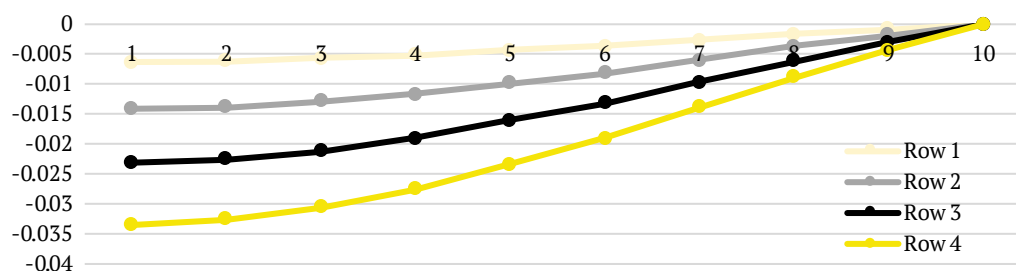


Figure 4. Deflection diagram of a finite beam on a two-parameter elastic base with the above parameters considered
Source: compiled by the authors

Several key points can be identified from a comparison of the results for different scenarios. With incomplete contact with the foundation, when the width of the trench section is $2a = 3$ m, the maximum deflection without compression reached -0.0074 m, while with compression forces incorporated, it increased to 0.0078 m, which corresponds to an increase of about 5%. For a wider trench section, $2a = 6$ m, the increase in deflection was even more noticeable and amounted to about 6-7%. Without consideration of compression, the deflection was -0.0098 m, and with consideration of compression, it increased to $-0.0104/-0.0105$ m and more. Separate calculations also indicate a range of values of $-0.0100/-0.0104$ m.

In most of the combinations considered, especially at higher values of $2a$, deflections increase and beam warping is possible, which can be a serious hazard. This effect can cause cracks in the foundation, especially if the reinforcement is insufficient or if the necessary structural measures are not taken. Thus, compressive forces can exacerbate the negative effects of incomplete contact with the foundation by increasing deformations. However, the extent of this effect is determined by the stiffness of the soil and the magnitude of the longitudinal forces.

In designing strip foundations, it is necessary to account for compression that can cause more significant deformations than assumed in simplified design models where longitudinal forces are not considered. The analysis of the calculations demonstrated that the difference in the maximum deflections with and without compression for large sections of the trench reaches 5-10%, which is a significant value for structures with a high level of responsibility.

Compressive longitudinal forces ($N_x < 0$) had the opposite effect, contributing to an additional increase in deflections, especially in conditions of incomplete contact. The calculations showed that at $N_x = 200$ t/m, the ultimate deflections increased by 5-10% compared to similar scenarios without compression. In the case of a longer "hanging" section of the foundation ($2a = 6$ m), the deflection increase was most pronounced and reached 6-7%. This effect was accompanied by an increase in internal stresses and an increased risk of crack development, which made it necessary to account for compressive forces in the design of structures, especially concerning possible temperature effects.

The analysis of the effect of compressive longitudinal forces demonstrated that their presence exacerbated

the negative effects of incomplete contact and led to an increase in deflections by 5-10%. At values of $2a$ up to 6 m, a significant increase in deformations and stresses in the central zone of the beam was observed. In conditions of weak or subsiding soil, the risk of localised damage increased significantly, especially if the influence of longitudinal compressive factors was underestimated. To compensate for such effects, it was advisable to include design measures such as expansion joints and reinforced reinforcement in the design, which reduced the negative impact of compressive effects and increased the overall reliability of the structure.

DISCUSSION

The results of the study confirm that the consideration of incomplete foundation-base contact and longitudinal forces is one of the determining factors in the design of strip foundations in difficult operating conditions. Increased attention to stabilisation and optimisation of the structure's performance plays a significant role here, as it can increase deflections in the central part of the beam and increase stress concentration. Since even a relatively small unsupported zone (e.g., a 3 m long trench) leads to a noticeable increase in deflections and stress concentration, it should be noted that the greatest impact on the stress-strain state of a structure is exerted by increasing the size of the incomplete contact zone, and not just the fact of its presence. The larger the area where the foundation does not rest on the ground, the greater the redistribution of forces and the increase in local deformations, which must be considered in the design.

The results of the study confirmed the importance of the incomplete contact of the foundation with the subgrade and the influence of longitudinal forces. The study determined that even a relatively small zone of "hanging" area significantly increased deflections and the appearance of local stress concentrations in the parts of the foundation adjacent to the trench. The largest increase in deformations was observed with the expansion of the unsupported zone, which was consistent with the conclusions drawn by A.T. Marufiy & A.S. Kalykov (2019), where incomplete contact between the beam and the soil was noted to cause a significant redistribution of bending moments. B. Mes-saouda *et al.* (2023) emphasise the importance of numerical modelling of the behaviour of a surface foundation



located near a slope. Their results demonstrated that the geometrical location of the foundation relative to natural objects has a significant impact on the load distribution, which harmoniously complements conclusions about the effect of the expansion of the incomplete contact zone on the local deformation of the structure.

The effect of longitudinal forces was ambiguous: tensile forces contributed to a reduction in deflections, increasing the stiffness of the beam-foundation system, while compressive forces, on the contrary, increased the magnitude of displacements and could provoke additional buckling. Similar trends were observed by A.T. Marufiy & A.S. Kalykov (2019), specifying that the presence of compressive forces can exacerbate the negative effects of incomplete contact, especially in the central zone of the structure. These conclusions were consistent with the results obtained earlier and described by A.T. Marufiy *et al.* (2021), who analysed various schemes of longitudinal load distribution and their influence on the flexibility of beams on an elastic foundation.

A.T. Marufiy & A.S. Kalykov (2019) investigated the stress-strain state of strip foundations, incorporating the factors affecting their actual operation. Various characteristics of the foundation and their influence on the durability of the structure were considered. Earlier, a methodology for calculating slabs and beams on elastic foundations was also proposed by A.T. Marufiy *et al.* (2021), which emphasised the need to incorporate soil heterogeneity and possible subsidence of individual sections. The results of the present study were consistent with their findings, demonstrating that the expansion of the incomplete contact zone increased local deformations and increased the risk of cracking, especially under compressive forces. This confirmed the feasibility of using prestressed reinforcement, as mentioned in the study by A.T. Marufiy *et al.* (2021) when it was necessary to increase the stiffness of the foundation and reduce deflections in problem areas.

Thus, the consideration of incomplete contact and longitudinal forces was a crucial condition in the design of strip foundations. Ignoring these factors could lead to errors in the assessment of the stress-strain state and reduce the reliability of the structure. Together with the recommendations given in the above works, the presented analysis confirmed the importance of an integrated approach combining analytical and numerical methods, as well as enabling detailed consideration of the characteristics of weak and subsidence soils in real operating conditions.

The transition to the use of big data and complex analytics for engineering is becoming an increasingly prominent trend. The presented study is limited to the linear-elastic formulation, but the transition to more complex models can be made based on modern computing technology and integrated solutions described by these authors. The review of finite element methods presented by G.D. Dhadse *et al.* (2021) was dedicated to modelling the interaction of the soil-structure system, incorporating interface phenomena. This review demonstrated the complexity

of calculations in incomplete contact, which confirms the need for an integrated approach used in the current study to optimise computational methods. The situations of deep excavation and weakened soil under foundations were further considered by S. Yang *et al.* (2023). Their Grey Wolf Optimiser-Extreme Learning Machine (GWO-ELM) model demonstrated that hybrid algorithms can achieve high accuracy in deformation prediction. No such methods were used in the calculations, but the general idea is the same: incorporation of additional parameters that determine the behaviour of the soil increases the accuracy and reliability of model assumptions.

Similar themes are present in a study by A. Ramos *et al.* (2024), where the application of machine learning to predict deformations of railway tracks has similarities with the methodology: although they are dealing with tracks rather than foundations, both are important for correct prediction of subsidence and displacements in the base. The results obtained on how longitudinal compression or tension affects the deflection shape can be reinterpreted for various types of linear structures, where the effect of a “hanging” section can be relevant. In a study by M. Sadegh Es-haghi *et al.* (2021), a model based on machine learning methods is proposed to predict the seismic load-bearing capacity of a shallow strip foundation located over a void in heterogeneous soils. This approach demonstrates the potential of using modern computational methods to improve the accuracy of structural stability assessment, which is also reflected in current analytical and numerical experiments.

It is necessary to incorporate the uncertainty inherent in soil systems and loaded structures. Approaches to probabilistic modelling are demonstrated by S. Chen *et al.* (2022) demonstrate probabilistic modelling approaches by applying machine learning methods to assess performance. A study that determines the maximum deflections under different scenarios can easily be supplemented with probabilistic parameters if the engineer has statistics on variations in the modulus of elasticity of concrete, density or soil bedding coefficient. The use of advanced computing technologies in geotechnical design was discussed in detail by H. Jürgens & S. Henke (2021), demonstrating how numerical algorithms improve the quality of engineering solutions. In practice, the advantage of such a strategy using a combination of analytical formulas and numerical iterations has been convincingly confirmed. Digital technologies enable flexible change of the parameters: the length of the trench section, the sign and N_x value, and the comparison of obtained results.

The issue of the reliability of engineering solutions, especially under complex loads, was addressed by M. Amin-isharifabad *et al.* (2021), proposing a deep-learning model for survival analysis. Although the case is not directly related to bioengineering, the approach to processing large amounts of data is similar: it is necessary to identify critical factors affecting the state of a structure and predict the time to limit state. In the context of geotechnics, this is





the service life of a foundation before unacceptable deformations or cracks appear. The study by K.C. Onyelowe *et al.* (2022) demonstrated that the use of artificial intelligence algorithms to optimise design methods can significantly improve the efficiency of design solutions. The author's findings on the influence of longitudinal forces and incomplete contact are consistent with the conclusions of this paper, indicating the prospects for integrating AI technologies into future research in geotechnics.

Neural network solutions for assessing the reliability of different types of foundations described by A. Savvides & L. Papadopoulos (2024) complement the overall picture of current trends. In shallow foundations, it is necessary to assess the cohesive properties of the soil, and the study highlighted the elastic coefficients of the foundation, which can be considered as an analogue of shear stiffness. These two areas are quite compatible, as the combination of classical soil mechanics methods and artificial intelligence algorithms increases the adaptability of calculations. The topic of integrating analytical and machine methods for modelling bases is also present in a study by Z. Zhou *et al.* (2024). The authors analysed large-scale hydraulic structures, but the nature of the interaction "structure-soil" is in many ways similar to the situation with strip foundations, when the presence of weakened zones or trenches can cause local stress redistribution. The difference is only in the physical scale and type of structure, but the fundamental deformation mechanisms are similar.

The issues of algorithmic comparison of different machine learning methods for predicting complex states raised by S. Sasane & Z.A.S. Mulla (2024) demonstrated that the choice of a particular strain prediction technique (whether it is gradient boosting, random forest or neural network) depends on the nature of the input data. Therefore, this means that if it is necessary to verify the model when statistics of foundation deformations during operation are collected, different algorithms can be tried to clarify the "dangerous" zones of the hanging section and effectively assess the risk. The structured application of modern multivariate computing algorithms was studied by X.-M. Gao *et al.* (2023), classifying methods per number of dimensions. In the case of the basic calculation, it is still focused on a one-dimensional beam model but can be extended to a two- or three-dimensional formulation if it is necessary to incorporate the effects in the transverse direction or significant variations in soil properties along the width of the foundation. The use of higher dimensions implies an increase in computational costs, which in turn raises performance issues.

The role of supercomputing resources and adaptive algorithms in solving complex scientific and engineering problems is mentioned by H. Sharma *et al.* (2020). The study illustrated that modelling large and complex structures requires distributed computing. For research purposes, this approach would be an additional step that can analyse scenarios in greater detail or introduce additional physical nonlinearity. This would provide an even more accurate

picture of the foundation-soil interaction, incorporating dynamic factors and load variability. Y. Du *et al.* (2022) proposed a new model for predicting the bearing capacity of large strip foundations under combined loading, which can incorporate the mutual influence of different loads. This approach complements the current analysis of the influence of longitudinal forces and emphasises that comprehensive modelling using modern technologies is a key factor in assessing the strength characteristics of a foundation.

Thus, the results analysed in this study are closely related to many modern trends that involve a complex combination of numerical methods, new technologies and proper data analysis. The study in the context of these advances demonstrated the importance of the parameters of incomplete contact and longitudinal forces in the calculation of strip foundations: simplified schemes can lead to an incorrect assessment of the stress-strain state and an increase in deformation, while high-tech and intelligent methods, on the contrary, can incorporate many factors and building more reliable, optimised structures.

CONCLUSIONS

The study developed a methodology for calculating strip foundations that considers incomplete contact with the ground and the effect of longitudinal tensile or compressive forces. The analysis demonstrated that if these factors are ignored, a significant discrepancy between the actual and calculated stress-strain state of the structure can occur, leading to errors at the design stage. The study was based on both analytical solutions reflecting the influence of the "hanging" section of the beam using the Heaviside function and numerical experiments performed in Delphi and verified by finite difference and finite element methods. The results demonstrated that incomplete contact causes a noticeable increase in deflections in the central zone of the foundation and an increase in bending moments in the areas adjacent to the trench. As the width of the unsupported section increased, local deformations increased, and stress concentrations increased. The tensile longitudinal forces created a favourable effect, which consisted of a reduction in deflections and a more even distribution of forces along the beam, leading to an increase in the stiffness of the foundation-soil system. The study determined that with a characteristic coefficient α , the maximum possible tensile deflections were reduced by 10-15%.

The calculations yielded the following key numerical values. With full contact between the beam and the ground, the maximum deflection was 0.0059 m, and with partial contact with a trench width of $2a = 3$ m, it was 0.0074 m; with an increase in $2a$ to 6 m, the deflection reached 0.0098 m, which meant an increase in deflection by 66-70%. With the tensile longitudinal forces included a decrease in deflections of approximately 10-11% was recorded, and when compressive forces were modelled, an increase of 5-10% was observed. The coefficient characterising the influence of longitudinal forces was approximately 0.102. The numerical data obtained confirmed the



effectiveness of the proposed method for calculating strip foundations under conditions close to real ones and made it possible to optimise the cross-sectional dimensions and reinforcement scheme of the structure. Further research could focus on the development of 3D models that consider lateral interactions between the foundation and the ground to more accurately predict stresses and strains. In addition, the introduction of monitoring systems that combine theoretical calculations with actual measurements will enable prompt detection of critical changes in the condition of the foundation and timely correction of design solutions. These areas contribute to improvement of the calculation

methodology, increasing the accuracy of determining the parameters of foundation performance and reducing the risk of undesirable deformation or failure.

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CONFLICT OF INTEREST

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Огляд та концепція пасивного індивідуального житлового будинку для умов континентального помірного клімату

Анотація. Метою дослідження була розробка методології розрахунку стрічкових фундаментів з урахуванням складних умов експлуатації. Для цього було розглянуто особливості фундаментів на слабких та просідаючих ґрунтах, досліджено вплив неповного контакту з фундаментом, а також вплив поздовжніх сил, що виникають внаслідок попереднього натягу арматури та зміни температури. Методологія розрахунку базувалася на моделюванні фундаменту як скінченної балки, що спирається на двопараметричний пружний фундамент. У дослідженні проаналізовано вплив неповного контакту між основою та фундаментом, що виникає у випадку локалізованих провалів або ослаблення ґрунту, а також поздовжніх сил, спричинених зовнішніми навантаженнями. Була розроблена розрахункова програма для числового моделювання та реалізована в Delphi. У дослідженні було визначено, що відсутність повного контакту між фундаментом та основою призводить до перерозподілу напружень, що може спричинити локалізовані концентрації деформацій. Поздовжні сили по-різному впливають на характеристики фундаменту: розтягуючі – зменшують прогини, а стискаючі – збільшують. Аналітичні та числові розрахунки підтвердили необхідність врахування цих факторів під час проектування, оскільки їх ігнорування може призвести до значних відхилень у напружено-деформованому стані конструкції. Розроблена математична модель враховує ці ефекти та визначає критичні області, що потребують коригування параметрів проектування. Отримані дані можуть бути використані при проектуванні стрічкових фундаментів у складних ґрунтових умовах, підвищуючи їх надійність та ефективність, а також мінімізуючи ризик утворення тріщин та нерівномірних осідань. Запропонована методологія може бути використана для розрахунку фундаментів будівель та споруд, що експлуатуються в неоднорідних ґрунтах

Ключові слова: модель ґрунтового фундаменту; функція Хевісайда; жорсткість на згин; узагальнені характеристики ґрунту; коефіцієнт нашарування; модуль пружності; момент інерції



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Urban planning foundations for the formation of training and production centres for folk art crafts

Abstract. The study aimed to substantiate architectural and planning solutions that facilitate the integration of training and production centres for folk arts and crafts into the modern urban environment of Kazakhstan. The study uses methods of urban planning concept, functional zoning, environmental sustainability and architectural solution analysis to develop design recommendations. The study substantiated urban planning approaches to the location and design of training and production centres of folk-art crafts in Kazakhstan. The study established that the best places for their creation are regions with a developed cultural and historical heritage and the presence of sustainable craft traditions. The author analysed the functional structure of craft centres, which demonstrated that their effectiveness depends on a clear zoning of the territory. It is recommended to distinguish the following zones: educational (workshops, lecture halls), industrial (workshops, laboratories), exhibition (museums, galleries, shops) and public (recreation and cultural

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events). The results of the study confirmed that the use of local natural materials (stone, wood, clay) in construction not only meets the requirements of environmental sustainability but also contributes to the preservation of the traditional appearance of architecture. The study determined that the integration of traditional Kazakh architectural elements into modern projects contributes to tourist and cultural attractiveness. As a practical conclusion, recommendations for the design of centres were developed, including the choice of locations, structural zoning and consideration of architectural features. An example of the successful application of the proposed solutions was the project of a centre in Turkestan, which demonstrated a significant contribution to the preservation of cultural heritage and the development of the local economy. Thus, the results of the study highlighted the importance of an integrated approach to the creation of training and production centres, ensuring their sustainable development and integration into the modern urban environment

Keywords: cultural heritage; functional zoning; environmental sustainability; architectural elements; tourist attraction; regional development

INTRODUCTION

Folk arts and crafts are an important component of the cultural heritage, contributing to the preservation of traditions, the formation of national identity and the development of regions. Interest in crafts is growing, which requires the creation of conditions for their preservation and promotion. Training and production centres for folk arts and crafts are central to the continuity of knowledge, training new generations of craftsmen and demonstrating products to a wide audience. The formation of such centres requires not only a competent approach to their organisational and economic component but also careful design of urban planning solutions. The architectural and planning features of these facilities should incorporate the cultural characteristics of the regions, harmoniously combine traditional and modern elements, and ensure functionality and sustainability.

Kazakhstan, with its rich cultural heritage, is a promising territory for the creation of training and production centres (Gamaliia & Artemenko, 2023). This is determined by the existence of stable traditions of folk crafts, such as carpet weaving, pottery, wood and metal artistic processing. However, in practice, their development faces several challenges, including the lack of specially equipped spaces and insufficient integration into the modern urban environment. The problem of the formation of training and production centres for folk art crafts is an important part of the study in the context of preserving cultural heritage and regional development. D. Arinaitwe (2021) analysed practices and strategies to improve learning through collaboration between teacher education institutions and workplaces. The author emphasised the importance of developing effective practices to improve the learning process, which contributed to the quality of teacher education. N. Tomaz & E. Caldeira (2021) considered the inclusion of traditional architectural elements in the design of such facilities as an important aspect of preserving cultural identity. The study argued that the use of national motifs in architecture maintained a connection with history and promoted the popularisation of folk crafts among young people.

A. Kalkanatov *et al.* (2023) studied the role of cultural centres and houses of culture in the Republic of Karakalpakstan, considering them important elements of the region's

social and cultural infrastructure. The study emphasised the importance of these facilities for the preservation and development of local traditions, supporting the social cohesion and cultural identity of the population. J. Santamarta *et al.* (2021) emphasised the importance of introducing renewable energy technologies, such as geothermal heating, into tourism infrastructure. The study argued that this not only reduced operating costs but also contributed to the creation of environmentally friendly and energy-efficient facilities. N. Bencheva *et al.* (2024) studied the role of social infrastructure in agrarian tourism, emphasising the importance of having a developed social infrastructure for the successful functioning of craft communities. The study noted that regions with sustainable infrastructure and high potential for the development of craft clusters can create favourable conditions for agrarian tourism and craft development. A. Wondirad *et al.* (2022) emphasised that transport accessibility and the inclusion of craft communities in tourist routes were important factors for their successful functioning. The study argued that this contributed not only to attracting visitors but also to strengthening the link between cultural heritage and the modern labour market.

D. Kalfas *et al.* (2024) studied the contribution of training and production centres to job creation. The authors argued that the centres have become important economic and social hubs, providing new employment opportunities for residents and small business development. G. Attanasio *et al.* (2022) proposed a business model for the sustainable development of training and production centres by examining the most important contributions of stakeholders such as employees and managers. The study analysed the creation of conditions for effective interaction of all stakeholders, which would contribute to sustainable development and preservation of traditional crafts. N. Wu & Z. Liu (2021) studied the development of higher education, technological innovation and the modernisation of the industrial structure, emphasising how these processes influenced the development of the urban environment. The study highlighted that training and production centres could become important cultural and educational facilities that could attract residents and tourists, playing a key role in the transformation of urban infrastructure. S. Deb *et*





al. (2022) analysed the potential and characteristics of family craft businesses, highlighting the most important factors for their success, such as motivation and other key aspects. The study emphasised that successful examples included a comprehensive approach that incorporated not only architectural and engineering solutions, but also a strategy for integrating the business into the socio-economic environment of the region.

Despite considerable research, gaps were identified that require further study. These include the integration of centres into the urban environment, their impact on public spaces and long-term sustainability, as well as a deeper analysis of the impact of the educational function of centres on the preservation of craft traditions. The study aimed to identify the optimal urban planning solutions for the creation of training and production centres for folk art crafts that contribute to the preservation of cultural heritage and regional development. Research objectives:

1. To analyse the possibility of integrating traditional architectural elements into the design of such facilities to preserve cultural identity.
2. To evaluate the use of environmentally friendly materials such as wood and clay in the construction of training and production centres.
3. To study the impact of transport accessibility and inclusion of centres in tourist routes on their successful functioning and development.

MATERIALS AND METHODS

The study conducted a comprehensive analysis of approaches to the design of training and production centres for folk crafts, as well as investigated the requirements for such centres and the spatial organisations in which they operate. First, the urban planning principles that underlie the design of such facilities were studied. For this purpose, several concepts used in design were studied to identify those that can be used to create training and production centres that provide a harmonious combination of educational, cultural and production functions.

One of the key stages of the study was the analysis of the spatial organisation of such centres. The functional areas necessary for the successful functioning of a folk crafts training and production centre were studied. These included training workshops for artisans, production facilities for creating folk crafts, cultural and exhibition spaces for demonstrating works, and public areas for holding masterclasses and cultural events. For each of these areas, the best way to integrate with the other functions of the centre was considered to ensure efficient use of space and meet functional requirements.

The study addressed environmental integration in the design of such centres. Methods of using environmentally friendly materials, such as wood, stone and clay, were considered, which can not only ensure the sustainability and durability of the facilities but also create a comfortable atmosphere. The possibilities of using renewable energy sources such as solar panels and rainwater recycling

systems were also analysed, which could reduce the ecological footprint of such facilities and improve their environmental sustainability.

An important aspect of the research was the study of architectural solutions that combine traditional elements of Kazakh architecture with modern approaches. The study analysed ways to integrate cultural symbols and ornaments into the architecture of buildings, which preserve the cultural identity of the region and meets modern requirements for functionality and aesthetics. Traditional shapes and colour schemes were also explored to maintain a connection with the historical context and create a unique atmosphere for residents and tourists. The study analysed the socio-economic aspect of the creation of training and production centres of traditional crafts, including their role in the development of regions. The possibility of creating new jobs, increasing tourism attractiveness and training of folk crafts masters was considered. Such centres are regarded as platforms for educational and cultural activities, which contribute to the improvement of the economic situation in the region.

The study also analysed successful examples of sustainable development in Turkestan, including examples of the integration of historical sites with modern architectural solutions. The analysis of these examples, including the role of the Azret-Sultan Museum-Reserve, demonstrated how such projects contribute to the preservation of cultural heritage, as well as to the development of the local economy and the attraction of tourists. The study developed recommendations for the design of training and production centres for folk arts and crafts. These recommendations include architectural, environmental, functional and socio-economic aspects, with a focus on preserving cultural heritage and developing crafts in regions with historically established craft traditions, such as Turkestan.

RESULTS

The urban design of training and production centres for folk crafts is key in the preservation and development of cultural heritage, and the creation of an effective educational and production environment. When designing such centres, it is important to consider several principles that ensure a harmonious combination of functionality and aesthetics, contribute to the psychological comfort of craftsmen, and create optimal conditions for the creative process (Arynov *et al.*, 2022). The main requirement that crafts training and production centres must meet is functionality. Spaces should be organised in such a way as to effectively combine the learning process with production activities. This implies the presence of different areas: for theoretical classes, practical workshops, and warehouses for materials and finished products. The project should include logistical solutions that facilitate convenient movement between areas and efficient labour organisation. In addition to functionality, aesthetics is an important aspect. The centres should be not only comfortable but also beautiful, harmoniously integrated into the natural or urban



landscape. Architectural solutions should be focused on preserving the traditions of folk art, which will create an atmosphere that inspires craftsmen and students to create.

An important factor in design is the psychological impact of the environment on the creative process of the artist. The workspace should create conditions for concentration and productivity. Light, space and colour schemes are important aspects. Natural light contributes to a more detailed perception of the material and improves the quality of architecture, while calm and pleasant colours in interiors help tune without overloading the psyche. Notably, the space stimulates creativity and ensures harmony between craftsmen, students and the surrounding world. Recreation areas where rest should also be present to contribute to a better psycho-emotional state.

The types of training and production centres for folk crafts depend on the age groups of students and their educational needs. For children and adolescents, it is necessary to design learning spaces that will facilitate easy learning of crafts, including play and creative areas where children can learn the basics of craftsmanship. In turn, for adult craftsmen, the design should be focused on specialised workshops where they can study craft techniques and technology in depth. This approach ensures not only the learning process but also the development of craftsmanship, which is an important part of the culture of folk crafts.

An important element of urban planning is the classification of buildings and their functional units. The main types of buildings are educational buildings, production workshops, and public and administrative premises. Educational buildings include lecture and practical classrooms, libraries and other resources for theoretical training. Production workshops should be equipped with the appropriate equipment to perform various types of work, from fabric processing to metal and woodworking. Notably, the production facilities provide sufficient space for craftsmen to work comfortably and safely. Administrative buildings include offices, employee areas, exhibition and sales areas where finished products can be displayed and sold.

The typology of training and production centres for folk crafts also depends on their location in the structure of settlements, from villages and small towns to regional centres. In rural areas, the design should incorporate compactness and functionality aimed at preserving local traditions and crafts. In regional centres and large cities, the design should be more ambitious, with the possibility of integrating cultural and tourist functions. Such centres can become important cultural and educational facilities that attract both residents and tourists. In large cities, it is also necessary to combine educational and production processes with exhibition and trade functions, which helps promote folk crafts and their wider distribution.

Thus, the principles of urban planning design for training and production centres for folk crafts include functionality, aesthetics, psychological comfort, and incorporate the age characteristics of students and the classification of buildings. These principles help create centres that not

only meet the requirements of education and production, but also preserve cultural traditions, inspire creativity, and develop craft skills. The functional zoning of folk-art training and production centres are key in organisation of the effective operation of such institutions. Each centre should include several zones, each with a specific role. These zones form an integrated structure that facilitates successful training, production and cultural exchange (Zabulis *et al.*, 2023).

One of the most important areas is the training area. These are workshops, lecture halls and laboratories that provide the necessary conditions for acquiring knowledge and practical skills. The workshops should have all the necessary tools and materials for handling traditional crafts such as pottery, carpet weaving or wood carving. Lecture halls are designed for theoretical classes where students learn about the history of crafts, as well as technological aspects and design. Laboratories are needed for experimentation and development of new materials or technologies, which promotes innovation in crafts. All these rooms should be arranged in a logical sequence to ensure the optimal flow of people and materials, as well as to create comfortable working and learning conditions.

Production areas are important in the structure of a training and production centre. These are workshops where products created by both students and professional craftsmen are manufactured. The workshops should be equipped with the necessary tools and equipment to work with various materials such as wood, metal, clay and fabrics. The spaces should be spacious, and safe, with good ventilation and sufficient lighting for comfortable work and production.

Cultural and exhibition spaces are equally important. Museums, galleries and shops located in these areas are substantial in promoting folk arts and crafts and integrating them into the cultural space of the region. Museums and galleries not only showcase the works of craftsmen but also introduce the history of crafts, showing the evolution of technologies and styles. These spaces host exhibitions, masterclasses, lectures and other events that help to better understand the significance of folk crafts. The shops, in turn, are used as sales outlets for the products produced, which contributes to the financial sustainability of the centre and increases interest in folk art among both locals and tourists.

Public areas are substantial in the structure of the centre. These spaces, including recreation areas, and areas for workshops and events, ensure a comfortable stay for both nail technicians and visitors. Lounge areas, equipped with comfortable furniture and green spaces, serve as a place for socialising, sharing experiences and relaxing. Workshop areas can be used to organise meetings, presentations and cultural events, which helps to expand public interest in folk crafts and their modern development. These spaces are also a place to interact with a wide audience and promote traditional crafts.

The principles of designing a green space system are also important for the harmonious functioning of a training and production centre. Green spaces (gardens, green



areas) are decorations that create favourable conditions for rest and recuperation, and improve the microclimate and atmosphere in the centre, creating a comfortable environment for work and communication. An example of successful zoning is the layout concept with the main pedestrian alley as the central axis of symmetry (Fig. 1). The alley became the main link between the main craft workshops and cultural and exhibition areas. The main craft workshops and shops are located along the alley, creating a convenient and logical route for visitors and craftsmen.



Figure 1. Layout concept with a central symmetrical axis – the main pedestrian walkway

Source: compiled by the authors

The functional and planning framework for the design of the training and production centre involves a combination of several key functions. The demonstration and production function includes workshops for carpet weaving, and artistic processing of wood, metal, stone, bone and horn, as well as workshops for sewing, embroidery and

knitting. The educational and production area includes drawing, painting, sculpture classes and lecture halls for theoretical training. The cultural and propaganda function includes exhibition halls, areas for entertainment and ethnographic festivals and a concert venue. The trade and fair function include shopping arcades, shops and a fairground. The tourist function is expressed in hotels and motels, as well as a water area with fountains and green spaces. It is necessary to provide for residential areas, including workshops for craftsmen. The facilities of such a centre can be placed in a group of free-standing and mobile (seasonal) buildings of small architectural form, which will ensure flexible adaptation of the structure and ensure the use of natural resources to create a harmonious and functional space.

Design of craft centres should incorporate not only functional and technical characteristics, but also the environmental component, which affects the psychological state of craftsmen and their creative process. One of the key factors is the architectural and spatial environment in which the craftsman works. Historically established architectural and natural elements of the environment are substantial in shaping the creative mood and perception of the working environment. The psychological impact of the environment on the artist is important, as creative activity is closely related to spatial and aesthetic conditions. The space in which the artist is located should contribute not only to physical comfort but also to the emotional state, creating an atmosphere that inspires the creation of new works. Architecture that uses natural elements and traditional forms can contribute to immersion in the atmosphere, creating harmony between humans and the world around them. Elements such as green spaces, natural light and the use of environmentally friendly materials create not only physical but also psychological comfort, which helps improve the mood of the craftsmen. Environmental integration in the design of folk art and craft training and production centres contributes to their harmony with nature and sustainability. It is important that the centres not only preserve traditional craft techniques but also incorporate environmental aspects, which reduces the negative impact on the environment (Table 1).

Table 1. Use of environmentally friendly materials in construction

Material	Usage	Environmental benefits
Wood	A natural renewable resource widely used in national construction	Excellent thermal insulation properties, harmony with nature, recyclable
Stone	A strong and durable material traditionally used in construction	High environmental performance, ability to regulate humidity and temperature
Clay	Natural material with a long history of use in construction (walls, bricks, decorative elements)	Environmentally friendly, regulates indoor climate and humidity
Straw	Insulation of buildings, construction of ecological buildings (adobe, pressed straw blocks), reconstruction of traditional buildings	Natural, biodegradable material with good thermal insulation properties, reduces the energy consumption of the building
Bamboo	A fast-growing plant used in the construction of residential buildings, public spaces, cafes, small warehouses	Environmentally friendly, easily renewable resource, high strength characteristics, mould resistance
Herbal materials	Use of local grasses and vegetation in construction and finishing works, planting on the roof, for insulation and protection against moisture	Environmental friendliness, use of local materials, minimisation of carbon footprint

Source: compiled by the authors based on Y. Nasr *et al.* (2023) and A. Almusaed *et al.* (2024)



One of the main aspects of ecological integration is the use of natural materials in construction. Materials such as wood, stone and clay are commonly used in vernacular construction and can be effectively used in the construction of training and production centres. Wood, as a natural and renewable resource, not only blends harmoniously into the natural environment but also has excellent thermal insulation properties, which contribute to a comfortable indoor climate. Stone and clay add strength and durability to buildings, and have high environmental characteristics, such as the ability to regulate humidity and temperature. The use of these materials in construction can be used to create environmentally friendly and energy-efficient facilities that preserve traditional technologies without harming the environment.

In addition, an important aspect of environmental integration is the use of renewable energy sources to ensure the sustainability of training and production centres. Solar panels, wind turbines and geothermal systems can significantly reduce the need for traditional energy sources,

reduce the carbon footprint of facilities, and provide electricity for lighting, heating and equipment operation. Geothermal heating systems can effectively regulate indoor temperatures, reducing energy consumption and improving comfort for employees and visitors (Sayed *et al.*, 2021). The use of these technologies and materials helps to promote sustainable development among craftsmen and students studying at the centre.

The architectural solution for training and production centres for folk arts and crafts should be based on harmony between tradition and modernity. Such centres should not only fulfil their functional duties but also become cultural monuments reflecting the rich historical heritage and unique traditions of folk crafts. One of the key aspects is the preservation of elements of traditional Kazakh architecture, such as ornaments, national colours and shapes. By incorporating these elements into a modern architectural solution, it is possible to create objects that will blend seamlessly with the surrounding nature and cultural landscape (Table 2).

Table 2. Integration of traditional architectural elements into the design

Traditional architectural elements	Usage	Role in preserving cultural identity
Ornaments	Use of national ornaments on facades, doors, windows	Emphasises uniqueness and connection to local traditions
Domes and arches	Use of traditional forms of domes and arches in building construction	Visual identification with the historical architecture of the region
National colours and materials	Use of traditional colours (red, gold, blue) and materials such as clay and wood	Preservation of national identity and harmony with nature
Symbolism in the decor	Inclusion of symbols in the decor that reflect folk customs and beliefs (traditional ornaments, mythological and religious symbols, symbols of protection and well-being)	Supporting the cultural and religious traditions of the local population

Source: compiled by the authors based on A. Tanzharykova & G. Maulenova (2024)

Traditional Kazakh ornaments, often used in building decoration, have a deep symbolism and connection with nature. For instance, patterns resembling stylised images of animals, plants or geometric shapes are important symbols reflecting the spiritual values of the people. These ornaments can be used both in the façade and in the decorative elements of the interior of the training and production centre. National colours such as blue, gold, green and red are traditionally associated with various aspects of Kazakh culture, such as nature, nomadic life and historical events. The inclusion of these colours in architecture helps to preserve cultural identity and emphasises the uniqueness of the object (Zhubanova, 2021).

However, despite the importance of traditional elements, architectural solutions must be adapted to modern conditions. The combination of modern technology and historical style creates buildings that not only preserve cultural traditions but also meet current requirements for energy efficiency, safety and comfort. For instance, the use of modern building materials such as glass and steel can be organically combined with traditional wooden elements and stone coatings. Insulation, soundproofing and ventilation technologies suitable for folk arts and crafts training and production centres should combine functionality with respect

for traditional architecture. For instance, natural materials such as eco-wool or linen insulation can be used for insulation, which provides thermal insulation and is environmentally friendly. For noise insulation, panels made of wood-fibre boards or natural cork effectively reduce the noise level in the premises without compromising their aesthetic appearance. Ventilation systems can be based on heat recuperators, which provide fresh air and energy savings, or on natural ventilation using ventilation shafts that are organically integrated into the architectural style of the building.

This combination of old and new achieves maximum functionality while preserving aesthetic value and historical identity. The use of innovative technologies in combination with traditional architecture makes it possible to create not only comfortable but also environmentally friendly buildings. For instance, solar panel systems or thermal insulation materials can be integrated into the roof without disturbing the architectural style, but at the same time significantly reducing energy costs (Jiang *et al.*, 2022).

The architectural design of a crafts training and production centre should combine the best traditions of Kazakh architecture, such as the use of yurt-shaped forms, national ornaments and elements reflecting the connection with nature (e.g. open courtyards or canopies with



traditional patterns), with modern requirements and technologies. Among modern requirements for the buildings of craft centres are ergonomic and safe premises, energy efficiency (including insulation and ventilation systems), convenient layout for the organisation of the educational process, the use of environmentally friendly and durable materials, and the possibility of adapting the buildings for different types of activities, including master classes, exhibitions and production. This will create functional and aesthetically pleasing facilities that not only meet the needs of modernity but also retain a deep connection to history and cultural heritage.

Craft training and production centres are versatile in support of traditional crafts, tourism development and improving social well-being through job creation and community involvement in sustainable economic activities (Nagorniuk *et al.*, 2022). One of the key aspects of the social importance of training and production centres is the preservation of cultural heritage. These centres become the main repositories of traditional knowledge and skills that are passed on to new generations of artisans and students. The learning process in such centres includes both theoretical and practical classes that help preserve and develop ancient craft techniques such as wood carving, pottery, carpet weaving and others. This not only preserves unique traditions but also helps to adapt them to modern requirements and markets. The transmission of knowledge by craftsmen and teachers is an important contribution to the development of cultural identity and the maintenance of historical heritage, thus strengthening the link between generations.

Folk craft centres are also significant in the tourism potential of the regions. The inclusion of these facilities in tourist routes popularises cultural heritage and creates new opportunities for tourism development. Craftsmen working in such centres can organise masterclasses, exhibitions and demonstrations, which becomes an additional attractive part of tourist programmes. The attraction of tourists not only promotes folk crafts but also increases the income of local communities, as sales of products and

services related to cultural exchange become a source of economic growth. Thus, training and production centres for folk arts and crafts can be linked to the development of cultural tourism, which in turn leads to an increase in the number of jobs and support for the local economy.

In addition, the establishment of such centres leads to the creation of jobs in several areas. In the educational sector, jobs are created for teachers and craftsmen who teach students and train new generations in the skills of traditional crafts. In the manufacturing sector, jobs emerge for craftsmen, equipment operators, and those who manage and sell products. The cultural sector also requires the involvement of workers to organise exhibitions, cultural events and other activities to promote folk crafts and raise public awareness. These jobs not only employ local people but also contribute to the development of professional skills and improve living standards. Thus, training and production centres of folk arts and crafts play an important role in the socio-economic development of the regions. The preservation of cultural heritage, development of tourism and creation of jobs all these aspects create a multifaceted impact on the local economy, the well-being of residents and the development of the region.

Turkestan, as one of the most important historical and cultural centres of Kazakhstan, has become an example of successful projects that harmoniously combine traditions and modern approaches in architecture and urban planning. The preservation of cultural heritage, the use of innovative technologies and environmental integration have transformed Turkestan, making it a model of sustainable development in a region that is growing rapidly. One of the most impressive examples is the reconstruction of the Azret-Sultan complex (Fig. 2). The centrepiece of this complex is the mausoleum of Khoja Ahmed Yasawi, the first monument of Kazakhstan included in the UNESCO World Heritage List. The modern building of the mausoleum was built on the burial place of the famous Sufi poet, who had a great influence on the development of Islam in Central Asia (Makhanov *et al.*, 2023).



Figure 2. Museum-reserve “Khazret Sultan”

Source: B. Makhanov (2021)



In addition to the mausoleum, the territory of the museum reserve includes many objects of historical and cultural value. These include the Kultobe settlement, the underground Hilvet mosque, the Shildekhan ritual structure, a medieval citadel and shahristan, as well as fragments of fortresses, ruins of ancient mausoleums and an oriental bath. The Azret-Sultan Museum-Reserve covers more than 100 historical and archaeological monuments and includes about 25,000 unique written, architectural and numismatic exhibits. The museum reserve is the spiritual centre of the Turkic-speaking peoples and the most popular tourist attraction in the region, receiving over 350,000 visitors annually. Its infrastructure successfully combines elements of traditional architecture with modern comfort and functionality requirements, making it a unique example of preserving and promoting cultural heritage.

Turkmenistan can become a centre for the development of crafts, as evidenced by the event held on 29 September 2024, when craftsmen and experts from 20 countries, including Australia, the USA, Iran and China, as well as the President of the International Organisation of World Craft Cities Saad Al Qaddoumi, gathered in the city. This event was an important step in the process of granting Turkmenistan the status of an international city of artisans. As part of this initiative, the City of Artisans tourist complex is being built in the city, which includes exhibition areas, an oriental market, restaurants and hotels. The complex is scheduled to be completed by the end of the year and will make a significant contribution to the development of craft traditions and increase the tourist attractiveness of the region (Craftsmen from 20..., 2024).

Examples of successful craft centres in Kazakhstan have demonstrated how traditional art can be organically integrated into modern life. The fine arts of Kazakhstan, which have incorporated various elements of national traditions, have created a unique style that has become part of the national cultural brand. Decorative and applied arts, represented by carpets, embroidery and jewellery, preserved the symbolism of the ancient steppe culture, while ethnic design was actively used in fashion and architecture, contributing to the revival of crafts. Cultural centres, such as the Qazaq-Oner Art Centre (Almaty) and the Crafts Centre (Astana), offered master classes and training sessions on crafts, combining traditional crafts with modern trends, and therefore became interesting to both locals and tourists.

Thus, the transformation of Turkestan, Astana and Almaty demonstrated how to preserve the rich historical and cultural heritage by integrating modern technologies and sustainable development principles. This approach transformed cities into models of successful implementation of major projects and inspiration for other cities in Kazakhstan and Central Asia. The design of training and production centres for folk arts and crafts requires a comprehensive approach that includes several key aspects: location selection, structural zoning and consideration of architectural features. All these factors are substantial in the successful implementation of such facilities, ensuring not

only functionality but also harmonious interaction with the culture and nature of the region.

The location is one of the most important stages of design. The centre should be in historically developed craft tradition locations, such as Turkestan, thus preserving and developing traditional craft technologies in a natural cultural environment. Furthermore, the centre should be in close proximity to transport hubs, such as railway and bus stations or airports, to provide convenient access for craftsmen, students and visitors, as well as to promote tourism and increase the number of visitors interested in traditional crafts. One of the key aspects of the design is structural zoning. The internal space of the centre should be divided into several functional zones. Each craft has specific characteristics, and effective training and production requires the creation of specialised areas, with specialised equipment to enable craftsmen to create high quality products. It is also necessary to provide space for storing the finished products and for displaying them, e.g. at fairs or exhibitions, which further promotes the crafts.

Carpet weaving requires a workshop with spacious workspaces for traditional handlooms, a place to prepare and dye yarns, and storage for materials. It is necessary to provide good lighting and ventilation, as weaving is labour-intensive and requires attention to detail. Embroidery requires separate areas with adjustable lighting and comfortable tables where craftsmen can work on complex and small stitches. In such workshops, it is necessary to provide storage space for fabrics, threads and other materials, as well as ensure the availability of modern embroidery machines, which will combine traditional and modern embroidery methods.

Pottery workshops should be equipped specifically for handling and firing clay. Space for shaping and firing, including traditional kilns or electric or gas-fired kilns, should be present. These workshops should be equipped with tools for finishing products and sanding machines. Furthermore, a workshop with an area for wood carving, sanding and coating should be set up for woodworking, including the production of wooden utensils and musical instruments. The woodworking area should be equipped with both traditional tools (chisels, saws, chisels) and modern equipment (sanders and routers). It is also necessary to provide safe areas for tool handling and specialised woodworking areas.

For the manufacture of yurts, spacious rooms should be allocated for working with wood and fabrics. There should be areas for creating wooden yurt elements and areas for preparing fabrics and felts. It is necessary to provide space for training in traditional yurt-making methods, as well as in the use of innovative materials and improved assembly and construction techniques. Cultural and exhibition spaces, such as galleries and museums, should be an integral part of the centres. These areas will be used for showcasing the works, exhibitions and masterclasses, and attracting tourists and folk-art enjoyers. Public areas, including cafes, recreation and lecture areas, should also be considered.





They will create a comfortable atmosphere for communication and, the exchange of experience and knowledge between craftsmen and visitors.

The architectural features of the designed centre should be given special attention. Architectural forms and styles should combine traditional elements with modern building techniques to create a unique atmosphere reflecting the cultural identity of the region. The use of traditional Kazakh architectural elements such as ornaments, national colours and shapes will reinforce the relationship between the centre and its cultural heritage. At the same time, the use of modern building materials and technologies will ensure the durability and sustainability of the building, as well as improve its energy efficiency. The use of eco-friendly materials and renewable energy sources, such as solar panels or geothermal systems, will help to create a sustainable building that will have minimal impact on the environment. Thus, the design of training and production centres for folk arts and crafts requires careful consideration of all aspects, from the choice of location to architectural solutions. It is important that these centres should not only provide comfortable conditions for training and production but also become cultural centres that contribute to the preservation of folk traditions and the development of crafts.

DISCUSSION

Urban design of training and production centres for folk arts and crafts requires an integrated approach that incorporates both the preservation of cultural traditions and modern requirements for sustainability and accessibility. The study of examples such as the Turkestan Training and Production Centre has shown that the integration of traditional architectural elements into the design can not only preserve but also highlight the uniqueness of the region's cultural heritage. This is particularly important in a globalised world where traditional crafts risk being forgotten. W. Zhou *et al.* (2022) confirmed that the integration of traditional architectural elements can create harmony between historical heritage and modern trends. Such elements maintain visual continuity, which is especially relevant for regions with a rich cultural history. This solution also increases tourist attractiveness by emphasising the uniqueness of each locality.

D. Giannakopoulos *et al.* (2022) also demonstrated that culturally sensitive urban design builds a sense of community among residents. The incorporation of national symbols and traditional motifs into architecture and landscaping preserves the unique character of the city. Such design also contributes to the transmission of cultural values to future generations by ensuring their visual and spatial presence. The successful integration of traditional elements into modern design requires a balance between functionality and aesthetics (Maznichenko & Moskalenko, 2024). It is necessary to incorporate the context in which these elements are used to avoid mechanical copying or loss of meaning. In addition, such solutions must be adapted to modern environmental and sustainability

requirements, which increases their relevance in the context of global change. Environmental integration in the design process is key to the sustainability of the centres. The use of environmentally friendly materials such as clay and other natural materials, as well as the use of renewable energy sources, have become important aspects of conserving natural resources and minimising the negative impact on the environment (Kunakh *et al.*, 2021). This solution is particularly relevant for training and production centres, which could be used as an example in the field of ecology and sustainable development.

F. Fan *et al.* (2021) highlighted that the use of environmentally friendly materials (bamboo, recycled wood, low-carbon concrete) reduces emissions at all stages of construction. Such materials are not only safe for health but also easily recyclable, reducing the burden on the ecosystem. Moreover, their use stimulates the development of innovative technologies in the construction industry, making this approach economically viable in the long term. F. Fan *et al.* confirmed the results of the study, demonstrating the practical effectiveness of sustainable solutions. The use of environmentally friendly materials and energy-efficient technologies reduces the cost of operating buildings and reduces the carbon footprint. In addition, the results highlight the importance of integrating such approaches into mass construction, which contributes to the development of the green economy and strengthening global environmental initiatives.

The design of a training and production centre requires a clear division of zones according to their purpose. The inclusion of training workshops, production workshops, and cultural and exhibition spaces helps to create comfortable conditions for both learning and production of traditional crafts (Dyomin *et al.*, 2020). It is important that such centres become not only educational institutions but also cultural centres that attract not only craftsmen but also tourists who want to get acquainted with traditional crafts. B. Liu *et al.* (2021) also highlighted that functional zoning organises space to ensure that each part of the space meets specific objectives. This is especially relevant in modern projects where a combination of different functions is required in a limited area. Proper zoning not only improves usability but also contributes to better ergonomics and work efficiency.

S. Krajewski & M. Khoury (2021) concluded that comfortable and multifunctional spaces provide the conditions for creativity and productivity, combining areas for individual and group activities. Modern technologies can be used to create adaptive spaces that can be transformed to meet current needs. This solution is ideal for educational institutions and manufacturing companies where flexibility and functionality are important. These findings by S. Krajewski & M. Khoury are consistent with the results of the study, as they demonstrate the key role of zoning in creating comfortable and efficient spaces. Well-divided zones ensure the rational use of available space, minimising time and resource losses. Furthermore, the combination of functionality and comfort in design contributes to



improved working and learning conditions, which directly affects productivity and user satisfaction. Selection of the location of the centres should be given special attention. The study emphasises that linking to regions with historically developed craft traditions, such as Turkestan, is of key importance for the successful implementation of project solutions. Such an approach maintains and develops traditional crafts and promotes economic growth by creating jobs and improving infrastructure. However, other regions may have unique crafts that also require the establishment of specialised training centres.

J. Block *et al.* (2021) confirmed that the choice of locations for project implementation plays a key role in the development of the region, influencing economic and social processes. Locating production and cultural facilities in historically established areas helps to attract investment and develop infrastructure. During investment evaluation of social enterprises, such criteria as social impact, business sustainability and its contribution to the development of the local community are analysed. K. Jones *et al.* (2021) also determined that historically developed craft regions play a key role in design success, as their rich cultural heritage serves as a source of inspiration for creating unique and sought-after products. The use of traditional techniques and materials in modern design preserves the uniqueness of local cultures and popularises the region (Wang & Shmelova-Nesterenko, 2023). Such regions often become centres of attraction for tourists, which contributes to additional economic and cultural development.

Thus, the choice of locations has an impact on regional development. Notably, not only the economic factor but also the cultural heritage of the territory is crucial for the successful implementation of projects (Ivashko *et al.*, 2020). The correct use of historically established craft traditions can be the key to creating unique and sought-after solutions that contribute to the sustainable development of the region. Another important finding was an understanding of the role of centres in the social and economic life of the region. The education and development of new craftsmen contributes to the preservation of cultural heritage and creates jobs in such areas as manufacturing, education and culture. The tourism potential of these centres can become an important source of income for local communities, drawing attention to folk crafts and traditions. This, in turn, creates new opportunities for regional economic development.

S. Rajabi *et al.* (2022) studied the improvement of the sustainability performance of construction projects during the construction phase and concluded that design in construction has a significant impact on socio-economic development. Well-designed buildings and infrastructure not only improve the quality of life but also become the basis for business growth. Successful construction projects contribute to job creation, improve the economic situation in the region and increase sustainability both at the regional level and in the broader context of countries and global markets. A. Ausat *et al.* (2023) determined that

cultural initiatives integrated into the construction process develop local economies by supporting craftspeople, artists and other creative professions. The creation of cultural facilities or the development of cultural tourism not only generates income but also promotes social inclusion and improves the quality of life. It stimulates the growth of small and medium-sized enterprises and increases the attractiveness of the region for investors.

The socio-economic significance of design in construction extends beyond infrastructure improvements. Projects that incorporate cultural initiatives can significantly stimulate the local economy by creating new jobs and supporting small businesses. This, in turn, improves the social atmosphere and attracts additional investment, reinforcing the sustainable development of the region. Thus, the successful functioning of training and production centres depends on a harmonious combination of traditional and modern elements in architecture. The design of such facilities should incorporate both the historical features of the region and modern construction technologies, which can be used to create unique architectural solutions that reflect the cultural identity, but at the same time meet modern safety and comfort requirements.

CONCLUSIONS

The urban planning framework for the formation of training and production centres for folk arts and crafts should incorporate several key factors that influence their successful functioning and development. One of the most important aspects is the preservation of cultural identity through architectural solutions that reflect national traditions and craft techniques. The integration of elements of traditional Kazakh architecture into the design of such centres contributes not only to the preservation of unique crafts but also to strengthening the cultural identity of the population. These centres become a place where craft practices are not only preserved but also passed on to new generations.

The study also demonstrated that environmental sustainability is important in the design of training and production centres. The use of environmentally friendly materials, such as wood and clay, helps to minimise the environmental impact, which is an important aspect of sustainable development. In addition, the use of renewable energy sources, such as solar panels or geothermal energy, not only reduces energy costs but also reduces the carbon footprint of the centres. These steps correlate with current global trends in sustainable construction and ensure long-term environmental sustainability.

The functional zoning of training and production centres is also important and should include a clear separation of different types of spaces, such as workshops, classrooms, production halls and cultural and exhibition spaces. This approach contributes to the creation of a comfortable learning and working environment and improves the organisation and interaction between masters and apprentices. Linking the centres to regions with historically devel-





oped craft traditions, such as Turkestan, demonstrated that the appropriate location is crucial in attracting students and craftsmen, as well as contributing to the development of the local economy and job creation. However, other regions may also have unique crafts for which it is advisable to build specialised training centres focused on local traditions and needs.

Training and production centres should be actively included in tourist routes, as this can significantly increase their economic attractiveness. Tourism becomes not only a source of income for the centres but also contributes to the promotion of folk crafts in the international arena. This creates additional opportunities for the professional growth of craftsmen and expands markets for their products. Thus, the urban planning approach to the design of training and production centres of folk arts and crafts

should be comprehensive, including both architectural and functional, environmental and socio-economic aspects. Importantly, such centres should combine traditions and modern approaches, ensuring not only the preservation of cultural heritage but also contributing to the sustainable development of regions. Future research could focus on analysing the experience of craft centres in other countries.

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Містобудівні засади формування навчально-виробничих центрів народних художніх промислів

Анотація. Проведене дослідження було спрямоване на обґрунтування архітектурно-планувальних рішень, що сприяють інтеграції навчально-виробничих центрів народних художніх промислів у сучасне міське середовище Казахстану. У дослідженні використано методи аналізу містобудівних концепцій, функціонального зонування, екологічної стійкості та архітектурних рішень для розроблення рекомендацій щодо проектування. Під час дослідження обґрунтовано містобудівні підходи до розміщення і проектування навчально-виробничих центрів народних художніх промислів Казахстану. Встановлено, що оптимальними місцями для їх створення є регіони з розвинутою культурно-історичною спадщиною і наявністю стійких ремісничих традицій. Проведено аналіз функціональної структури центрів ремесел, який показав, що її ефективність залежить від чіткого зонування території. Рекомендовано виокремлювати такі зони: навчальні (майстерні, лекційні аудиторії), виробничі (цехи, лабораторії), виставкові (музеї, галереї, магазини) та громадські (зони відпочинку та проведення культурних заходів). Результати досліджень підтвердили, що використання місцевих природних матеріалів (камінь, дерево, глина) у будівництві не тільки відповідає вимогам екологічної стійкості, а й сприяє збереженню традиційного вигляду архітектури. Виявлено, що інтеграція традиційних казахських архітектурних елементів у сучасні проекти сприяє підвищенню їхньої туристичної та культурної привабливості. Як практичний висновок розроблено рекомендації з проектування центрів, що включають вибір локацій, структурне зонування та врахування архітектурних особливостей. Прикладом успішного застосування запропонованих рішень став проект центру в Туркестані, який продемонстрував значний внесок у збереження культурної спадщини та розвиток місцевої економіки. Таким чином, результати дослідження підкреслили важливість комплексного підходу до створення навчально-виробничих центрів, що забезпечує їхній сталий розвиток та інтеграцію в сучасне міське середовище

Ключові слова: культурна спадщина; функціональне зонування; екологічна стійкість; архітектурні елементи; туристична привабливість; регіональний розвиток

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Characteristic stylistic and compositional features of the sculpture works of J.G. Pinsel and his students in Lviv

Abstract. In the 18th century in Western Ukraine, sculptural works played a significant role in the decoration of temples and residential buildings, especially in the architecture of Lviv buildings. The article was devoted to examining the characteristic artistic features of the baroque sculptures of J.G. Pinsel and his students F. Olenskyi and A. Osynskyi in the decoration of architectural buildings in Lviv. The research methodology consisted of a thorough study and plastic analysis of unique works of art, which impress with their greatness and unique beauty, and were the cultural heritage not only of a single territory but of the whole of Ukraine in a historical context. In the process of analysis, it was found that the brilliant sculptor J. Pinsel and his students F. Olenskyi and A. Osynskyi created unique masterpieces in Lviv, full of harmony and artistic perfection. Based on the analysis of the sculptural works of Pinsel and his students, the specific features of their artistic worldview in the creation of artistic sculptural works were determined. It had been established that sculptural works were saturated with plastic energy, expression of dynamic movement, expressive poses, unique silhouettes, and a peculiar geometric interpretation of draperies. The artistic value of the Lviv sacred sculptures of J.G. Pinsel and his students F. Olenskyi and A. Osynskyi, which were highly artistic works and belong to the artistic heritage of Ukraine, was determined. These sculptural works were an integral part of the world's cultural heritage, which arouses the interest of the international scientific community and the interest of tourists. The research results can be used in the history of Ukrainian art and in the educational process to prepare students of art historians and architects

Keywords: prominent sculptor; carvers apprentices; altar; structure of a statue; figure; plastic solution

INTRODUCTION

The rich historical and architectural artistic legacy of the city of Lviv constitutes a significant part of the cultural heritage of Ukraine. In the context of the study of late

Baroque sculpture in the decoration of sacred and public buildings in Lviv, special attention was paid to the work of the brilliant sculptor Johann Georg Pinsel and his students

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Frantsysk Olenskyi and Antonii Osynskyi, who formed the “Lviv school of sculpture”. The works of these outstanding artists play not only an important role in the decoration of buildings in Lviv but also demonstrate the aesthetic preferences and artistic worldview of masters who started a new direction in the plastic interpretation of sculpture of the late Baroque era. The problem of the research consists of the analysis of stylistic features and the identification of the characteristics of the plastic interpretation of their works and the influence of other sculptural schools on the formation of the artistic manner of Lviv Rococo sculpture. The relevance of this research was emphasised by the insufficient study of this topic and the need for a deeper understanding of the brilliant sculptors’ contribution to the development of art in the region. This will not only allow a better understanding of the history of Rococo sculpture in Lviv but will also make an important contribution to the pan-European history of art.

The phenomenal sculptural works of the outstanding sculptor J.G. Pinsel of the Rococo era were studied by Ukrainian and worldwide researchers, art critics, and scientists. In her thorough work, L. Chen (2022) highlighted the characteristic stylistic and compositional features of the highly artistic sculptural works of J.G. Pinsel of temples and roadside sculptures in Buchach. B. Mazur (2020), analysing the influence of Ukrainian sculpture on modern artistic culture, noted that Ukrainian sculpture was the driving force of the formation of the general culture of the individual. S. Pobozhii (2020), in his work, characterised Ukrainian sculptors by name and their role in the history of Ukrainian art. O. Stelmakh (2024), considering the creative heritage of the outstanding master of the Ukrainian Baroque of the 18th century – Joan George Pinsel – paid special attention to the analysis of the expressiveness of his sculptures, emphasising their role in the formation of national cultural identity. In her work, R. Shertiuk (2021) investigated the stylistic connection of the late Baroque sacral sculptural art of Volyn with European artistic trends, which was clearly visible in the building of the Roman Catholic order of PRs. C. Cassar Meli (2022), in her doctoral dissertation, analysed the influence of the Bernini style on the regional sculpture of the Late Baroque in Malta. M. Caroselli *et al.* (2021) reviewed the historical techniques used for the production of decorative stucco and high-relief compositions with an emphasis on technological aspects and materials. They also revealed certain specific technological approaches to the production and processing of high reliefs. The analysis of scientific works proves that the unique sculptural works of outstanding artists J. Pinsel, F. Olenskyi, and A. Osynskyi were little studied; therefore, there was a need for their thorough research.

The purpose of the research was to identify specific features and techniques of plastic interpretation of forms to determine the artistic value of unique works of art in the process of analysing the sculptural works of J. Pinsel, F. Olenskyi, and A. Osynskyi located in Lviv.

MATERIALS AND METHODS

The methodological basis of the research was made up of general scientific (empirical, theoretical) and special professional methods (stylistic, artistic, and compositional analysis). On their basis, a comprehensive methodology was formed for studying the characteristic features of the sculptural work of J. Pinsel, F. Olensky, and A. Osynsky in the city of Lviv. The most interesting Lviv works of art by the outstanding sculptor I. Pinsel were selected for the study – the sculptural composition of Yuri Zmieboryts on the attic of St George’s Cathedral, the figures of bishops Leo and Athanasius on the main portal of the cathedral, the “Crucifixion” from St Martin’s Church, and the figures of Atlantes on the facade of the tenement house. To compare plastic features and identify common features and differences, the sculptural works of his students F. Olensky were selected – the Mother of God from St Martin’s Church, Atlantes on the facade of the tenement house and the figure of Glory on the attic of the tenement house, the bas-reliefs of the Archangels on the deacon’s doors of the Assumption Cathedral and the sculptures of A. Osynsky from the Dominican Church. Most of the literary sources used in the article were personally researched by the author in the city library.

The on-site survey of sculptural works conducted at the first stage of the research made it possible to identify a number of urgent problems of the phased research. The content of sculptural works and artistic qualities were revealed by the method of stylistic analysis. Using the method of art analysis, specific artistic features of the studied sculptural works were revealed, and their place in the art history of the Baroque era was clarified. Based on the analysis of the plasticity of the sculptural works of J. Pinsel, F. Olenskyi, and A. Osynskyi, it can be stated that it gravitates towards the late Baroque style. With the help of theoretical methods of analysis, systematisation, comparison, and generalisation, it was possible to trace the formation and development of the creative manner of performing sculptural works of J. Pinsel, F. Olenskyi, and A. Osynskyi. The compositional analysis of the researched sculptural works helped to reveal the three-dimensional form of the sculptural works of art and reveal the regularities of their composition. Stylistic and compositional analysis made it possible to study the individual features of the solution of sculptural works, studying their artistic value and forming the theoretical part of the study.

RESULTS AND DISCUSSION

Lviv’s late-baroque religious and residential buildings, decorated by the brilliant sculptors J. Pinsel, A. Osynskyi, and F. Olenskyi, were an outstanding achievement of not only Ukrainian but also world culture. These representative buildings with exquisite decorative finishes demonstrate the high aesthetics and artistic values of the Rococo era. His exceptional sculptural works, filled with great emotionality and expressive dynamics, decorate the sacred buildings of numerous cities and villages of Western Ukraine. Pinsel worked with Bernard Meretyn, a popular architect



of German origin at that time, who settled in Lviv in 1738. Together they created unique masterpieces of architecture and art of world importance. Genius sculptor of the 18th century. J.G. Pinsel, working in Lviv, left a great cultural and artistic heritage. He worked on the decoration of the main facade of St George's Cathedral in Lviv, built according to the project of the architect B. Meretyn in 1744-1764 (Chen, 2022) (Fig. 1), which was a highly artistic embodiment of the baroque desire for magnificence. The spatial composition of the cathedral was expressed by the cruciform volume formed by the high nave and transept. Due to the corner rooms, it was perceived in the plan as a three-nave church with an elongated altar part and narthex (babinets), which had the same width as the middle nave. The bath on a massive tetrahedron serves as an organising element to which other architectural volumes of the building were subordinated. The central part of the temple, which ends with a dome and was designed in the form of a high and rather massive tetrahedron, was an organising element to which the other architectural volumes of the building were subordinated, conveniently arranged in a monumental and at the same time light harmonised integrity. The combination of traditional features with baroque, smoothly elongated wall surfaces; architectural and sculptural solutions of the facade with flexible plastic; and rich gradations of light and shadow complement the overall impression of integrity and completeness. The rich plastic work of St George's Cathedral was harmoniously combined with monumental volumetric sculpture and decorative carvings. J. Pinsel executed the sculptural composition "George the Dragon-slayer" on the attic of the cathedral facade and two monumental statues of St Athanasius of Alexandria and Pope Leo I at the entrance portal of the temple.



Figure 1. St George's Cathedral in Lviv by J. Pinsel

Source: authors' photo (2022)

The exquisite dynamic stone statuary "George the Dragon-slayer", made by J. Pinsel in 1761 (Shengera, 2019) (Figs. 2-3), impresses with the distinctive integrity of the dynamic composition, where many of its elements were "in the air" and were strengthened with special thin bayonet supports. It was characterised by perfect proportions, refined plasticity, and the excellence of composition. The sculptor realistically and energetically conveyed the strong tension of St George as a rider competing with the dragon, which was the personification of evil passions and sins of man. St George was represented as a warrior with a determined, concentrated expression on his face, a helmet on his head, and an interesting pose of two hands holding a spear and piercing the dragon's mouth victoriously. Geometrically interpreted, swirled in the air, as independent elements, the cut planes of the drapery of St George's clothes, the horse's tail and mane, which were inherent for Pinsel's rococo plastic manner, were related to the works of Czech sculptors Matthias Braun, Ignaz Franz Platzer, Lazar Widmann and Austrian sculptor Franz Anton Kuen (Hornung, 1976). The rearing horse that rises above a dragon with wings, a crest, paws, and a large toothy mouth, and on which Saint George was sitting depicted in a dynamic movement, was related to the work "Marly Horses" by the French sculptor Guillaume Coustou. However, J. Pinsel had his own peculiar and unique plastic interpretation of the characters of the statuary "George the Dragon-slayer", full of an emotionally saturated plot, sophisticated pictorial plasticity and expressive dynamics, geometrisation of clothing planes, characters' expressive features and facial expressions, and a wealth of artistically designed small elements.



Figure 2. Statuary St George the Dragon-slayer on the attic of the St George's Cathedral in Lviv

Notes: photo 1920-1930

Source: author unknown, from authors' collection





Figure 3. Composition George the Dragon-Slayer on St George's Cathedral facade (1761)

Source: The celebration of Lviv Day... (2024)

As opposed to the dynamic sculptural composition of George the Dragon-slayer, the figures of saint bishops Leo and Athanasius on the main portal of the cathedral were depicted in calm, dynamic poses (Figs. 4-5). They were made by J. Pinsel in 1759-1761 (Shengera, 2019). Representative figures of saints were organically inscribed in the architecture of the St George's Cathedral façade. The slightly curved postures of the saints emphasise the light movement of the characters due to the protruding legs. The curved folds of the draperies of richly decorated bishop's clothes picturesquely fit the bodies of the saints. In masterfully carved stone statues of Saints Leo I and Athanasius, one can read the Pinsel manner of interpreting images, manifestations of their deep spiritual virtues. In the statues of Saints Leo and Athanasius, the sculptor skilfully conveyed their rich spiritual life. St Athanasius' bent right hand holding the bishop's staff, the slight turn of the head dressed in a mitre, the picturesque strands of hair on the head and beard, and the focused look of the eyes reading the book held by the saint in his left hand emphasise the slight dynamic movement of the character. In the statues of Saints Leo and Athanasius, J. Pinsel demonstrated a new approach of a unique interpretation of the plasticity of forms, which was manifested in interesting angles of poses, rhythms of broken and curved folds of draperies of bishops' clothes with ornaments and religious symbols, and pictorial effects of light and shadow. In the interpretation of the curves of the exquisite poses of the figures, the perfectly designed facial expression, and the geometrisation of the picturesque draperies of clothes, his works were somewhat similar to the works of the Austrian sculptor Franz Anton Kuen and the Czech sculptor of Austrian origin Matthias Bernard Braun, as well as Severin Tischler (Hornung, 1976). The compositional and technical methods of Austrian and Czech sculptors influenced the formation of J. Pinsel's individual artistic style. Despite analogies in technical and

compositional methods, Pinsel was a distinctive master with his own special manner of plastic interpretation of forms, stylistic techniques, compositional unity, and spatial integrity (Prybieha, 1993).



Figure 4. J. Pinsel, St Leo

on St George's Cathedral facade in Lviv (1759-1761)

Source: authors' photo (2023)



Figure 5. J. Pinsel, St Athanasius

on St George's Cathedral facade in Lviv

Source: authors' photo (2023)

For the monastery church of St Martin of the Carmelite order in Lviv, J.G. Pinsel executed the "Crucifixion" (Figs. 6-7) and sculptures for the main altar. The church was built in 1736-1753 in the Baroque style according to the project of the architect Bernard Meretyn (Mankowski, 1937).



The church had a single nave, was rectangular in plan with a transept and a rectangular altar, and had a main facade characteristic of the Baroque. The curved lines of the pediment, deep niches decorated with flowerpots, and strong bracing with double pilasters give it a picturesque appearance. Of the sculptures preserved until 2024, only the “Crucifixion” sculpture, created by J. Pinsel in 1758-1759 for the side altar of the church, remains (Mankowski, 1937). As of 2024 it was located in the Johann Georg Pinsel Museum in Lviv. The master executed the late-Baroque sculpture “Crucifixion” from linden wood, depicting perfectly a still Jesus figure. Pinsel, orienting himself on Baroque models, conveyed the martyrdom of Christ the Saviour in a deeply naturalistic manner. The image of crucified Jesus on the cross depicts the suffering body, exhausted by tortures, with a lifeless face, a head thrown back, lowered and bent over the shoulder, wounded by a wreath of thorns, with wrinkles on the forehead, and penetratingly carved drooping hands with stiffened vessels that encircle the wrists. The sculptor depicted the feet crossed, where the feet were placed on top of each other and nailed with one nail, as was characteristic of the Western iconographic tradition. The swollen ribs of the bust, the modelled bandage on the hips that trembles in the air, and the anatomical structure of the legs with stiffened feet emphasise the spiritual suffering image and, at the same time, the outstanding sculptor’s awareness of the anatomically perfect structure of the body of Jesus, who endured terrible torment and died on the cross for the redemption of sinful people. The sculpture “Crucifixion” was emotionally saturated with an expressive realistic image of Jesus. The stylistic kinship of plastic modelling of the Crucifixion can be found in the Spanish sculptor Juan de Mesa y Velasco (1583-1627) of the Baroque era.



Figure 6. Interior of St Martin’s Church in Lviv
Source: I. Kotlobulatov (1908)



Figure 7. J. Pinsel “Crucifixion”
 from St Martin’s Church in Lviv
Source: authors’ photo (2022)

Besides sacred buildings, J. Pinsel performed sculptural works for the decoration of residential tenements in Lviv. In 1761, for the decoration of Zukhorovichivska tenement house No. 40 on Rynok Square, built in the 17th century and rebuilt in the second half of the 18th century, J.G. Pinsel created two balcony consoles with male torsos (Figs. 8-9). The building was made of bricks, elongated in plan, three-storeyed with an attic, had preserved an asymmetric three-part internal layout and vaulted ceilings in some rooms of the first floor, and belonged to the monuments of national importance. Some works during the reconstruction of the house were performed by B. Meretyn, who, before his death, instructed J. Pinsel to make sculptures of Atlanteans for its decoration. The figures of the Atlanteans, who support the balcony, were distinguished by an unusual interpretation of male figures. The perfectly designed muscles of the body and arms, with which the Atlanteans support the balcony, were highlighted in the expressive, haggard male torsos. The geometrised folds of the draperies on the hips complement the symmetrically placed bent bodies of the Atlanteans, the tense muscles of their arms and torsos. The correct proportions of the bodies of the Atlanteans testify to Pinsel’s anatomical awareness. The master successfully combined the intense expressiveness of the body with the bright individual features of the Atlanteans in sculptures. J. Pinsel quite originally designed the openwork head hair, which, as if from some internal force, creates a whole composition of intertwined, in-expression, individual, calmly twisted strands, which lie on its larger planes. Distinctive in technique and methods, the pencil compositions of the Atlanteans were harmoniously resolved and aesthetically decorate the facade of the building.





Figure 8. Tenement house No. 40 on Rynok Square in Lviv
Source: authors' photo (2024)



Figure 9. Consoles in the form of male torsos of house No. 40 on Rynok Square in Lviv
Source: authors' photo (2024)

Lviv sculptor of the late Baroque era Francisk Olenskyi was a student of the outstanding sculptor J.G. Pinsel. He was the son of Lviv bourgeois Andrzej Olenskyi. F. Olenskyi worked with various materials: limestone, stucco, marble and wood. Traditional linden remains the master's main material for making sculptures. He studied in Buchach until 1750 (Voznytskyi, 1995) and collaborated there on the interior decoration of the Church of the Holy Intercession together with J. Pinsel, who made two side altars, an ambon and antependia for the main altar. In the late 1750s, Olenskyi continued to work with J.G. Pinsel; therefore, the influence of Pinsel's manner was strongly felt in his works (Voznytskyi, 1995; Krvavych, 1998), which was manifested in the dynamic poses of the characters' bodies and the geometrisation of the interpretation of clothing draperies. A vivid example was St The Mother of God, which was made for the altar of St Martin's church in Lviv (Fig. 10). Olenskyi's figures were characterised by a short body;

the head and neck seem to be tucked into the shoulders (Voznytskyi, 1995). In the interpretation of the face, a special type had developed, with a slightly forward nose and upper lip. The external effect prevails in the plastic of the Mother of God sculpture; the theatricality of movement was felt in the pose of the figure. It was through external effects that the inner power of the sculptor's works was achieved.



Figure 10. Mother of God. St Martin's church in Lviv, F. Olenskyi (1770)
Source: authors' photo (2022)

After the loss of his teacher, J.G. Pinsel, Francisk Olenskyi became more individualised. In 1772, the master completed another work in Lviv – the Atlanteans under the balcony (Fig. 11) and the figure of Glory on the attic of building No. 3 on Rynok Square (Voznytskyi, 1995) (Fig. 12). Atlanteans were depicted in bent postures and in light military armour, through which the muscles of the body were visible. Inclined heads with a distinctive interpretation of faces and elongated necks add dynamic movement to the statues (Bahley & Chen, 2024). They support the balcony with one hand while resting on the torso with the other, and the body's curvature adds lightness to the figures. Sculptor F. Olenskyi perfectly designed the muscles of the arms and bodies and angles of the heads of the Atlanteans' sculptures. The dynamic sculptural composition "Glory" in the attic of the house was emphasised by the solemnity and splendour of a female figure blowing a trumpet (Fig. 13). The spectacular and expressive posture of an energetic female figure was enriched with picturesque folds of drapery clothes beautifully enveloping her body and was placed in the surroundings of military paraphernalia with draperies swirling in the air. F. Olenskyi seductively conveys natural female beauty through open breasts, arms and legs. In 1773, he married in Lviv Marianna Polyanska, daughter of Lviv caster Teodor Polyanskyi. In 1780, F. Olenskyi received from his wife's father, Teodor Polyanskyi, a plot of land and a yard in the Halytskyi suburb of Lviv (Shengera, 2019). In 1789, he bequeathed half of his estate to his son, Joseph Olenskyi, the future Lviv sculptor.



Figure 11. Atlanteans supporting the balcony of building No. 3 on Rynok Square in Lviv. F. Olenskyi (18th century)
Source: authors' photo (2024)

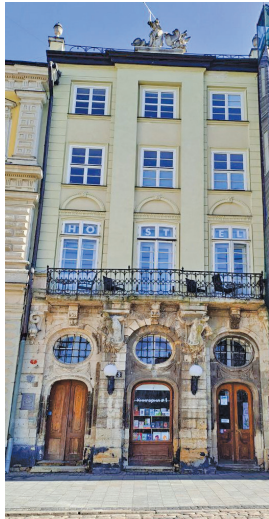


Figure 12. Building No. 3 on Rynok Square in Lviv
Source: authors' photo (2024)



Figure 13. Figure of Glory on the attic of building No. 3 on Rynok Square in Lviv. F. Olenskyi (18th century)
Source: authors' photo (2024)

In 1773, in Lviv, F. Olenskyi, together with the Lviv sculptor Mykhailo Filevych, worked on the creation of the main altar and iconostasis for the Renaissance Orthodox Church of the Assumption of the Blessed Virgin Mary on Pidvalna Street (Fig. 14) (Shengera, 2019). The unique Assumption Church, made of white hewn stone, was built in 1591-1629 according to the project of the architect Pavlo Rymlianyyn with the participation of local architects Wojciech Kapinos and Amvrosii Prykhylnyi, due to the order of the Lviv Brotherhood in the style of the Italian Renaissance, based on the traditions of Ukrainian wooden church construction with a domed finish. The Church of the Assumption of the Blessed Virgin Mary was a three-nave basilica in plan, elongated from west to east with a semicircular apse. It was crowned by three domes with lanterns above the altar, nave, and narthex. The ensemble of the church consists of the 66-metre-high Kornyakt bell tower, the Chapel of the Three Saints, and the church of the Assumption of the Blessed Virgin Mary itself. In the opinion of the authors of this study, the church was an architectural masterpiece of the Ukrainian Renaissance of European and world significance. Elements of the Renaissance order system were used in the architectural decoration of the church facades: the walls were divided by Tuscan pilasters into symmetrical fields, each of which was inscribed with blind semicircular arches with rhythmically placed windows with archivolts. A Doric frieze in which triglyphs alternate with metopes stretches under the energetically outlined large cornice. The fields of the metopes of the Doric frieze were filled with stone-carved, stylised rosettes and story bas-relief compositions on biblical and evangelical themes. The entrances to the temple were decorated with unique Renaissance portals – real masterpieces of Ukrainian Renaissance art.



Figure 14. Iconostasis of the Church of the Assumption in Lviv
Source: photo by L. Chen (2024)

The main altar and the low three-tiered iconostasis attract attention in the interior of the church (Fig. 14). The original solution of the central altar of the Church of the Assumption in the semicircular apse impresses with its dynamic and unique artistic perfection. Examining the compositional scheme of the altar's construction, a synthesis of the arts can be observed, where painting and polychrome decorative motifs were organically combined with a plot-gilded sculptural composition. It was accentuated by six columns of the composite order on sophisticated high plinths and designed in the form of three arches around arched windows, completed by dynamic plot sculptural compositions. In the centre of each arch was an arched window with stained glass made by the artist Petro Kholodnyi. The central part of the altar was emphasised by a window with the stained glass of the Intercession of the Mother of God, above which a dynamic sculptural composition of Jesus Christ – the one God in three hypostases in the bishop's vestment – was placed. Christ was depicted as the first hierarch in heavenly glory, around whom angels hover, honouring him. In the skilfully carved figure of Christ and angels, one can read an expressive and at the same time calm manner of interpreting the image of God as if he were alive, hovering in the air above the throne. The drapery folds of his bishop's robes flicker and sway in the air, creating the impression of dynamic movement. The side arch compositions of the main altar were represented by the image of angels in dynamic movement, holding the icon in an oval decorative frame, harmoniously complementing the altar composition.

The low three-tiered iconostasis of the Church of the Assumption was made in 1773 in the Rococo style (Fig. 14) and installed on the site of the original iconostasis created by the artist Fedir Senkovych. It was a synthesis of arts peculiar to the late Baroque Rococo style, which combines bas-relief compositions on the deacon's gate, carving, and icon painting in Rococo openwork frames. In the deacon's door, Olenskyi repeats the motif of the archangel Gabriel from the Church of the Holy Intercession in Buchach and adds an image of Michael to the pair, based on the graphic model that was used in the creation of the same figure in the central altar in Monastyriska. The gilded rococo bas-reliefs of the deacon's door with graceful bas-relief figures of the archangels Michael and Gabriel, bending in strange poses, with geometrised draperies enveloping the body, complemented by rocaille ornamentation, make a wonderfully captivating impression (Fig. 15). Although Olenskyi was a student of J.G. Pinsel and inherited the techniques of geometrising forms from him, especially in the composition of dynamic draperies enveloping the body with sharp lines in the figures of saints, his works had differences manifested in stylistics. He conveys the nature of the characters more naturalistically in calm poses. The influence of classicism was already felt in his plastics, where the baroque dynamic movement was lost and poise, solemnity, and harmony prevail.



Figure 15. Deacon's gates

Notes: author – F. Olenskyi

Source: photo by L. Chen (2024)

Antonii Osinskyi was one of the most outstanding artists of Rococo sculpture in Lviv. He was a native of Lviv. Antonii Osinskyi married Rosalia Poleiovska, sister of the Lviv sculptors Matvii, Petro and Jan Poleiovskiy (Shengera, 2019). The influence of J. Pinsel's manner was felt in his works. He worked with various materials: limestone, marble, and most of all with linden wood. According to D. Krvavych (1998), A. Osinskyi worked in J. Pinsel's workshop and took over his experience of stylistic manners. His wooden sculptures in the Dominican Church in Lviv were marked by spirituality, elegance, refined forms, anatomical knowledge, and aesthetic lightness (Fig. 16). The sculptural works were characterised by exquisite forms and virtuosic execution of wood carvings, which include influences from the art of the Czech Republic and Austria, as well as indirect connections with Bavaria and Franconia. Antonii Osinskyi was distinguished by his unique ability to embody the aesthetic ideals of Rococo through the elegance and lightness of forms. In his sculptural works, in addition to Pinsel's manners, influences from various European regions were reflected due to the fact that he had contacts with various masters from southern Germany and Austria, which were manifested in the stylisation of forms and the imposition of picturesque draperies on the figure, adding expressiveness.

In the sculptures of the saints in the Dominican church, an incredible sense of plasticity and composition can be observed, which at the same time emphasises the picturesque interpretation of the geometrised draperies and makes the works unique and aesthetically attractive. The creators of these highly artistic works of Lviv carving were orientated on Western European models (Bochnak, 1931). These sculptural works were filled with mysticism and dynamic



plasticity, which testifies to the master's understanding of form and movement. The arrangement of the figures, the composition, the anatomical proportions of the saints, and the deep, prayerful expression on the faces testify to the fact that Osinskyi was knowledgeable in religious topics and skilfully depicted the emotional state of the saints not only figuratively but also spiritually.

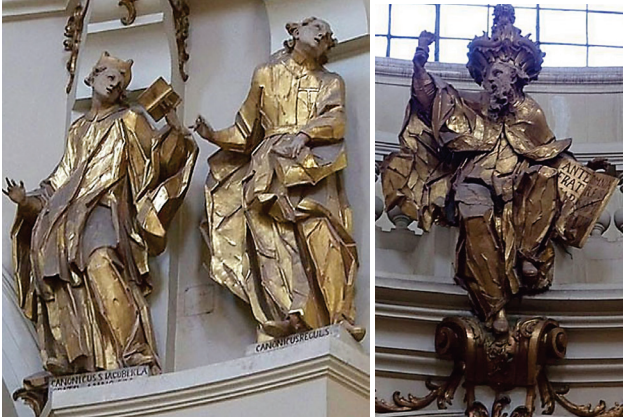


Figure 16. Sculptures in Dominican Church in Lviv

Notes: author – A. Osinskyi

Source: authors' photo (2024)

Therefore, the period of the highest rise of Lviv sculpture falls on the 18th century, when talented, highly professional artists J.G. Pinsel and his students F. Olenskyi and A. Osinskyi, who left a bright mark in the artistic culture of Lviv, appeared in the creative artistic environment (Lylio, 2017). Their sculptural works were a phenomenon in the sculptural art of the Rococo era, which had not yet been properly studied and appreciated (Sieve, 2008). All the above-considered works of sculptural art had high artistic value. The protection of the artistic sculptural masterpieces of Johann Georg Pinsel and his students Francisk Olenskyi and Antonii Osinskyi, as a historical and cultural heritage of Ukraine, was a priority task of the Ukrainian state.

The unique works of the enigmatic and brilliant sculptor J.G. Pinsel were poorly studied, and therefore there were various assumptions regarding the manner of their execution and characteristic stylistic, compositional, and plastic features. There were many hypotheses about the origin of the talented artist and his education. Researchers of J.G. Pinsel's work claim that he was of aristocratic origin and received a European education (Krvavych, 1991; Stetsko, 2010). J. Pinsel worked in Lviv during the late Baroque era and created perfect works of art, which, in terms of their artistic image, unique plasticity, and perfect anatomical structure, can be in the same row as the outstanding works of Michelangelo Buonarroti, Lorenzo Bernini, and the Prague sculptors Braun. The Polish researcher T. Mankowski (1937) characterised Pinsel as an exponent of a peculiar direction of expressive dynamics with his bold treatment of material, dramatic image of characters, and peculiar geometric interpretation of draperies.

M. Ghembarovych (1968) and D. Stepovyk (1991), in their works, conducted a thorough analysis of Baroque sculpture in Ukraine and in the historical context, suggesting that a similar treatment by Pinsel of the drapery of characters can be found in Byzantine mediaeval frescoes.

G. Logvin (1982), analysed the art of the Baroque era, recognised the works of the sculptor Pinsel as outstanding artistic masterpieces of the 18th century. He compared Ukrainian Baroque sculpture with world examples of this style, emphasising the uniqueness of Ukrainian Rococo works with exquisite carvings. B. Voznytskyi (2005) most thoroughly studied Pinsel's work, collecting his works during the creation of the museum of the same name in Lviv. V. Stetsko (2010), researching the works of J. Pinsel, noted the virtuoso technique of wood and stone carving and new approaches in the interpretation of plasticity of forms, which contributed to the emergence of a new stylistic direction of Rococo art. Y. Ostrowski (1996), studied and analysed Pinsel's works in the European context, expressed his hypotheses regarding the German origin of the artist, his education, and his creativity. The Polish researcher Z. Hornung (1976) put forward an assumption about the stylistic and ideological kinship of the sculptural works of J.G. Pinsel with the sculpture of the Czech school of the first half of the 18th century, namely, the works of Matias Braun, Jan Kwatainer, Ignat Plätzer, and Lazar Widman. He claimed that the plastic of the works of John Georg Pinsel was close to the relief plastic of Austrian masters and emphasised the influence of Italian and South German plastic.

Studies of the works of Franciscus Olenskyi and Antony Osynskyi were highlighted in the works of B. Shengera (2019), who emphasises that they were expressions of expressive dynamics, which were manifested in the interpretation of the forms of characters. F. Olenskyi's works were characterised by the impressiveness and expressive posture of the female figure, which envelops the picturesque folds of drapery clothes with open arms and legs. He also makes men's torsos more elongated. F. Olensky was characterised by a special type of interpretation of the face developed by him, with a slightly protruding nose and upper lip (Bahley & Chen, 2024). Unlike J. Pinsel, F. Olensky conveys the character of the characters more naturalistically in calm poses. A. Osynskyi's works were noted for their slenderness, complex hand gestures, sophistication and elegance of forms, and spirituality of the image of the characters. In his works, he emphasised the transfer of spirituality to the character. The arrangement of the figures, the composition, the anatomical proportions of the saints, and the deep, prayerful expression of the faces testify to Osynsky's knowledge of religious themes. He figuratively conveyed the emotional and spiritual state of the saints. All the works of J. Pinsel, F. Olenskyi, and A. Osynskyi were characterised by the richness of the artistic language, a new approach in the plastic interpretation of forms, harmony, the energy of movements, and emotional transfer of the image of the characters, which became a new stylistic direction in the Rococo art of the 18th century.





CONCLUSIONS

The Lviv sculptural works of the outstanding Ukrainian sculptor Johann George Pinsel belong to a peculiar direction of expressive dynamics in carving, which contributed to the emergence of a new style of pictorial plasticity in Rococo art. This was expressed in the subtle emphasis on individual forms and the geometric interpretation of draperies as if swirling in the air, in the expressive features of the faces, and in the expressive manner of the realistic interpretation of sculptural compositions, united by a rich plot, which testifies to the high skill of the outstanding and mysterious sculptor J.G. Pinsel. He created his own unique style of a peculiar interpretation of the plasticity of sculptural works and his own Lviv school of sculpture and a symbol of Western Ukrainian sculptural art. His talented students F. Olen-skyi and A. Osynskyi continued to work in the expressive Pinsel style and created a number of unique works of art.

The sculptural works of F. Olenskyi were characterised by the stylistic features of the plastic solution: the influence of classicism was felt in his plastic, where the baroque dynamic movement was lost. His figures were more squat,

with a neck and head that seem to be drawn into the shoulders and a face with a slightly forward nose and upper lip. A. Osinsky's sculptures were characterised by the modelling of faces with expressive features and facial expressions and a detailed head, which was the main accent. Instead, in Pinsel's works, the head was the completion of the work, to which the entire composition was reduced. In Pinsel's works, the emotions of the characters were poured out, and a dialogue with the creator and the world was reflected, while in the works of A. Osinsky, inner experiences, asceticism, and prayerfulness were emphasised. The results of the research can be used for further art studies.

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Характерні стилістичні та композиційні особливості скульптурних творів Й. Г. Пінзеля та його учнів у м. Львові

Анотація. У XVIII ст. у Західній Україні скульптурні твори відігравали значну роль в оздобленні храмів і житлових споруд, особливо в архітектурі львівських будівель. Стаття була присвячена дослідженню характерних художніх особливостей барокових скульптур Й. Г. Пінзеля та його учнів Ф. Оленського і А. Осинського в оздобленні архітектурних споруд м. Львова. Методологія дослідження полягала у ретельному вивченні та пластичному аналізі унікальних творів мистецтва, які вражають своєю величиною та неповторною красою і були культурним надбанням не лише окремої території, а й усієї України в історичному контексті. У процесі аналізу з'ясовано, що геніальний скульптор Й. Пінзель та його учні Ф. Оленський і А. Осинський створили у м. Львові неповторні шедеври, сповнені гармонії та мистецької довершеності. На основі аналізу скульптурних творів Пінзеля та його учнів визначено особливості їхнього мистецького світогляду у створенні художніх скульптурних творів. Встановлено, що скульптурні твори були насичені пластичною енергією, вираженням динамічного руху, виразними позами, неповторними силуетами, своєрідним геометричним трактуванням драпіровок. Визначено мистецьку цінність львівської сакральної скульптури Й. Г. Пінзеля та його учнів Ф. Оленського і А. Осинського, які є високохудожніми творами і належать до мистецької спадщини України. Ці скульптурні твори стали невід'ємною частиною світової культурної спадщини, що викликає інтерес міжнародної наукової спільноти та зацікавленість туристів. Результати дослідження можуть бути використані в курсі історії українського мистецтва та в навчальному процесі для підготовки студентів мистецтвознавців та архітекторів

Ключові слова: видатний скульптор; учні-різьбярі, вівтар; структура статуї; фігура; пластичне вирішення



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**Development of the composition and properties
of a wall block made of non-autoclaved aerated concrete based
on secondary raw materials of the Kyrgyz Republic**

Abstract. The aim of this study was to develop the composition of non-autoclaved aerated concrete using local secondary and technogenic materials to reduce production costs while ensuring compliance with strength standards. The methodology involved laboratory tests conducted at the Kyrgyz State University of Construction, Transport and Architecture named after N. Isanov, using Portland cement, quicklime, gypsum, aluminium powder and various mineral aggregates: substandard clay sand, feldspathic sand, and antimony ore beneficiation tailings (AOBT). The study varied component ratios to determine their effect on average density and compressive strength. Results showed that a minimum density of 575-580 kg/m³ was achieved with 60-70% AOBT and 30-40% feldspathic sand, owing to the increased porosity

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of the active dispersed phase. Increasing the proportion of feldspathic sand raised the density to 800 kg/m³. The use of clay sand in the range of 30-35% reduced the density to 625-650 kg/m³ due to the activation of gas formation and the development of a well-formed porous structure. The maximum strength of 2.23 MPa was achieved with 100% AOBT, owing to the high content of reactive silica and the synthesis of calcium hydrosilicates. Increasing the share of feldspathic or clay sand reduced strength to 1.61-1.66 MPa. The addition of up to 1% NaOH promoted gas generation and activation of aluminosilicate components, improving pore distribution and increasing strength while lowering density. Macroscopic structural analysis confirmed that using fine sand fractions (≤ 0.315 mm) ensures a uniform porous structure, improving both strength and thermal insulation properties of the material, whereas coarse fractions caused structural defects and a decline in performance. The practical value of this work lies in the potential application of the developed compositions in low-rise and rural construction, in the production of lightweight wall blocks by small and medium-sized enterprises, and in the expanded use of local mineral waste in the construction industry while simultaneously reducing environmental impact

Keywords: porous structure; mineral additives; pore distribution; structural strength; alkaline activation; thermal insulation properties

INTRODUCTION

The rapid development of the construction sector in the Kyrgyz Republic is accompanied by a growing demand for affordable and energy-efficient wall materials that meet modern requirements for thermal insulation, strength, and environmental safety. Particular attention is given to the production of cellular concretes, which are characterised by low density and high thermal insulation performance. Among these, non-autoclaved aerated concrete occupies a prominent position, as its production does not require expensive equipment or complex technological processes. However, a key issue remains the high cost of raw materials, driven by limited local resources and the need to import some components – a significant concern in the Kyrgyz Republic, where the construction industry is highly sensitive to price fluctuations and transportation costs.

One of the pressing challenges in developing effective wall materials is the optimisation of the structure and porosity of non-autoclaved aerated concrete while maintaining standardised strength (Shumakov *et al.*, 2024). Excessive gas formation can impair material structure, while insufficient gas generation reduces thermal insulation performance. A. Maltschik (2024) notes that in the production of non-autoclaved aerated concrete, one of the most critical issues is the selection of an effective gas-generating composition that can ensure uniform pore distribution without large defects. His studies involved various types and modifications of aluminium powder, but the author concluded that even slight deviations in the gas-forming composition result in reduced structural integrity and strength, underscoring the need for additional methods to enhance gas formation.

Equally significant is the impact of mineral aggregates on the formation of the material's porous structure. Research by Z. Mamatov *et al.* (2024) showed that the use of technogenic sands with high silica content increases strength due to the synthesis of calcium hydrosilicates. However, the study also noted that coarse aggregate fractions lead to uneven pore formation and reduced strength, necessitating further processing and grading of the raw materials. A key feature of using secondary materials is

their influence on chemical processes within the aerated concrete mixture. According to E. Boronbaev (2020), the presence of reactive minerals in technogenic raw materials promotes accelerated gas generation and the synthesis of calcium hydrosilicates. However, in some cases, excessive fine particles disrupt the material structure and reduce strength, emphasising the importance of careful dosing and mixing regimes when using such components.

The economic viability of using secondary resources in aerated concrete production also warrants separate attention. A study by J. Zhang *et al.* (2022) demonstrated that the use of industrial waste significantly reduces the cost of finished products. However, the authors emphasised that failure to account for the specific chemical composition and physico-mechanical properties of secondary materials may compromise product quality, limiting the broader application of such technologies. A particularly important aspect of research is the control of density and strength of non-autoclaved aerated concrete through varying component ratios. L. Mészárosóvá *et al.* (2024) found that changes in the percentage of different sands and technogenic raw materials directly affect product density and strength. While a higher proportion of active components enhances strength, it simultaneously increases density, thus diminishing the material's thermal insulation capacity. The use of chemical additives to intensify gas formation and activate mineral components has been studied by E. Michelini *et al.* (2023). They established that the introduction of alkaline activators such as NaOH increases gas output and improves pore distribution. However, the authors also noted the risk of microcracks forming when alkaline content is excessive, necessitating strict dosage control.

The formation of a uniform porous structure in aerated concrete remains one of the most complex tasks. K. Zhang *et al.* (2023) highlighted the influence of sand grain size on the material's macroscopic structure. Their study showed that fine-grained sand contributes to a uniform porous structure and enhances product strength, whereas coarse grains lead to structural defects and reduced performance





characteristics. Finally, the issue of environmental safety and the rational use of waste in construction materials is addressed by H. Song *et al.* (2023). Their work emphasised the importance of developing technologies for converting industrial waste into useful products to reduce anthropogenic environmental impact. The authors concluded that the use of such materials in aerated concrete requires careful refinement of production regimes to ensure consistent product quality.

Thus, the analysis of existing studies confirms the high relevance of developing non-autoclaved aerated concrete based on local secondary and technogenic materials in the Kyrgyz Republic. The aim of the present study was to justify the composition and examine the properties of non-autoclaved aerated concrete using local secondary raw materials to reduce costs while ensuring the standardised strength of wall blocks.

MATERIALS AND METHODS

The study was conducted in 2023 at the laboratory of the Department of Building Materials and Products Technology, Kyrgyz State University of Construction, Transport and Architecture named after N. Isanov, located in Bishkek. The laboratory was selected for its specialisation and advanced experimental facilities, enabling complete reproduction of the technological cycle for producing aerated concrete. The main components of the composite binder included Portland cement grade M400 D20 in accordance with GOST 31108-2020 (2020), quicklime of the second grade in lump form with a combined content of active components (MgO and CaO) of 82%, and a fraction of unreacted particles not exceeding 1.2%, as well as construction gypsum grade G-5 in accordance with GOST 125-79 (1980). Gas formation in the mixtures was achieved using aluminium powder grade PAP-2 produced in China, compliant with GOST 5494-95 (1996).

The mineral fillers included substandard fine-grained clay sand from the Kyzyl-Kyshtak and Ak-Zhar deposits in the Kara-Suu district of Osh region, feldspar sand, and antimony ore beneficiation tailings (AOBT) from the Kadamjai Antimony Plant in Batken region. AOBT was formed during the extraction of antimony from ores under thermal treatment at 1200°C and had the following chemical composition (in %): CaO – 12.67; R₂O – 0.67; Al₂O₃ – 6.92; Fe₂O₃ – 0.73; SiO₂ – 70.93; MgO – 0.03; SO₃ – 0.82; loss on ignition – 7. The mineral composition was dominated by quartz and calcite, with minor amounts of clay minerals. The grindability coefficient of AOBT was 1.2, indicating high friability and good grindability.

The substandard clay sand contained the following components (in %): CaO – 0.86; SiO₂ – 73.74; R₂O – 4.27; Al₂O₃ – 12.52; Fe₂O₃ – 0.93; SO₃ – 0.4; MgO – 2.85; loss on ignition – 4.41. Its mineralogical composition included 31.67% Al₂O₃ • 2SiO₂ • 2H₂O, 59.01% free silica, 5.98% magnesite, 1.03% calcite, and 0.68% gypsum. The sandstone was dry-ground for 20-25 minutes to a fraction below 0.16 mm, achieving a specific surface area of 2,200-2,250

cm²/g. Feldspar sand had the following oxide composition (in %): Al₂O₃ – 14.21; SiO₂ – 68.72; MgO – 2.68; CaO – 3.25; SO₃ – 2.61; Fe₂O₃ – 3.24; TiO₂ – 6.63. To activate the clay component and intensify gas formation, up to 1% sodium hydroxide (NaOH) of Chinese origin was added to the mixtures. The development of aerated concrete mixtures involved varying the mass ratios of dispersed fillers and feldspar sand from 0/100 to 100/0. The binder-to-filler ratio was maintained between 0.5 and 1. Mixing was carried out until a homogeneous mass was achieved. The workability was evaluated using the Suttard Viscometer (USA), which determines the structural viscosity of aerated concrete mixtures. The average value was 29-30 cm.

Test samples were moulded in metal forms measuring 15×15×15 cm. Curing was performed under natural conditions at a temperature of 20-25°C and relative humidity of 60-70% for 28 days. The average density was determined in accordance with GOST 31359-2024 (2024), and compressive strength was tested in accordance with GOST 10180-2012 (2012). Compressive strength was measured using a hydraulic press machine Controls MCC8 50-C10A05 (Italy) with a maximum load of 3,000 kN and a digital force registration system with an accuracy of 0.01 MPa. The pore structure of the aerated concrete was analysed using a Levenhuk 700M optical microscope (USA), providing up to 40× magnification, allowing visualisation of pore geometry, distribution, and the nature of inter-pore walls. Studies were conducted on horizontal polished sections of samples after 28 days of curing. Microphotographs were taken using the microscope's digital camera for further morphometric analysis. Statistical analysis of the experimental data was conducted using Student's t-test at a significance level of $p < 0.05$. All measurements were performed in triplicate to ensure high data reliability. Calculations were carried out using Microsoft Excel 2019 (USA) and the Statistica 10.0 (USA) statistical software package, enabling reliable analysis of variance, normality testing, and construction of confidence intervals.

RESULTS

The study of the influence of various ratios of technogenic and natural mineral fillers on the average density of non-autoclaved aerated concrete revealed a clear pattern of variation in this parameter. The lowest density values were recorded with 60-70% AOBT and 30-40% feldspar sand. In these compositions, the average density was 575-580 kg/m³, which represented the best performance among all tested variants (Table 1). As the proportion of feldspar sand increased, the density of aerated concrete rose, reaching 800 kg/m³ at 100% feldspar content. The use of off-spec sand with a clay component also influenced the density. When its content was within 30-35%, the density reached minimum values of 625-650 kg/m³. This dependence is attributed to the material's overall mass reduction due to high porosity, ensured by the active clay fraction. Therefore, the optimal filler ratio allows regulation of aerated concrete density across a wide range.

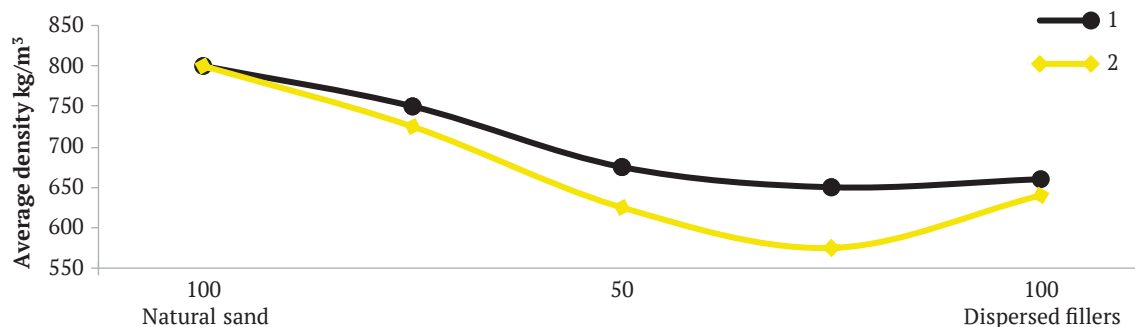
**Table 1.** Influence of filler ratios on the average density of non-autoclaved aerated concrete

Mix No.	AOBT/Feldspar sand (%)	Off-spec sand/Feldspar sand (%)	ρ_{avg} , kg/m ³
1	0/100	-	800
2	15/85	-	760
3	30/70	-	730
4	40/60	-	670
5	50/50	-	630
6	60/40	-	580
7	70/30	-	575
8	85/15	-	610
9	100/0	-	640
10	-	0/100	800
11	-	15/85	761
12	-	30/70	740
13	-	40/60	720
14	-	50/50	670
15	-	60/40	650
16	-	70/30	625
17	-	85/15	640
18	-	100/0	655

Source: compiled by the authors

The obtained experimental results established a clear relationship between the content of the technogenic component AOBT, natural feldspar sand, and off-spec clayey sand, and the average density of non-autoclaved aerated concrete. Minimum density values were observed in compositions

containing 60-70% AOBT and a reduced proportion of feldspar sand (30-40%) (Fig. 1). The corresponding density reached 575-580 kg/m³, attributed to the high reactivity of the dispersed phase, which facilitated intensive gas formation and the development of a well-formed porous structure.

**Figure 1.** Dependence of average aerated concrete density on filler composition

Notes: 1 – off-spec sand and feldspar sand; 2 – AOBT and feldspar sand

Source: compiled by the authors

The high effectiveness of AOBT is linked to its mineral composition, which is dominated by quartz and calcite. This facilitated the formation of loosely bound frameworks among the porous formations, reducing the overall material mass without significant strength loss. Increasing the feldspar sand content led to a rise in average material density up to 800 kg/m³. This process is explained by the low dispersity of feldspar sand, reduced gas formation, and, consequently, decreased volume of closed pores.

A similar trend was observed in mixtures with off-spec clayey sand, where minimum density values of 625-650 kg/m³ were achieved with 30-35% active clay content. The high aluminosilicate content in the clayey sand promoted additional gas formation activation and enhanced porosity due to interactions with sodium hydroxide

and binder components. This enabled the formation of a looser structure dominated by small, spherical pores, reducing the final product's mass.

It is worth noting that further increases in feldspar sand content or its complete substitution resulted in higher material density. This is due to the insufficient activity and weak propensity of feldspar sand to participate in pore-forming reactions, thereby limiting the development of a microporous structure. A higher proportion of coarse fractions led to a loss of connectivity among porous elements and increased the density of inter-pore walls.

Thus, the optimal reduction in average density was achieved within a narrow range of compositions combining active technogenic additives with a controlled amount of feldspar sand. These patterns highlight the importance



of selecting the granulometric and mineralogical composition of fillers to obtain lightweight porous materials with adjustable density.

Experimental data demonstrated a clear dependence of the compressive strength of non-autoclaved aerated concrete on the percentage content of different types of fillers (Fig. 2). The highest strength values – up to 2.23 MPa – were recorded when using 100% AOBT due to the high activity of its siliceous component. Strength indicators consistently

increased with the proportion of AOBT, reaching a peak within the 70–100% range of the total filler content. Conversely, the lowest compressive strength values (1.61–1.66 MPa) were observed in compositions where the main component was either feldspathic sand or substandard clay sand with insufficient content of active siliceous material. These results confirm that a high proportion of active technogenic material contributes to the formation of a robust framework and enhances the mechanical properties of the aerated concrete.

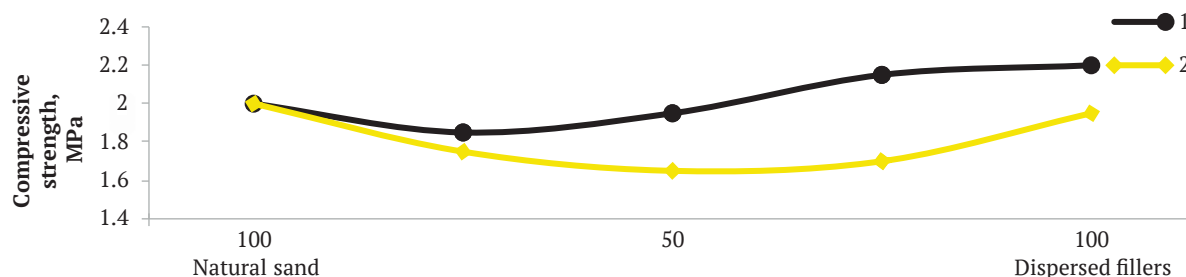


Figure 2. Dependence of compressive strength of aerated concrete on filler composition

Notes: 1 – AOBT and feldspathic sand; 2 – substandard sand and feldspathic sand

Source: compiled by the authors

The experimental results revealed a distinct correlation between the compressive strength of non-autoclaved aerated concrete and both the qualitative and quantitative composition of the mineral fillers. A significant increase in strength was observed in mixtures where the mass fraction of CRIW as an active component ranged from 60 to 100%. Peak strength values reached 2.23 MPa when feldspathic sand was completely replaced by AOBT. This is attributed to the high free silica content and the presence of active phases in AOBT, which actively participated in cement hydration processes and reacted with calcium hydroxide hydrate to form additional quantities of calcium hydrosilicates, thus strengthening the inter-pore walls and improving the structural characteristics of the concrete.

An additional factor enhancing strength was the mineralogical nature of AOBT: the predominance of quartz and calcite facilitated the synthesis of robust silicate and carbonate phases, forming a dense crystalline structure within the aerated concrete. The formation of the primary framework through AOBT stabilised the structure formation process, prevented shrinkage cracking, and ensured uniform pore distribution, thereby reducing the risk of local deformations and increasing the mechanical stability of the material. In contrast, increasing the content of feldspathic sand had the opposite effect – reducing the concrete's strength to minimum values in the range of 1.61–1.66 MPa. This is due to its low chemical reactivity and minimal participation in the formation of new durable phases. Feldspathic sand hardly integrated into the hydrosilicate structure, acting instead as an inert mass, disrupting cement matrix cohesion and worsening strength characteristics. The large and dense feldspar particles impeded the formation of a robust fine-pored structure, leading to local stress redistribution and microcrack formation.

Substandard clay sand exhibited a similar trend of strength reduction, especially at high contents and insufficient alkaline activation. High clay mineral content without NaOH treatment led to the formation of loose, weakly bonded aggregates that did not contribute to the formation of a durable crystalline framework. However, introducing up to 1% sodium hydroxide into the mix activated the clay component. This facilitated additional calcium hydrosilicate synthesis and partially offset the reduction in strength characteristics, which was clearly evident in intermediate compositions with an active component content of at least 60%.

An interesting feature was the stabilisation of strength in mixtures that combined the active siliceous additive with a moderate amount of feldspathic sand. Here, strength reached 2.15–2.2 MPa due to the combined influence of mineralogical composition and a properly managed gas generation process, which led to the formation of a stable cellular structure. These systems exhibited a synergistic effect: active components promoted the formation of a strong crystalline phase, while the inert portion ensured volumetric stability. In conclusion, the highest compressive strength values of non-autoclaved aerated concrete were achieved through the combined action of active AOBT phases, optimal material macrostructure, and the synthesis of hydrate formations that effectively reinforced the inter-pore walls. This highlights the importance of carefully selecting filler types and their ratios when designing strong and durable cellular construction materials.

Macrostructural analysis of horizontal cross-sections of aerated concrete samples revealed a direct dependence of pore structure formation on the granulometric composition of the sands used (Fig. 3). When sand fractions between 0.63 and 0.315 mm were introduced into the mix, large elongated and interconnected pores of 0.5 to 3 mm



in size were observed. These pores predominantly had slit-like or irregular shapes, which negatively affected the density and homogeneity of the inter-pore walls. Such

structures reduced the overall strength of the aerated concrete by up to 10% compared with samples made with finer sand fractions.

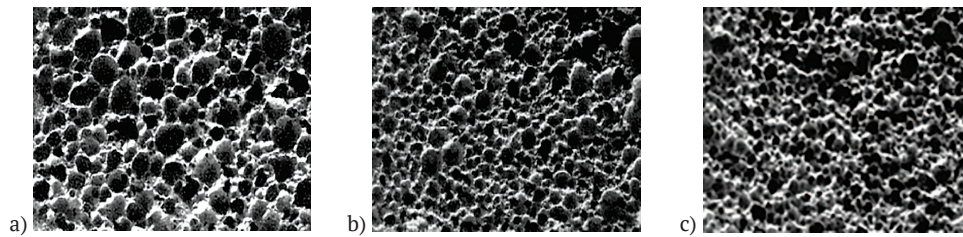


Figure 3. Macrostructure of horizontal cross-sections of aerated concrete samples using different sand fractions ($\times 10$)

Notes: a) coarse fraction; b) medium fraction; c) fine fraction

Source: compiled by the authors

At the same time, the use of fine sand fractions – 0.315 mm and smaller – ensured the formation of a uniform fine-pored structure, which significantly influenced the morphological and performance characteristics of the resulting material. The pore sizes in these specimens ranged from 0.3 to 1.2 mm, with most of the pores being oval or nearly spherical in shape, indicating the stability of the foaming process and the uniform distribution of the gaseous phase throughout the material's volume. Such a porous structure contributed to the reduction in the thickness of the inter-pore walls, thereby increasing the density and strength of the framework. This, in turn, led to the formation of a denser and more robust system capable of efficiently withstanding mechanical loads. Additionally, the presence of small, evenly distributed pores reduced the likelihood of defect formation and localised stresses, which positively affected the material's durability and resistance to external influences. Thus, the use of fine sand can be regarded as one of the effective methods of controlling the structure and mechanical properties of the material.

The results of macrostructural analysis confirmed the critical role of the granulometric composition of sand aggregates in the structuring processes of non-autoclaved aerated concrete. The size and shape of the sand fractions directly affected not only the overall density and strength of the material, but also the nature of pore distribution, and consequently, the durability and reliability of aerated concrete products in service. The use of coarse sand fractions ranging from 0.63 to 0.315 mm in the aerated concrete mix resulted predominantly in the formation of a macroporous structure. In such specimens, large, deformed and interconnected pores ranging from 0.5 to 3 mm were observed. The geometry of the pores was mainly elongated, with a pronounced slit-like or irregular shape. This had a negative effect on structural homogeneity – inter-pore walls became loose and less robust, which led to a considerable reduction in overall material strength, by up to 10%.

The reasons for this effect are associated with the insufficient wettability of large sand grains by the cement slurry and their limited involvement in the structure-forming processes. Coarse fractions hindered the

uniform distribution of the gas-generating medium, creating zones of local stress redistribution. This promoted the formation of microcracks and disrupted structural continuity, thereby reducing the mechanical stability of the aerated concrete. The opposite effect was observed when fine-grained sand with a particle size of 0.315 mm and smaller was used in the aerated concrete mix. In this case, the material structure was characterised by the uniform distribution of small pores ranging from 0.3 to 1.2 mm. Most of the pores were rounded or oval, close to spherical, which helped reduce stress concentrations in the inter-pore walls. This structure not only improved the strength characteristics of aerated concrete but also enhanced its thermal insulation properties due to the increased proportion of closed air voids.

The high dispersion degree of fine sand fractions ensured intensive interaction with binding components and active participation in gas generation processes. This made it possible to create a well-developed fine-pored structure with increased specific surface area, capable of effectively resisting mechanical stress. Moreover, the reduction in pore size contributed to an increase in their number per unit volume, thereby lowering the overall density of the material without loss of strength. An important factor in improving the strength and uniformity of the aerated concrete structure was also the ability of fine sand particles to form strong and dense inter-pore partitions. This hindered the development of microcracks and ensured the material's resistance to long-term service loads.

Thus, the use of fine-grained sand in aerated concrete mixtures is a necessary condition for producing high-quality non-autoclaved aerated concrete with a uniform cellular structure, optimal density, and enhanced strength. The research results emphasise the need for strict control of the granulometric composition of aggregates at the stage of raw material selection and mix preparation. The introduction of sodium hydroxide (NaOH) into aerated concrete mixtures in quantities up to 1% of the total component mass had a significant effect on the intensification of gas formation and the activation of the clay component of the mineral aggregates. The alkaline environment created by





NaOH contributed to the increased activity of aluminosilicate minerals contained in substandard clay sand and ensured fuller expression of their reactive potential. Simultaneously, the rate of gas formation from aluminium powder increased due to the accelerated chemical reaction with hydrated lime. This led to the formation of a more uniform and developed porous structure with an increased number of fine closed pores. As a result, the strength characteristics of the aerated concrete improved, and its density decreased due to more efficient synthesis of calcium hydrosilicates and the formation of a dense macrostructural framework.

Primarily, NaOH, by creating a highly alkaline environment in the system, activates aluminosilicate minerals contained in substandard clay sand and high-activity mineral waste (HMW). Under the influence of the alkali, the crystal lattice of clay minerals such as montmorillonite and kaolinite is destroyed, releasing active silicon and aluminium ions into solution. These ions, reacting with the hydrated phase of the cementitious binder, initiate the formation of new strong crystalline compounds, primarily calcium hydrosilicates and calcium hydroaluminosulphates. As a result, the macrostructural framework of the material is significantly strengthened, the strength of inter-pore partitions increases, and the overall mechanical strength of the aerated concrete is improved.

Equally important is the role of NaOH in intensifying gas formation. Aluminium powder, used as the gas-generating agent, reacts much faster and more intensively in the alkaline environment with water and hydrated lime. This ensures uniform pore distribution throughout the mass, prevents the formation of large voids and local defects. As a result, an optimal fine-pored structure with predominantly round closed pores is formed, providing not only mechanical strength but also excellent thermal insulation properties. Alkaline activation also promotes the involvement of previously inert mineral fractions, particularly components of feldspathic sand, in the structure-forming process. Under the influence of NaOH, partial degradation of the feldspar surface occurs, facilitating better bonding with the binder and strengthening the overall structure of the material. Thus, NaOH offsets the negative effects of low-reactivity components in the composition, expands the raw material base, and increases the efficiency of local mineral waste utilisation.

Experimental studies established that the introduction of NaOH in quantities up to 1% of the dry component mass ensures the optimal balance between density and strength of the aerated concrete. At this concentration, maximum synthesis of calcium hydrosilicate phases and uniform pore distribution are achieved. Exceeding the optimal dosage leads to excessive gas formation rates, which can result in macro-defects and, consequently, a decrease in the strength of the final material. Hence, NaOH performs a dual role – as both activator and modifier. On the one hand, it significantly enhances the utilisation of siliceous and clay components, thereby promoting the recycling of local technogenic wastes. On the other hand, it stimulates the

formation of a robust macrostructural framework through targeted synthesis of hydrated phases. These combined effects allow the production of non-autoclaved aerated concrete with high physical and mechanical performance and stable structure at minimal density. The findings demonstrate that the use of NaOH not only improves the efficiency of structure formation processes but also significantly expands the applicability of local secondary resources, reducing costs and environmental impact.

DISCUSSION

The findings of this study demonstrated a pronounced effect of the ratio between technogenic and natural mineral aggregates on the density and strength of non-autoclaved aerated concrete. The lowest density values were recorded when 60-70% HMW was introduced into the mixture, confirming their effectiveness in forming a lightweight porous structure. Similar patterns were obtained in the study by A. Paul *et al.* (2025), which showed the effect of highly dispersed technogenic waste on reducing the density of cellular concretes through enhanced gas formation. The observed correlation between increased feldspathic sand content and increased material density aligns with the findings of Y. Peng *et al.* (2021), who demonstrated the limited activity of feldspars in chemical interaction with binders. However, their study did not take structural effects into account, whereas the present work has shown that feldspar reduces the intensity of gas formation, increasing mass and density.

The use of substandard clay sand in the range of 30-35% led to a reduction in aerated concrete density to 625-650 kg/m³, which is explained by the high pore-forming capacity of active aluminosilicate phases. Similar conclusions were drawn by G. Murali & M. Azab (2023), who emphasised the role of the clay fraction in enhancing system porosity. At the same time, the study by F. Seddighi *et al.* (2021) did not find a significant impact of clay sand on the density of cellular concretes, attributing this to the low activity of the components. Unlike their work, the present study demonstrated that activation of the clay component is achieved through the alkaline environment, which enables the full reactive potential of the minerals to be realised.

Maximum compressive strength (2.23 MPa) was recorded when 100% AOBT was used, which is attributed to the high content of free silica and calcite. These results are consistent with the findings of R. Wu *et al.* (2021), who demonstrated the strengthening of aerated concrete structure through the synthesis of calcium hydrosilicate phases with an increase in active siliceous components. A reduction in strength to 1.61-1.66 MPa with an increasing proportion of feldspar sand supports the conclusions of J. Xia *et al.* (2021), who pointed to the inertness of feldspars and their weak participation in hydration reactions. However, the present study provides a more detailed insight into the mechanism of structural disintegration due to the formation of weak inter-pore partitions.

Particular attention is drawn to the stabilisation of strength at the level of 2.15-2.2 MPa when combining the



active siliceous component with a moderate amount of feldspar sand. A similar synergistic effect was reported by S. Mollaei *et al.* (2022), who observed structural optimisation through the combination of active and inert fillers. A contrasting viewpoint is presented by O. Oladiran & D. Simeon (2023), who claimed that the addition of inert fractions always leads to a decrease in strength. However, their study did not account for the effect of particle size distribution on stress redistribution and the formation of a stable framework, which is considered in the present research. Macrostructural analysis confirmed the key role of sand particle size in the processes of structural formation. The formation of a macroporous structure when using coarse fractions (0.63–0.315 mm) led to a 10% decrease in strength.

Conversely, the use of fine fractions up to 0.315 mm ensured the formation of a uniform microporous structure with pore sizes ranging from 0.3 to 1.2 mm. The effectiveness of this approach is supported by the study of C. Liu *et al.* (2021), who demonstrated significant improvements in the mechanical properties of cellular concrete when using fine fillers. Additionally, it was found that the application of fine fractions not only ensures uniform distribution of the gas phase but also increases the density of inter-pore partitions due to the tighter packing of small particles against the binder matrix. This contributes to the formation of a strong and homogeneous framework, resistant to external loads and minimising the risk of microcracks. As a result, aerated concrete acquires not only high strength but also improved thermal insulation properties due to the increased proportion of closed spherical pores (Basok *et al.*, 2023). Furthermore, the uniform microporous structure reduces water absorption and enhances the durability of the material under humid operating conditions.

An opposite result was reported by B. Aramburu *et al.* (2024), where fine sand fractions led to reduced strength due to increased water demand of the mixture. The additional water required to maintain the necessary workability of the mix with fine fractions resulted in excessive porosity and structural weakening. However, the present study shows that the active interaction of fine particles with the binder reinforces the inter-pore partitions and enhances strength. Fine fractions contribute to more uniform component distribution and close adhesion to the binder matrix, reducing the likelihood of weak zones and increasing the number of closed pores (Montayev *et al.*, 2016). This not only improves strength characteristics but also enhances the thermal insulation properties of aerated concrete through the formation of a uniform microporous structure.

Special emphasis was placed on the effect of sodium hydroxide on the structural formation of aerated concrete. The introduction of NaOH up to 1% of the component mass activated aluminosilicate minerals, enhancing the synthesis of calcium hydrosilicate phases and structural reinforcement (Astakhova & Astakhov, 2024). The alkaline environment facilitated the breakdown of the crystalline lattice of clay minerals such as montmorillonite

and kaolinite, allowing the release of reactive silicon and aluminium ions into the solution and their further participation in hydration reactions. This had a positive impact on the formation of a dense macrostructural framework, improving the strength characteristics of the material. Similar results were presented by W. Jin (2022), where alkaline activation improved the strength properties of cellular materials and contributed to a more uniform distribution of the porous structure.

However, X. Ma *et al.* (2022) highlighted the risk of excess alkali, which causes excessive gas formation and reduces strength. According to their findings, exceeding the permissible NaOH dosage leads to uneven gas phase expansion, the formation of macro-defects, and weakening of the material structure. The present study confirmed this observation, recording a reduction in strength when the optimal NaOH dosage was exceeded, underscoring the necessity of strict dosage control to achieve the required performance characteristics of the material.

It is noteworthy that additional activation of feldspar sand under the action of NaOH was identified. This effect was previously described by B. Muthusubramanian *et al.* (2023), who showed the possibility of partial destruction of feldspars and enhanced bonding with the cement matrix. The breakdown of feldspar grain surfaces and the increase in their reactivity result in a stronger bond between inert particles and the binder, which contributes to the overall improvement of the material structure and reduces the risk of weak zones in aerated concrete.

In contrast, A. Thakur & S. Kumar (2022) expressed doubts about the feasibility of using NaOH to activate low-reactivity components, citing potential economic costs and limited effectiveness of such additives in mixtures with high inert content. However, the present study demonstrates a positive outcome when the optimal dosage is observed, allowing the activation of feldspars and clay minerals without adverse effects on gas distribution uniformity and material strength.

The findings also agree with the conclusions of W. Quan *et al.* (2024), who proved that the use of alkaline activators expands the raw material base and allows for the effective utilisation of industrial waste. Furthermore, W. Quan *et al.* emphasised that this technology helps reduce reliance on traditional natural resources and enables the creation of building materials with specified performance characteristics through the incorporation of previously unsuitable components.

Meanwhile, G. Chen *et al.* (2021) noted the limited effectiveness of aluminosilicate activation under high humidity conditions. According to their results, high humidity prevents the full development of the reactivity of aluminosilicate minerals and limits the formation of durable hydrate phases, which negatively affects the material's strength properties. However, in the present study, these negative effects were mitigated by strict control of the moisture regime at all stages of the technological process and by optimising the mixture composition, including





adjusting the water-cement ratio and introducing additional modifiers. This ensured the stability of hydration and gas-forming processes, contributing to the formation of a strong and homogeneous structure of aerated concrete even under potentially high moisture conditions.

Particular attention should be paid to the establishment of the positive effect of NaOH on pore distribution uniformity and the formation of a stable cellular structure. Alkaline activation promotes the even distribution of the gas phase within the material volume, preventing the formation of local compactions and voids, which is critically important for structural stability during operation (Yakovkin *et al.*, 1998). As a result, the likelihood of defects such as through-channels or large open pores that could negatively affect strength and thermal insulation properties is reduced. Similar results were reported by M. Arslan *et al.* (2021), who demonstrated increased thermal insulation properties of aerated concrete when using alkaline activators. Moreover, M. Arslan *et al.* noted improvements in macrostructure due to the formation of uniform and predominantly spherical pores, further contributing to the material's durability and its ability to maintain performance under long-term exposure to external factors.

Conversely, T. Pi *et al.* (2021) reported a reduction in thermal insulation properties due to excessive material density when using NaOH. T. Pi *et al.* emphasised that increased density impairs the thermal insulation efficiency of aerated concrete, limiting its use as an energy-saving construction material. However, the present study demonstrates the achievement of an optimal balance between density and strength, allowing good thermal insulation properties to be maintained while ensuring the required level of mechanical strength. This is achieved through precise control of NaOH dosage, which promotes the formation of a uniform microporous structure with a predominance of closed pores that ensure low thermal conductivity and resistance to thermal deformation.

The influence of NaOH on pore redistribution and the prevention of large void formation correlates with the findings of P. Walczak (2023), who demonstrated a reduction in the likelihood of defects and microcracks under alkaline activation. This effect is explained by the fact that the presence of alkali promotes a more uniform progression of gas-forming reactions and stabilises the size of the forming pores, thereby preventing the coalescence of individual gas bubbles into large cavities (Timchenko *et al.*, 2023). This ensures structural homogeneity and contributes to the formation of dense inter-pore partitions with enhanced strength. Furthermore, alkaline activation enhances the bonding of silicon and aluminium ions within the material's structure, facilitating the synthesis of additional durable phases, which has a positive effect on the mechanical stability and durability of aerated concrete under cyclic loads and external influences.

At the same time, C.Q. Wang *et al.* (2020) criticised the use of NaOH, claiming that it increases production costs and environmental risks. They point out that the use of

alkaline additives requires additional expenditure for chemical reagents and the establishment of control systems for their dosing. It may also lead to an increased burden on wastewater treatment facilities due to the formation of alkaline effluents. However, the present study, in contrast, demonstrates that the application of NaOH in optimal dosages can reduce costs through the utilisation of waste materials and the expansion of the raw material base by incorporating low-reactivity and difficult-to-utilise mineral components. Moreover, the use of NaOH intensifies gas evolution processes and the synthesis of strong phases, allowing a reduction in binder consumption and improving overall production efficiency, thereby minimising reliance on traditionally expensive components.

The final conclusions are supported by the studies of E. Yusrianto *et al.* (2022) and E.K. Sardarbekova *et al.* (2022), who highlighted the importance of a comprehensive approach to the selection of aggregates and modifiers for producing aerated concrete with high physical and mechanical properties. Particular emphasis is placed on the necessity of considering not only the chemical and mineralogical composition of the components but also their granulometric characteristics, which enables control over gas evolution and the formation of the porous structure. Additionally, E. Yusrianto *et al.* noted the significance of optimal activator dosages, including alkaline components, to maximise the efficiency of strong phase synthesis and enhance the durability of the material. Such an integrated approach makes it possible to improve the performance characteristics of aerated concrete, including strength, density, and thermal insulation parameters, thus rendering the material competitive for use in various climatic zones and structural applications.

Thus, the study proved the effectiveness of the complex selection of mineral aggregates and the use of NaOH to regulate the properties of non-autoclaved aerated concrete. The optimum ranges of components content have been established, providing the achievement of minimum density while maintaining high strength and stability of the structure. The results emphasise the importance of further study of alkaline activation mechanisms and possibilities of technogenic waste utilisation for the creation of energy-efficient building materials.

CONCLUSIONS

The conducted experimental research made it possible to establish clear correlations between the content of various mineral fillers and the physical-mechanical properties of non-autoclaved aerated concrete. It was determined that the use of AOBT contributes to a reduction in the material's average density and an increase in strength due to the high reactivity of its silica component. The optimal composition 60-70% AOBT and 30-40% feldspathic sand ensured the formation of a uniform porous structure with a minimum density of 575-580 kg/m³ and a compressive strength of up to 2.15-2.2 MPa. Increasing the proportion of feldspathic sand led to a rise in the density of aerated concrete up to



800 kg/m³ and a reduction in strength to 1.61-1.66 MPa, which is attributed to its inertness and weak contribution to the formation of a robust macrostructural framework. The introduction of substandard clay sand in amounts of up to 30-35% resulted in a decrease in density to 625-650 kg/m³ due to the activation of gas evolution by the aluminosilicate fraction.

Maximum compressive strength values up to 2.23 MPa were achieved with a AOBT content in the range of 70-100%. This is associated with the formation of additional hydrate phases that reinforce the inter-pore partitions and increase the structural integrity of the material. Macrostructural analysis showed that the use of fine-grained sands (fraction <0.315 mm) supports the formation of a uniform cellular structure with small, closed pores, thereby improving the strength and thermal insulation properties of the aerated concrete. The addition of up to 1% NaOH effectively activates the clay components and enhances gas evolution, which further improves the material's structure and mechanical properties. Alkaline activation also broadens the possibilities for recycling local

mineral waste and increases the raw material flexibility of the technology.

In practice, it is recommended to focus on formulations with high AOBT content and fine-grained sands, as well as to employ alkaline activation to produce lightweight and strong aerated concrete with controlled density. A limitation of the study is its laboratory scale, which necessitates further full-scale testing and evaluation of performance under real construction conditions. Promising directions for future research include optimisation of curing regimes and the study of material durability in different climatic conditions.

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Розробка складу і властивості стінового блоку з неавтоклавною газобетону на основі вторинної сировини Киргизької Республіки

Анотація. Метою дослідження було розроблення складу неавтоклавною газобетону із застосуванням місцевих вторинних і техногенних матеріалів для зниження собівартості при забезпеченні нормативної міцності. Методологія включала лабораторні випробування на базі Киргизького державного університету будівництва, транспорту і архітектури з використанням портландцементу, негашеного вапна, гіпсу, алюмінієвої пудри і різних мінеральних заповнювачів: некондиційного глинистого піску, польовошпатового піску та хвостів збагачення сурм'яних руд (ХЗСР). Дослідження проводили за варіювання співвідношень компонентів для визначення впливу на середню густину і міцність на стиск. Результати показали, що мінімальна густина 575-580 кг/м³ досягалася за вмісту 60-70 % ХЗСР і 30-40 % польовошпатового піску за рахунок збільшеної пористості активної дисперсної фази. Підвищення частки польовошпатового піску збільшувало щільність до 800 кг/м³. Використання глинистого піску в межах 30-35 % знижувало густину до 625-650 кг/м³ за рахунок активізації газоутворення і формування розвиненої пористої структури. Максимальна міцність 2,23 МПа досягалася при 100 % ХЗСР завдяки високому вмісту активного кремнезему і синтезу гідросилікатів кальцію. Збільшення частки польовошпатового або глинистого піску знижувало міцність до 1,61-1,66 МПа. Додавання до 1 % NaOH сприяло інтенсифікації газоутворення та активації алюмосилікатних компонентів, покращуючи розподіл пір і підвищуючи міцність при зниженні щільності. Макроструктурний аналіз підтвердив, що застосування піску дрібних фракцій ($\leq 0,315$ мм) забезпечує рівномірну пористу структуру, покращуючи міцність і теплоізоляційні властивості матеріалу, в той час як великі фракції викликали структурні дефекти і зниження характеристик. Практична цінність роботи полягає в можливості застосування розроблених складів у малоповерховому та сільському будівництві, при виробництві легких стінових блоків в умовах малого та середнього бізнесу, а також для розширення використання місцевих мінеральних відходів у будівельній галузі з одночасним зниженням екологічного навантаження

Ключові слова: пориста структура; мінеральні добавки; розподіл пір; структурна міцність; лужна активація; теплоізоляційні властивості

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Architectural and structural decor of Lviv tenement houses in the late 19th and early of the 20th centuries

Abstract. Valuable historical buildings in Ukrainian cities, particularly in Lviv, that do not have architectural monument status are sometimes overlooked by architects and restorers. The physical deterioration of materials and structures, neglect of roofs, and damage to drainage and sewage systems have resulted in significant façade degradation. This study aimed to assess the preservation of architectural and structural elements on the façades of Lviv's artificial stone buildings, evaluate their structural stability, and formulate scientifically grounded recommendations for their restoration. The methodology was based on general scientific and specialised research methods. Through analysis, synthesis, systematisation, and generalisation of bibliographic materials, the research establishes the current state of knowledge on the topic and summarises and expands the available information on the formation of architectural monuments of the late 19 and early 20th centuries, as well as their architectural and decorative solutions. The most significant architectural and structural decorative elements of Lviv's townhouses from the first half of the 20th century are identified using systematic analysis and specialised research methods, including graphical comparison, retrospective modelling, and architectural composition. For a high-quality restoration that preserves the authentic substance of these buildings, it is essential to study the architectural and structural decor of Lviv's townhouses in detail. Restoration work should integrate modern technologies and materials, and restorers should apply innovative approaches that align with contemporary architectural and construction practices

Keywords: historic residential buildings; elements and details; artificial stone; reconstruction; façade renovation

INTRODUCTION

The historical significance of artificial stone in architecture during the late 19th and early 20th centuries represents a crucial phase in the evolution of building technologies and architectural styles. This material not only transformed

construction and design methods but also played a pivotal role in shaping the urban landscape. However, as of 2025, a comprehensive study of its technical, aesthetic, and functional aspects remains lacking.

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Scientists such as M. Bevcz(2022), in their preliminary studies on the conservation of the interiors of the Main Building of Lviv Polytechnic National University, note that the first half of the 20th century witnessed significant architectural transformations, with the use of artificial stone emerging as one of the most important innovations. They also demonstrate that this period was characterised by the search for new materials and technologies that would allow the creation of more dynamic, functional, and aesthetically pleasing buildings. A detailed examination of the study's relevance underscores its importance in the historical, technical, cultural, and socio-economic contexts, as well as its significance for contemporary architecture and heritage conservation.

The study by M. Demkiv & I. Pohranychna (2022) identifies the reasons for the reconfiguration of historic residential buildings, the stages involved in developing a reconstruction project, and an analysis of the regulatory documents governing the reconstruction of the historic housing stock. The paper notes that reconfiguration and reconstruction projects for apartments can only proceed after evaluating the building's technical condition, structural framework, inventory plans, surrounding environment, and roof structures. The initial phase of field surveys is particularly crucial, as the final reconstruction project cannot be developed without high-quality data from this stage.

Research by M. Demkiv & S. Popova (2021) and A. Merezko (2023) examines experiences in the reconstruction of historic façades and their decorative elements. According to M. Demkiv & S. Popova (2021), in European countries, the share of investment in reconstruction in total investment is lower or equal to the investment in new buildings. However, the cost of new construction in Europe is considerably higher than that of reconstruction or modernisation of existing housing. For example, in Austria, 45,000 new housing units are built annually, whereas 100,000 existing units undergo renovation. In Finland, investments in housing reconstruction account for about half of all construction expenditures and are projected to increase significantly. Between 2016 and 2025, they are expected to reach 1.9 billion EUR annually. In France, two-thirds of investments are allocated to reconstruction, while the remainder goes to new buildings. In Germany, 62% of investment is directed towards the reconstruction of existing residential buildings, with the remaining 38% allocated to new construction. In the Netherlands and Sweden, the number of renovated housing units is twice that of newly built ones. In Switzerland, modernised homes also outnumber newly constructed buildings. A. Merezko (2023) examines the history of historic building renovation outside Ukraine and identifies financial programmes and grants used in European countries and America. The study highlights the primary renovation methods most commonly employed in Europe and the United States.

Researchers D. Moroz *et al.* (2022) investigate the use of natural materials in architecture. They emphasise that in the 21st century, the issue of preserving natural resources

is particularly pressing, making the use of artificial substitutes in construction and architecture increasingly relevant. Innovative technologies enable the use of artificial stone for both new construction and reconstruction. An analysis of the literature suggests that a project for the conservation of the architectural and structural decor of Lviv townhouses from the first half of the 20th century requires an integrated approach, ranging from the training of specialists in the field of conservation to the development of professional conservators. This perspective is supported by the research of K. Cherkasova (2021), whose article explores the historical, theoretical, scientific, and practical aspects of architectural and restoration activities, particularly concerning the evolution of architectural and conservation education in Ukraine. The training of specialists in the conservation of immovable heritage is a crucial aspect of higher architectural education, given the need to develop research, design, and production expertise in this field.

This study aimed to analyse the previous research in this field, assess the technical condition of the façades of Lviv townhouses from the early 20th century, identify the types and causes of architectural and structural decor deterioration, and develop recommendations for the conservation and preservation of architectural, structural, and stucco decor on these façades.

LITERATURE REVIEW

Published works in the fields of art history and architectural theory focus on the study of architectural decor, its classification, and its stylistic characteristics. An analysis of the academic literature on architectural decor, its classification, and stylistic approaches reveals a lack of research in this area in Ukraine. The classification of architectural decor and the definition of its key elements are presented in the articles of V. Tymofienko (2002) and I. Kreizer (2014). The body of sources highlighting the main factors and prerequisites, characteristic features, compositional aspects, and other distinctive elements of early 20th-century townhouses' architectural and structural decor includes the study of Yu. Zakharov *et al.* (2019) examined the specifics of residential building reconstruction across various structural systems. The reconstruction of historic residential buildings and façade renovation has been widely studied. H. Onyshchuk (2004) and I. Novosad (2015) analyse the experience of historic residential building reconstruction in European countries. Written sources describing the authentic and present-day condition, history of construction, and transformation of early 20th-century townhouses, along with their architectural and decorative features, include the research by M. Bevcz (2013). In particular, the author provides examples of buildings that confirm the widespread use of Roman cement in decorating the façades of public and residential buildings in Lviv during the second half of the 19th century.

The article by F. Fatiguso *et al.* (2013) describes a general methodology for studying artificial stone façades constructed between the 19th and 20th centuries, focusing on



selection criteria and the correlation of diagnostic methods. Researcher R. Kotiv (2011) conducted a detailed study on the manufacturing technology and characteristics of artificial stone, particularly Roman cement, used on the façades of Lviv townhouses. Artificial stone was frequently used to create unique decorative elements on façades. There remains insufficient research on how this material has influenced architectural and structural forms, as well as its integration with other building materials and techniques. Artificial stone emerged as a result of innovations in materials science, enabling the production of materials with desirable properties such as strength, ease of processing, and aesthetic appeal. This facilitated new opportunities for architectural experimentation and creative solutions. Due to its unique properties, artificial stone has had a significant impact on architectural design solutions. This material enabled the realisation of more complex architectural forms and structures that would not have been possible with traditional materials.

M. Demkiv & I. Pohranychna (2022) outline the stages of investigating historic residential buildings in their research. They note that a survey of the technical condition of a residential building is conducted to establish the degree of physical deterioration, assess the load-bearing capacity of structures, and, if necessary, develop measures to reinforce these structures, stabilise the soil beneath the foundations, and strengthen the foundations themselves. The scientific and practical aspects of restoration incorporate the works of researchers in theory and practice across all forms of fine arts and architectural restoration, as well as applied sciences such as construction, materials science, and engineering. For instance, it was found that the sculptural decor of Renaissance townhouses has been examined by O. Rybchynskyi (2022) and S. Linda & O. Kulynska (2023). Based on scientific research and practical restoration work, the development stages of the townhouses at 4 Rynok Square and 23 Rynok Square have been identified. Their architectural and structural features, along with the principles of façade conservation, are highlighted.

The technologies and methods for reproducing façade decoration using artificial stone are examined in the articles of G. Sheliong *et al.* (2012) and M. Bezv *et al.* (2022). The researchers note that through the study of archival materials and field research, it has been determined that in the late 19th and early 20th centuries, building mixtures based on Roman cement were widely used in western Ukraine. To ensure the preservation of architectural and structural decor, it is essential to restore historical buildings using a comprehensive scientific approach. This includes thorough research, the development of appropriate new materials, and the careful selection of materials when used on suitable for valuable historical sites.

MATERIALS AND METHODS

A comprehensive methodology for studying the reproduction of architectural and structural elements made of artificial stone in Lviv townhouses from the late 19th to the early

20th century is founded on two types of scientific methods: general scientific methods and specialised scientific methods. In this study, the following general scientific methods were employed: analysis, synthesis, comparison, systematisation, classification, and generalisation. Additionally, the following specialised methods were applied: visual inspection, system analysis, graphoanalytical comparison, retrospective modelling, three-dimensional analysis, and comparative historical synthesis. The initial objective of studying townhouses from the first half of the 20th century was to review the scientific literature and assess the extent of research on this topic. To achieve this, the general scientific methods of comparison, analysis, and synthesis were utilised. Subsequently, research objects were selected for in-depth analysis. A list of buildings constructed with Roman cement was compiled for further study. For a detailed analysis in this article, residential buildings located at 1-19 S. Krushelnytskoi Street in Lviv were selected.

After identifying the research objects, the state of preservation and functional use of the townhouses from the first half of the 20th century were examined. During field research, visual inspection and photographic documentation methods were applied, while desk-based research employed analytical techniques such as systematisation, generalisation, comparison, graphoanalytical comparison, and systemic and structural analysis of object integrity. Additionally, retrospective modelling was conducted. Field and desk-based studies were carried out in parallel, complementing one another. The collected information on the studied townhouses was systematised to facilitate further source analysis. As part of historical and archival research, attention was given to previous studies as well as cartographic and iconographic materials.

During field research, visual inspection was conducted to gather comprehensive data on the existing buildings within the studied complexes, including the number of storeys, structural conditions, causes of deterioration, visual qualities, land use, and terrain characteristics. Findings from the visual inspection were recorded using sketches, diagrams, and photographic documentation to support subsequent desk-based and analytical research. This approach helped ensure a comprehensive examination of the deterioration of artificial stone elements on building façades from the first half of the 20th century. During photographic documentation, particular attention was given to decorative and stylistic elements, architectural details, material losses, and the condition of individual features. Characteristic forms of deterioration and challenges related to the preservation of architectural and structural elements made of artificial stone were also documented.

The abstraction method was employed to analyse proportioning systems, architectural and decorative features, and compositional techniques. This method involves systematically eliminating nonessential properties, connections, and relationships while identifying and recording the most significant characteristics of buildings from the first half of the 20th century. Abstraction enables complex



structures to be simplified without losing their fundamental attributes, thereby allowing for a clearer understanding of key architectural elements.

RESULTS AND DISCUSSION

Most historic buildings in Ukrainian cities are residential structures built between the 1860s and 1910s. This period of industrial growth brought about significant transformations, leading to substantial changes in the architectural landscape of many historic cities within just half a century. The central component of urban complexes and ensembles was the tenement house (Vereshko *et al.*, 2019). The tenement house became the most widespread architectural form in 20th-century capitalist cities, functioning not only as a multi-purpose building combining housing, shops, and various institutions but also as a source of income generation. In the challenging conditions of the market economy, apartment buildings emerged as the most practical type of housing, a role they continued to fulfil in the early 21st century. Various layout configurations were employed in tenement houses – rectangular, L-, T-, U-, and H-shaped – depending on the dimensions and positioning of the plot. At the turn of the 19th and 20th centuries, urban development in Ukraine was particularly characterised by single-section apartment buildings, typically T-shaped or rectangular, with two apartments on each floor.

Due to population growth in Ukrainian cities in the early 20th century, there arose a pressing need to provide housing for the general population. During this period, large multi-sectional residential buildings with substantial architectural volumes and courtyard wings extending deep into the plot began to appear. To mitigate overcrowding, developments incorporated compact geometric layouts and complex planning solutions featuring multiple courtyards. In the early 20th century, apartment architecture increasingly favoured the construction of large residential quarters or housing complexes. This trend was facilitated by the acquisition of small, fragmented plots by wealthy developers – either companies or individual owners – who consolidated them into larger, more practical parcels. A common urban planning approach involved the creation of an elongated open-front courtyard, around which residential volumes were arranged. In Ukraine, this type of apartment development was limited to major cities with well-established industrial bases. A distinguishing feature of perimeter-block developments, which primarily comprised apartment buildings, was the consistent rhythmic arrangement of façades elements, creating a unified streetfront composition. This continuity was punctuated by architectural accents such as bay windows, towers, domes, balconies, and decorative sculptures. As a result, the primary façades formed a decorative screen distinct from the overall structure, embodying a specific architectural style. In contrast, courtyard façades – unlike the highly ornamented front façades, which served as a visual

representation of the owner's status – were typically understated, featuring minimal or no decorative elements.

The ground floors of tenement houses frequently accommodated commercial establishments, such as shops, offices, and workshops, while basements were utilised for warehouses, laundries, and other service spaces. The most desirable apartments were typically located on the second or third floors, while furnished rooms were often positioned on the upper levels. Great attention was given to the design of residential interiors and the main staircase. Interior decoration commonly featured stucco ceiling mouldings, ornamental metalwork in staircase railings, carved doors, decorative stoves, and fireplaces (in the absence of steam heating). Thus, the decoration of these buildings followed a tripartite compositional principle (Fig. 1):

- 1st level – at the level of visual perception from the pavement, extending to the plane of the plinth and the first floor, this zone is vertically limited by the inter-floor cornice of the second floor. It represents the primary zone of active perception, emphasised by rusticated framing around windows and door openings and further accentuated by colour contrasts. Key architectural attributes that contribute to the individuality of each building include shopfronts, signage, nameplates, entrance doors, gates, and passageways;

- 2nd level – the wall space above the primary visual perception zone extends up to the cornice and serves as the canvas for individual stylistic and artistic expressions. Decorative elements include variations in window geometry, stucco mouldings, and painted window frames. During the Austrian period, two distinct shades of ochre were designated for Lviv, reflecting its status as an eastern capital in façade painting traditions;

- 3rd level – the cornice of the building forms the transition between the wall and the roof. Positioned above the ceiling of the top floor, it is distinguished by a horizontal band, a frieze with dormers, and a projecting cornice adorned with decorative elements that create a sculptural relief, casting shadows beneath the roofline. Cornices and pediments serve as defining architectural elements that complete the composition of the façade (Kupranets & Pohranychna, 2024).

The historic buildings from the early 20th century are richly decorated with stucco and sculptural elements, which deteriorate over time due to environmental exposure and building use (Table 1). Additionally, the architectural and structural decor of Lviv townhouses is frequently damaged due to substandard restoration and repair work. To preserve these elements, a comprehensive inspection by specialists with the requisite education and expertise is essential. Such assessments typically commence with a visual examination of all exterior and façade walls, followed by an inspection of interior surfaces. Throughout this process, façades are systematically photographed, with each image documented by date.

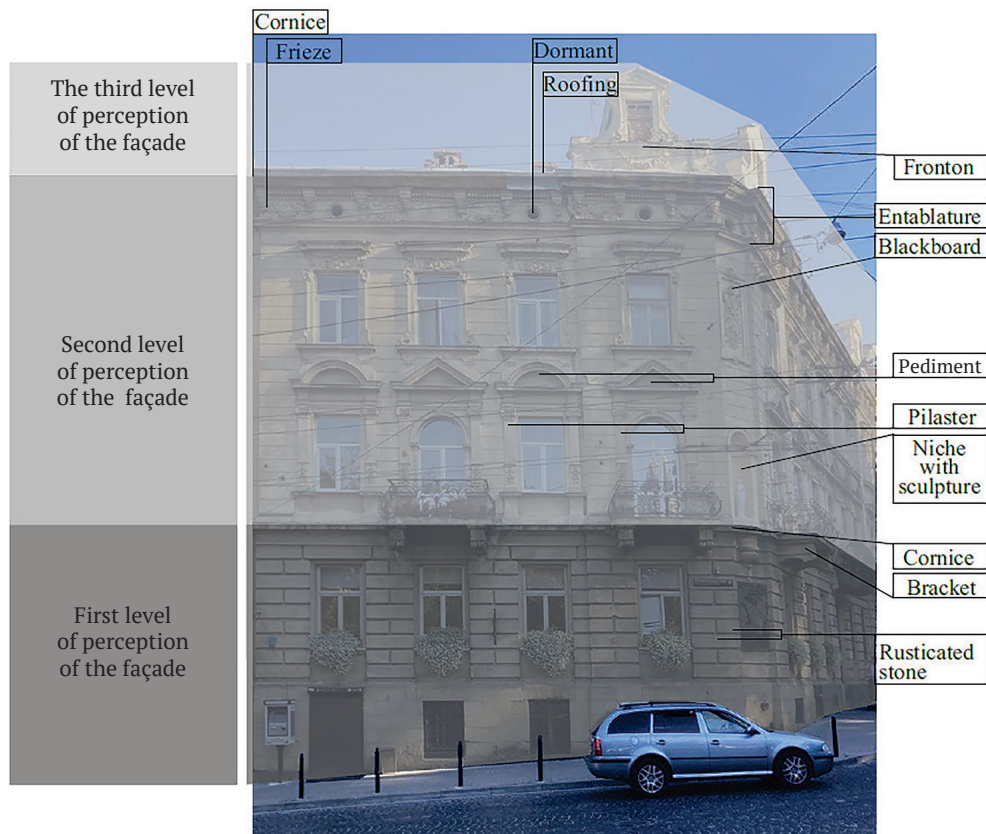


Figure 1. Architectural and constructive decor of Lviv townhouses from the first half of the 20th century

Source: compiled by the authors

Table 1. Examples of deterioration to architectural and structural elements of façades

Field of perception of the façade	Type of deterioration	Photo
1 st level of façade perception (the plane of the basement and the first floor)	- soaking and delamination of plaster - erosion of rusticated surfaces - destruction of the inter-floor cornice - damage to sculptural elements - loss of stucco decoration	

Table 1. Continued

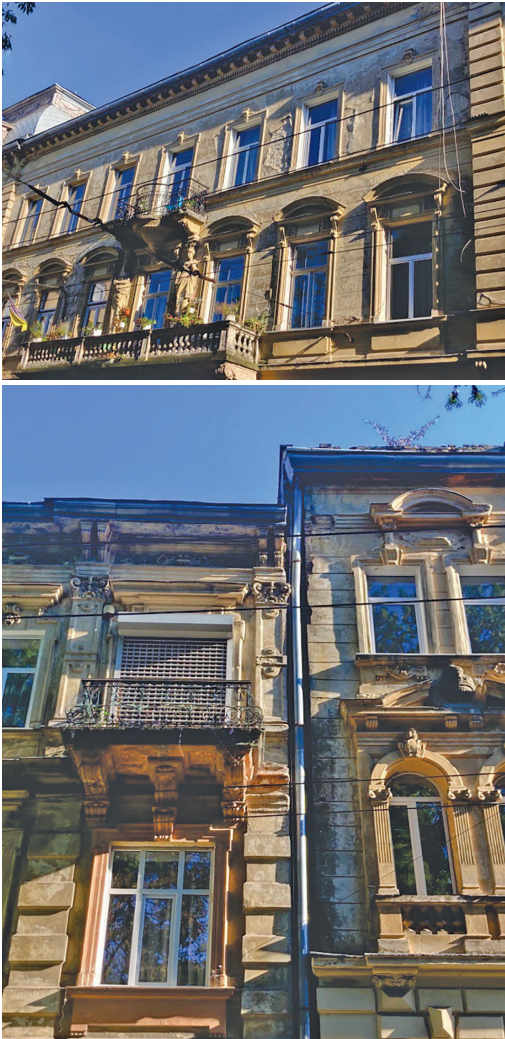
Field of perception of the façade	Type of deterioration	Photo
1 st level of façade perception (the plane of the basement and the first floor)	- soaking and delamination of plaster - erosion of rusticated surfaces - destruction of the inter-floor cornice - damage to sculptural elements - loss of stucco decoration	
2 nd level of façade perception (wall space above the primary visual perception zone, extending to the roof eaves)	- soaking and peeling of plaster - loss of stucco decoration	



Table 1. Continued

Field of perception of the façade	Type of deterioration	Photo
2nd level of façade perception (wall space above the primary visual perception zone, extending to the roof eaves)	- soaking and peeling of plaster - loss of stucco decoration	
3rd level of façade perception (the section of the façade above the eaves, forming the boundary between the wall and the roof)	- deterioration of the corbeled cornice - damage to the roof covering - failure of the drainage system	

Table 1. Continued

Field of perception of the façade	Type of deterioration	Photo
3 rd level of façade perception (the section of the façade above the eaves, forming the boundary between the wall and the roof)	- deterioration of the corbeled cornice - damage to the roof covering - failure of the drainage system	

Source: compiled by the authors

In the context of preliminary studies required for the development of a restoration project, photography serves as a highly effective method of documentation, capturing an accurate and comprehensive visual record in a short period. However, it is crucial to avoid taking photographs from extreme angles, as this distorts building proportions. Additionally, diffused lighting conditions provide better image quality than high-contrast lighting. Where possible, photographs should be taken in a nearorthogonal manner to ensure accuracy in documenting both entire façades and individual details or fragments. Furthermore, to accurately determine the proportions or dimensions of a building, it is advisable to include a reference object such as a measuring scale, a person, or a study marker in the frame.

During photographic documentation, attention should be given to both the overall appearance and key architectural accents of the exterior and interior. Additionally, a detailed focus on smaller elements, layered structures, or areas of damage will facilitate a comprehensive assessment of the building's condition. Particular records should be made of historical architectural elements and remnants of decorative finishes that have been preserved in attics, basements, or concealed within later modifications, as well as the materials from which they were constructed. The next stage of the building assessment involves a detailed examination of structural damage, including the condition of the masonry walls, the presence of cracks, and the structural integrity of load-bearing elements.

During the inspection, existing technical documentation should be cross-referenced with the building's actual condition, and necessary corrections should be made

where discrepancies arise. Additionally, damage locations for specific architectural elements should be recorded. The presence of essential infrastructure systems, including sewerage, water supply, boiler room facilities, gas supply, air conditioning, heating, and ventilation networks, should also be assessed. To conduct a thorough survey, it is essential to establish the building's construction date. This can often be determined from inscriptions or plaques embedded in façades during construction. In the absence of such markers, historical research and archival materials should be consulted to verify the building's period of construction.

A critical evaluation should be conducted to assess the preservation of the building's aesthetic integrity. Historic buildings have often undergone modifications, sometimes repeatedly, and in many cases, insufficient care has been taken to maintain the compositional and stylistic unity of the façades. Therefore, when inspecting a building, it is essential to identify and document historical layers, additional storeys, extensions, basement deepening, changes in the building's function, roof configurations, façade alterations, and other modifications. These include the creation or sealing of window and door openings in the main walls, as well as other structural changes. Architectural surveys should be accompanied by the following documentation: survey plan drawings indicating the nature of masonry joints, locations of test soundings, and sampling sites for mortar analysis; a façade cartogram detailing areas of material loss and variations in mortar types; measurements of test soundings recorded in a log, supplemented with photographic documentation (Chen & Hnidec, 2015).



Before commencing external cladding work, all activities that may damage the cladding surfaces must be completed. The texture of the cladding should replicate the original material as closely as possible. During the repair and restoration of the façade with natural stone, the upper edges of protruding granite elements (such as cornices, string courses, and pediments) should be inclined outward to facilitate water drainage. In cases where the façade cladding consists of ceramic or other types of slabs, the front surface must be free from efflorescence, stains, mortar residue, and cracks. Additionally, the joints between slabs should be smooth, and surface imperfections such as notches, edge chips exceeding 0.5 mm in depth, and corner damage should not be present (Senkovskiy *et al.*, 2011).

Paint mixtures should serve not only a decorative function but also a protective function one concerning the façade of the heritage structure. The following requirements apply to the paint coatings used on such façades: vapour and air permeability; weather resistance (resistance to solar radiation, atmospheric pollutants, weathering, temperature fluctuations, and industrial emissions); strong adhesion; a decorative appearance that aligns with the building's historical character; a colour scheme that is historically appropriate both to the building and its surroundings. Paints and coatings are classified as either aqueous or non-aqueous. The painting of heritage façades should be carried out as the final stage of the restoration process. It is imperative to avoid the use of finishing materials that may later contribute to the deterioration of authentic plaster, masonry, or decorative elements. Painting should commence no sooner than 14 days after the plaster application, crack-filling, and embedding processes have been completed.

Restoration and conservation works for architectural and stucco decoration should be carried out based on a comprehensive, developed, and approved project plan and technological procedures. Stucco work should adhere to working drawings and correspond to the original form and material. Depending on the degree of preservation of stucco elements on architectural monuments, it is permissible to undertake restoration and conservation of the original forms and decorative features, and reproduction of lost elements. According to restoration guidelines, damaged stucco components should be restored, supplemented, or replaced with new ones. To restore gypsum stucco, the "doping" method is applied, which involves the application of gypsum mortar to the damaged areas (DBN V.3.2-2-2009, 2010). For external stucco elements, materials must be waterproof, or adequate protection against water absorption should be provided using hydrophobic solutions. All actions to restore decorative elements should be reversible and utilise materials and technologies appropriate to the historical style and period of the structure. For tinting gypsum elements to resemble bronze, cast iron, ivory, wood, marble, or other materials, artistic oil paints diluted with drying oil, turpentine, or varnish should be used. To protect stucco elements, waxing is necessary; beeswax diluted in turpentine is commonly used. Wax coatings

provide hydrophobic protection. On façades, stucco elements and projecting components must be shielded from damage and weathering by covering them with galvanised roofing iron, copper, or a layer of protective paint. If ferrous iron is used, it must be oiled and coated two or three times with oil-based or waterproof paint. After drying, the stucco should be primed with a light oil mixture containing whitewash, followed by two or three coats of oil paint or a hydrophobic solution.

In his research, the scholar I. Kreizer (2014) argues that decorative elements in architecture have played a fundamental role since antiquity, serving as symbols, carriers of encoded information, and essential components of architectural composition. Such conclusions reinforce the importance of preserving and restoring architectural and structural decoration on the façades of historic buildings. As of 2025, particularly during the Russian-Ukrainian war, the issue of preserving the authenticity of Ukrainian culture has become especially urgent. F. Fatiguso *et al.* (2013), as well as M. Demkiv & S. Popova (2021), discuss examples of the reconstruction of historic buildings in Europe and America. However, these studies do not examine the conservation of exterior façade decoration; instead, they provide predominantly descriptive accounts and do not explore the specific features of stucco decoration conservation on historic façades.

Researchers Yu. Doroshenko & A. Merezko (2020) assert that the renovation of the outdated housing stock is a critical issue for Ukraine, addressing which would facilitate the modernisation of the country's residential infrastructure, enhance living standards, extend the lifespan of buildings, and conserve national resources by improving energy efficiency. However, their research lacks graphic examples of such modernisation, which limits a comprehensive understanding of how the architectural and structural elements of buildings are preserved.

The scientific study of T. Grøntoft (2017) analyses the costs of conserving and renovating limestone façades in Kraków, Poland, focusing on damage caused by weathering, air pollution, and periodic exposure to aggressive atmospheric conditions. Although this topic is highly relevant, the study does not address the specific challenges associated with restoring stucco decoration on historic façades, which is the primary focus of this research. Instead, L. Chen & R. Hnidec (2015) offer detailed explanations of repair and conservation techniques for architectural monuments, providing recommendations ranging from the preservation of archaeological sites to the conservation of masonry and architectural decor.

A comprehensive study of artificial stone elements requires an interdisciplinary approach that integrates knowledge from architecture, art history, chemistry, and engineering. Such an approach is essential for further research aimed at expanding the understanding of material properties, environmental impact, and mechanisms of deterioration. A well-rounded understanding of these issues will support the development of conceptual and methodological



frameworks for the reconstruction of architectural and structural decor using both traditional and modern materials.

CONCLUSIONS

The use of artificial stone in the late 19th and early 20th centuries to adorn buildings represented an innovative and progressive stage in the development of architectural plasticity, particularly in Lviv. This method enabled the creation of complex architectural forms more quickly, at a lower cost, and with a high level of aesthetic appeal and durability. The concept of artificial stone is broadly defined and includes composites of various materials, with a particular emphasis on novelty cement decor. Based on the analysis of the technical condition of buildings, it has been demonstrated that, as of 2025, the preservation and restoration of decorative architectural elements on façades remain highly pressing issues. The exposure of architectural monuments to an aggressive urban environment requires a comprehensive, research-driven approach to both the study and application of new materials in restoration efforts. Over more than a century of use, Lviv's historic buildings have exhibited various forms of façade damage, including cracks, plaster deterioration, and the loss of decorative elements or their components. Prior to undertaking restoration work, thorough scientific research should be conducted, incorporating an analysis of the technical condition and architectural, as well as the compositional features of the building.

During the restoration or preservation of masonry surfaces and architectural and contouring decor in Lviv townhouses from the late 19th and early 20th centuries, it is essential to consider that the primary objective of these works is to preserve the monument's authenticity to the greatest extent possible, along with the features characteristic of specific construction periods that illustrate key historical stages in Ukrainian architecture. Depending on the nature and extent of damage, two approaches to surface restoration may be employed: conservation of historical material through the supplementation of damaged areas with specialist solutions or partial replacement of damaged elements with compatible substitutes, provided that their prototypes exist. All work must adhere to a pre-approved restoration project and comply with the relevant technologies. Further studies will explore the technological aspects of artificial stone conservation, contributing to the preservation of the authentic appearance of Lviv townhouses from the early 20th century.

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Архітектурно-конструктивний декор львівських кам'яниць кінця XIX – початку XX століття

Анотація. Цінні історичні будівлі в українських містах, зокрема у Львові, які не мають статусу пам'ятки архітектури, іноді залишаються поза увагою архітекторів та реставраторів. Фізичний знос матеріалів і конструкцій, занедбаність дахів, пошкодження дренажних і каналізаційних систем призвели до значної деградації фасадів. Метою цього дослідження були оцінка збереженості архітектурно-конструктивних елементів на фасадах будинків зі штучного каменю міста Львів, визначення їхньої конструктивної стійкості та розробка науково обґрунтованих рекомендацій щодо їхньої реставрації. Методологія дослідження ґрунтувалася на загальнонаукових і спеціальних методах дослідження. Шляхом аналізу, синтезу, систематизації та узагальнення бібліографічних матеріалів, встановлено сучасний стан вивчення теми, узагальнено та розширено наявну інформацію про формування пам'яток архітектури кінця XIX - початку XX ст., а також їх архітектурно-декоративне вирішення. За допомогою системного аналізу та спеціальних методів дослідження, зокрема графічного порівняння, ретроспективного моделювання та архітектурної композиції, визначено найбільш значущі архітектурні та конструктивно-декоративні елементи львівських таунхаусів першої половини XX ст. Для якісної реставрації зі збереженням автентичної субстанції цих будівель необхідне детальне вивчення архітектурно-конструктивного декору львівських таунхаусів. Реставраційні роботи повинні інтегрувати сучасні технології та матеріали, а реставратори повинні застосовувати інноваційні підходи, що відповідають сучасним архітектурно-будівельним практикам

Ключові слова: історичні житлові будинки; елементи та деталі; штучний камінь; реконструкція; реновація фасадів

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Some iconographic features of the mural paintings in the churches of Vithkuq

Abstract. This study examined the iconographic features of the wall paintings in the churches of Vithkuq in Albania with the aim to explore the origins, evolution, and significance of the iconographic features of the murals. The study focused on revealing the hybrid style of these frescoes, which combine Byzantine, post-Byzantine and local traditions, and also analysed specific iconographic themes such as the “Trinity of Christ” and the “Communion of the Apostles”. The study also revealed how local traditions and external influences are woven into the visual language of these religious artworks. The analysis showed that these frescoes were not simply reproductions of established iconographic types, but rather adaptations that reflected the local theological and cultural context. The study also highlighted the high artistic sensitivity of the frescoes, particularly in terms of their use of colour, composition and symbolism. This study identified the influence of itinerant artists who brought new stylistic elements to the region, contributing to a dynamic exchange of artistic traditions in the Balkans. The results highlighted the challenges of preserving these frescoes due to environmental factors and insufficient restoration efforts. The study offered valuable insights into how local and external artistic traditions intersected in the creation of these paintings, and contributes to a deeper understanding of the social, religious, and artistic dynamics of the post-Byzantine period in the Balkans. It was concluded that the frescoes in the Vithkuq churches are not only important religious works of art, but also key cultural artifacts that reflect the complexity of the region’s historical and theological developments in the post-Byzantine era

Keywords: frescoes; Byzantine influence; Balkan religious art; artistic evolution; cultural heritage

INTRODUCTION

The wall paintings of the churches of Vithkuq, created in the 16th-18th centuries, are a vivid testimony to the artistic, spiritual, and cultural interaction that took place in the territory of modern Southern Albania. Located in the historical region of Korçë, Vithkuq served as a significant centre of Orthodox culture, preserving and transforming the Byzantine artistic tradition under Ottoman rule. Churches of this region, such as St. Nicholas and other local temples, were decorated with frescoes that amaze with the richness of iconographic subjects and the skill of execution, combining Byzantine stylistics with local cultural motifs.

Despite their importance, these post-Byzantine masterpieces have been overshadowed in broader studies of Balkan and European religious art.

The artistic tradition in Vithkuq developed during a complex historical period marked by Ottoman rule, which significantly influenced the social, political, and cultural aspects of the region’s life. F. Zeneli (2023) provides a comprehensive study on how local artisans in Vithkuq navigated the complexities of preserving and reinterpreting Byzantine artistic traditions under Ottoman rule. Their research emphasises that, despite the sociopolitical

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pressures of the period, these artisans managed to uphold the core principles of Byzantine iconography while simultaneously adapting them to the evolving cultural and religious landscape. One of the key challenges they faced was the need to balance adherence to established Orthodox artistic conventions with the incorporation of regional stylistic influences. Author highlights that this adaptation was not merely a passive continuation of earlier artistic norms but rather an active process of transformation, in which canonical subjects and stylistic elements were recontextualised to resonate with local cultural sensibilities.

T. Shkira (2022a; 2022b) conducts an in-depth examination of the artistic evolution in Vithkuq, focusing on the region's distinctive fresco tradition. The researches highlight how local artisans managed to maintain the fundamental principles of Byzantine painting while simultaneously incorporating regional folk motifs, symbols, and ornaments. This process was not merely an act of preservation but rather a dynamic reinterpretation that allowed Vithkuq's frescoes to develop a distinctive character. The author argues that the integration of vernacular elements, such as stylised floral patterns, geometric designs, and locally significant iconographic details, reflects the socio-cultural context of the period. The studies also underscore how these adaptations reinforced communal identity by visually linking sacred spaces with the artistic expressions of everyday life.

A broader understanding of Vithkuq's artistic development necessitates engagement with research on post-Byzantine art, particularly regarding the influence of the Archbishopric of Ohrid and the Gramos School of Art. As noted by I. Vitaliotis & A. Palushi (2022), these artistic institutions were instrumental in shaping sacred art in Albania and neighboring regions. Their study explores how the Archbishopric of Ohrid functioned as a major ecclesiastical and cultural hub, facilitating the transmission of artistic techniques and theological themes across different Orthodox communities. The authors emphasise that the Ohrid school was particularly influential in preserving Byzantine artistic traditions while also fostering localised stylistic variations. A significant contribution to the study of Albanian painting is made by R. Rousseva (2011), who examines the works of renowned artists such as Onufri, Constantin Shpataraku, and David Selenikasi. In her view, their works are not only artistic masterpieces but also serve as valuable sources for understanding the spiritual life, values, and ideology of the time. Analysing their artistic legacy, she underscores the high level of artistic skill and aesthetic culture in Albania from the 16th to the 18th centuries.

Previous studies of the artistic heritage of the Balkans have mostly been limited to general stylistic analyses or thematic classifications of religious art. M.A. Rossi & A.I. Sullivan (2023) focused on the persistence of Byzantine motifs, such as depictions of the life of Christ, saints, and liturgical scenes, and on the adaptation of these subjects to the specific needs of local communities. At the same time, these analyses have often lacked a deeper dive into the

unique features of individual regions, particularly Vithkuq. Its artistic heritage is distinguished by a specific iconography that reflects the complex interaction between traditional aesthetics and local artistic practices, which gives its study a special relevance. The Vithkuq frescoes represent not only artistic, but also cultural, social and spiritual value. They testify to an attempt to preserve Orthodox identity in difficult historical conditions and at the same time develop art that met the needs of the local population. However, the lack of attention to this aspect in modern research highlights the need for a more focused analysis that would not only document this heritage, but also expand understanding of the dynamics of post-Byzantine art in the Balkans.

The iconography of the frescoes reflects a complex interplay of cultural and socio-political factors (Nesterenko, 2024). Scenes such as the Passion Cycle and depictions of local saints illustrate how the artisans of Vithkuq negotiated between canonical Byzantine themes and local narrative traditions. Scholars such as I. Vitaliotis (2021) have pointed to similar processes in the artistic traditions of neighbouring regions, suggesting a broader network of influences that extended to Vithkuq. However, questions remain about how this dynamic is uniquely manifested in the Vithkuq frescoes. Another pressing issue is the physical preservation of these works of art. Environmental and anthropogenic factors, including neglect and inadequate conservation practices, threaten their longevity (Zhangabay *et al.*, 2023). Research into the mechanisms of decay in post-Byzantine churches highlights the urgency of developing sustainable conservation strategies. The Vithkuq frescoes, which are often housed in remote and poorly maintained buildings, are an example of these challenges. Addressing these challenges requires interdisciplinary approaches that combine art historical analysis with conservation science.

In summary, the research aimed to answer key questions about the origins, development, and meaning of the iconographic features of the Vithkuq murals. The research objectives were to: examine how these works of art reflect the intersection of Byzantine heritage and local traditions; uncover the sociocultural identity of the Vithkuq community through the murals; developing strategies that can be applied to ensure the preservation of wall paintings for future generations.

MATERIALS AND METHODS

To achieve the aim of this study, a systematic approach was applied to the analysis of existing scientific literature, visual documentation and conceptual frameworks related to post-Byzantine wall paintings and their socio-cultural significance. This approach provided a comprehensive understanding of how the wall paintings in the churches of Vithkuq reflect the intersection of Byzantine artistic heritage and local traditions, and helped to reveal their socio-cultural role and develop conservation strategies. The study was carried out in 2024 and focused on the analysis



of the iconographic features of these works, their thematic aspects, stylistic elements and symbolic content, as well as the challenges associated with their conservation.

The theoretical framework of the study integrated concepts from art history, cultural heritage studies and conservation methodology. The basis was established theories of iconography and post-Byzantine art, especially those concerning the interaction between ecclesiastical traditions and local artistic influences. This foundation was enriched by contemporary research on the sociocultural function of religious art, which allowed for a deeper interpretation of the role of frescoes in the formation of the community identity of Vithkuq. The criteria for selecting sources gave preference to materials that highlight post-Byzantine art in the Balkans, with a focus on the analysis of iconographic themes and the influence of regional factors on artistic creativity.

A systematic literature review was conducted to identify the main trends and gaps in the research on the Vithkuq murals and similar examples in the Balkans. The review included international and regional perspectives, ensuring a holistic understanding of the context. The search was conducted in databases such as JSTOR, Scopus and Google Scholar, using the keywords: “post-Byzantine wall paintings”, “iconography in Vithkuq”, “religious art of the Balkans”. Priority was given to publications from the 2019-2024 period, taking into account fundamental research in the field of post-Byzantine art and iconography. The materials used in the study covered a wide range of academic sources, historical records, and visual documentation. Archival materials provided detailed information about the iconographic programs of the frescoes, while visual records, such as photographs and sketches, allowed for a deeper study of their stylistic and compositional features. To uncover the sociocultural identity of the Vithkuq community, themes such as the depiction of local saints, the integration of folk elements, and the adaptation of canonical Byzantine subjects to local religious and cultural needs were explored. The analysis showed how the frescoes functioned not only as religious artifacts, but also as expressions of community values and identity.

Conservation strategies were examined through the lens of modern methodologies in the field of art conservation. State-of-the-art conservation researches were analysed and conservation methods described to identify effective approaches to ensuring the longevity of the Vithkuq paintings. Particular attention was paid to minimising environmental impact and applying the latest technologies for monitoring and restoration.

RESULTS

In the 17th-18th centuries, the growth of large-scale church buildings in Vithkuq and their rich decoration were the result of a multifaceted interaction of social, political, religious and artistic factors typical of the wider Balkan region or South-Eastern Europe during the period of Ottoman rule (Tzedopoulos, 2023). This period was defined by complex political realities, when Orthodox communities under

Muslim domination sought ways not only to preserve their identity, but also to emphasise their own spiritual autonomy. It is in this context that the churches of Vithkuq became the embodiment of the resilience of the Orthodox tradition and its ability to adapt to new conditions.

Among the numerous churches built during this period in Vithkuq, only a few have preserved sufficiently clear fresco paintings and iconographic programs that allow for a full-fledged analysis. These frescoes, although developed within the framework of the post-Byzantine artistic canon, demonstrate unique local features that testify to the creative approach of the artists to solving artistic problems. In this region, elements appear that harmoniously combine traditional Byzantine subjects with local details, which makes Vithkuq a special example of the synthesis of sacred art and socio-cultural environment.

The frescoes of Vithkuq churches created during the Ottoman period served a dual function. On the one hand, they were an integral part of the religious life of the community, contributing to spiritual upliftment and support of faith. On the other hand, they served as an important means of preserving an original culture and historical memory, allowing the local population to identify themselves as a community with a unique heritage in conditions of foreign pressure. These images reflected not only religious themes, but also local traditions, everyday life and even political realities.

One of the most impressive compositions is the fresco of the altar area of the Church of St. Michael in Vithkuq, depicting the Annunciation of St. Anne. Located high on either side of the scene of the Holy Liturgy, it was created in 1728 and is distinguished by a clear structure that gives the plot a monumentality. Unlike similar images in the churches of Ohrid or the monastery of Osios Loukas in Greece, where symmetrical composition dominates, the Vithkuq fresco demonstrates the dynamics of movement and an emphasis on the emotional component. Local artists apparently sought to make sacred plots closer to the community, adding details that resonated with the everyday life of parishioners (Mihaljević, 2021).

An equally important example is the composition “The Communion of the Apostles”, which contains a unique iconographic detail – Judas, depicted on the left with the devil on his shoulders, moving in the opposite direction from the other apostles (Fig. 1). Such a motif, although rare for post-Byzantine art, is extremely eloquent. It focuses attention on moral weakness and betrayal, while emphasising the idea of responsibility before God and society. The Vithkuq artists sought to achieve not only aesthetic expressiveness, but also symbolic depth that was understandable to parishioners.

The image of Judas with the devil on his shoulder in Vithkuq is distinguished by its expressiveness and versatility, significantly surpassing the similar scene in the church of St. Sophia in Ohrid both in colour variety and compositional complexity (Fig. 2). The Ohrid composition, despite its mastery, remains within the framework of



static symmetry and canonical rigor, which are characteristic of traditional icon painting of that period. In contrast, the Vithkuq scene impresses with its dynamics, which gives the image a special drama. The saturation of colours, smooth transitions and contrasting accents create the effect of depth, and the asymmetrical arrangement of ele-

ments adds energy and movement. In this composition, the artist clearly sought to convey not only the plot basis, but also the psychological tension of the moment, which enhances the emotional impact on the viewer. This makes the Vithkuq scene a unique example of an innovative approach to the visual language of medieval art.



Figure 1. “Communion of the Apostles” Church of Saint Michael, Vithkuq

Source: photo by the author



Figure 2. “Communion of the Apostles” Church of Saint Sophia, Ohrid

Source: photo by the author

Another unique motif is the image of the Three-Faced Christ in the apsidal zone of the Church of Saints Cosmas and Damian, built in 1736 and painted between 1746 and 1750 (Fig. 3). This choice of image differs from the traditional practice, according to which in single-nave Byzantine churches of this period the image of the Holy Mandylion was usually placed in the apse – a symbol of the divine incarnation, which emphasised the immutability of Christian dogma (Studer-Karlen, 2023). In contrast, the Three-Faced Trinity, borrowed from Western European iconography of the 14th century, testifies to the evolution of theological ideas and the readiness of local artists to

integrate new ideas. This composition represents the unity and equality of the three persons of the Holy Trinity, while leaving room for symbolism and abstract interpretation, which was atypical for the Eastern Christian tradition. This choice of image emphasises not only theological flexibility, but also artistic innovation, demonstrating a synthesis of Western and Eastern traditions. It could also have been an attempt to strengthen interfaith dialogue, given the historical context of the 18th century, when the interaction between the Orthodox and Catholic traditions became increasingly active (Gagu, 2023). Thus, this motif is not only an artistic, but also a theological testimony of the era.

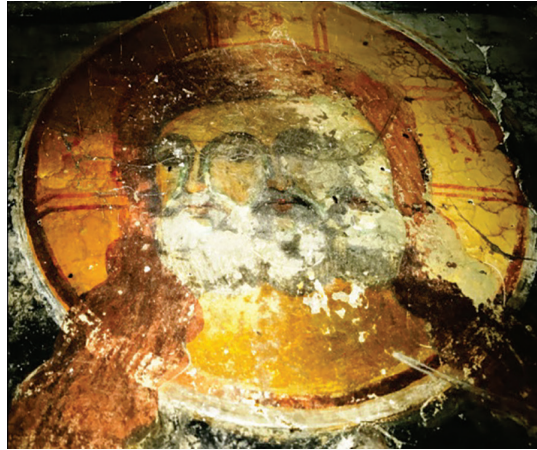


Figure 3. The Three-Faced Christ, Church of Saints Cosmas and Damian, Vithkuq

Source: photo by the author

The domes of the side aisles of the Church of St. Michael are decorated not only with images of heavenly figures, such as the Archangels, St. Mary and St. John the Baptist, but also with martyrs, in particular St. Paraskeva and St. Catherine. The inclusion of these saints in Vithkuq's iconographic programs reflects their widespread veneration in the Orthodox centres of the Ohrid diocese, which indicates a close connection between the local artistic tradition and the general religious trends of the region (Kirchhainer, 2007). The images of these saints not only strengthened the cult identity of the community, but also performed a didactic function, introducing the faithful to examples of holiness and martyrdom. Among the traditional images of standing saints in the full-length frieze of the

Church of St. Michael, the composition *Deisis*, located on the south wall near the iconostasis, attracts special attention (Fig. 4). In the centre of the composition is Christ, surrounded by the Virgin Mary and John the Baptist, who pray for the salvation of humanity. This image, deeply symbolic in nature, resembles a prayer triptych and emphasises the role of the Virgin Mary and John as intercessors standing between humanity and God. The image is characterised by a refined harmony of colours and attention to detail, which give the scene not only spiritual grandeur, but also artistic beauty. The style of the *Deisis* in the Church of St. Michael demonstrates the skill of local artists in combining the traditions of Byzantine iconography with the influences of the post-Byzantine period.



Figure 4. Deisis, Saint Michael, Vithkuq

Source: Kristaq Balli: The symbolic universe of the icon (2024)

A similar arrangement of the *Deisis* scene is found in the Hagia Sophia in Istanbul, where the mosaic composition represents Christ Pantocrator with the Virgin Mary and John the Baptist, creating a solemn mood and emphasising the importance of intercessory prayer (Fig. 5). However, in the context of the Church of St. Michael, this

composition takes on somewhat different characteristics: it is more localised in its iconography, enriched with details that reflect the specifics of the local artistic tradition. For example, the image uses characteristic colour palettes typical of post-Byzantine art, with strong contrasts between gold and red tones, symbolising greatness and sacrifice.



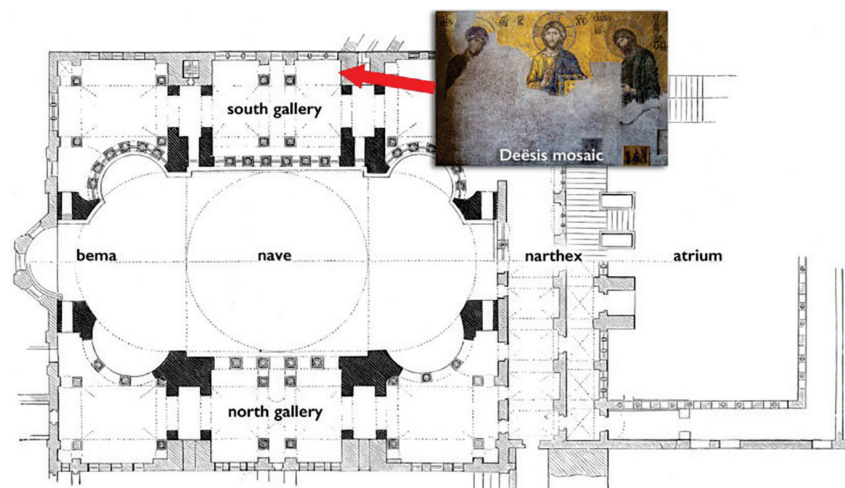


Figure 5. Location of the Deësis mosaic

Source: developed by the author

Historically, the Deësis scene appeared in Byzantine art during the Komnenian period, but it was during the Palaiologoi period that it reached its greatest popularity (Vapheiadēs, 2021). In the post-Byzantine period, this iconographic subject spread to the Balkans, where it adapted to regional artistic styles and symbolism. In the Church of Saint Michael, the Deësis is integrated into the iconographic program of the temple as an expression of key theological ideas: salvation, intercession and divine glory. A special role in the paintings of the churches of Vithkuq is played by saints supported by the Ohrid Patriarchate, which emphasises the close connection between religious policy and the artistic tradition of the region (Belba, 2019). Among them, the Sancti Septenarii group stands out, which includes

Saints Sava, Naum of Ohrid and Clement of Ohrid. These saints, known as defenders of Orthodoxy and educators of the Slavic peoples, are widely represented in the paintings of key churches in the region – St. Michael, St. Cosmas and Damian, and St. Peter and Paul (Fig. 6). Their cult not only contributed to the preservation of spiritual traditions, but also emphasised the cultural heritage of the Ohrid diocese, which played the role of a centre of education and theology. Icons and frescoes depicting the Sancti Septenarii are distinguished by the sophistication of details and deep symbolism. The saints are depicted in liturgical vestments with scrolls, symbolising their educational mission, or in prayerful poses, emphasising their mediatorial role between the faithful and God.



Figure 6. Sancti Septenarii in Church of Saints Cosmas and Damian

Source: photo by the author

Of particular importance in supporting their cult were the liturgies and liturgical works printed in Voskopoj between 1740 and 1742. These printed materials spread the veneration of saints among the faithful and helped to strengthen their status as important spiritual symbols.

The inclusion of these figures in the paintings of Vithkuq's churches not only perpetuated their memory, but also created a connection between the tradition of the past and the current theological and cultural challenges of the time.



The Coronation of Mary, represented in the churches of Saints Cosmas and Damian and Saints Peter and Paul in Vithkuq, is a striking example of post-Byzantine art, combining Byzantine traditions with new iconographic elements (Fig. 7). This scene, which honours Mary as the Queen of Heaven, takes on special significance in the

Orthodox context, since the coronation motif is traditionally more characteristic of Catholic art (del Mar Dov-al Trueba, 2024). The uniqueness of this scene lies in the combination of traditional Orthodox iconography with influences from Catholic art, which gives it a special aesthetic and theological value.



Figure 7. The Coronation of Mary, Church of Saints Peter and Paul; Church of Saints Cosmas and Damian

Source: photo by the author

Similar images are found in the Sucevita Monastery in Romania, dating from the late 16th century (Fig. 8). Here, the Coronation of Mary is executed with rich decorative design, combining features of both Catholic and Orthodox traditions. The Sucevita Monastery played an important role as a centre of iconographic innovation in the Balkans, and its influence can be traced in the artistic programs of other regions, such as Epirus and Macedonia (Ogden, 2002). The depiction of the Coronation of Mary in Vithkuq is not only a sacred image, but also evidence of the cultural dialogue that shaped the artistic heritage of the post-Byzantine world.



Figure 8. The Coronation of Mary, Sucevita Monastery

Source: K. Kontopanagou (2013)

The figure of Saint John Vladimir occupies an important place in the iconographic programs of the churches of Vithkuq, which emphasises the harmonious combination of local and pan-Orthodox traditions in post-Byzantine

art. As a famous martyr and ruler, they embodied the ideal of holiness, which had a deep resonance in the region. In the church of Saint Michael, the image of the saint in the form of a “cephalophore” is a unique example of this type in the territory of Northern Epirus (Fundić, 2022). This interpretation emphasises the martyr nature of his biography, symbolising sacrifice and spiritual triumph (Fig. 9). Of particular interest is the fact that this image was commissioned by the diocese of the Ohrid Patriarchate in Venice, which demonstrates the openness of the Orthodox tradition to Western artistic influence (Saraçi, 2024). The details of the image show feature of a Western style: delicate modelling of form, sophistication of decorative elements, and special attention to textures, reflecting general European trends of the 18th century.



Figure 9. Saint John Vladimir, Saint Naum and Archangel Gabriel, Church of Saint Michael

Source: photo by the author



Later, similar images of St. John Vladimir appeared in other churches in the region, in particular in the Church of Saints Peter and Paul in Vithkuq and the Church of Saint Nicholas in Voskopoja. This indicates a gradual expansion of the cult of the saint, which became an important component of regional identity. The spread of this image could be associated with both religious and political motives, since the cult of St. John Vladimir emphasised the unity of Orthodox communities and their cultural traditions. Thus, the image of St. John Vladimir in Vithkuq reflects not only theological and iconographic innovations, but also the cultural dialogue between the Orthodox East and the Catholic West, which shaped the unique artistic environment of the region.

A unique iconographic contribution is the image of the young martyr Nicodemus of Vithkuq, created by the brothers Athanasius and Kostandin Zografs. This type of iconography is noted in the churches of Saints Cosmas and Damian and Saints Peter and Paul in Vithkuq (Fig. 10). Its spread was probably the result of the Zografs' connections with Mount Athos, where they worked on the paintings of monasteries. The cult of the New Martyr Nicodemus, presented in these frescoes, emphasises the Albanian ethnocultural component integrated into the general Orthodox tradition.



Figure 10. Saint Nicodemus, Saints Cosmas and Damian Church, Vithkuq

Source: The New Martyr Nicodemus of Korytsa was honoured in his place of origin and in the place of his martyrdom (2022)

Portraits of the New Martyrs became an important part of Orthodox iconography during the Ottoman period. They responded to the challenges of the time, in particular the conversion of Christians to Islam, and served as a reminder of courage and steadfastness in preserving the faith. Similar images can be found in Serbian and Bulgarian churches, but in Vithkuq they received a local interpretation through the inclusion of local motifs and symbols. The narthex of the church of St. Michael in Vithkuq also presents scenes from the Apocalypse cycle, which were innovative for the region. In the church of St. Peter and Paul, painted by the

Zograf brothers in 1764, apocalyptic subjects reach a new level of artistic interpretation. In Orthodox art, especially of the post-Byzantine period, such subjects were rarely depicted, and complete cycles of the Apocalypse first appeared in the monasteries of Dochiariou and Dionysius on Mount Athos in 1547 (Bernet, 2024). Their iconography was significantly influenced by Western models, in particular 16th-century engravings. The depiction of the Apocalypse in Vithkuq predates similar scenes in the church of St. Nicholas in Voskopoia by 17 years, which indicates the innovativeness of the artistic approach in this region. Similar motifs were common in Macedonian churches, such as the Church of St. Clement in Ohrid, but in Vithkuq these scenes take on a more local character thanks to specific symbolism and compositional solutions.

The direct influence of Mount Athos on the iconographic programs of the churches of Vithkuq is evident. The paintings in the narthex of the church of St. Michael interpret typical variants of post-Byzantine art developed on Mount Athos, in particular in the monasteries of Karea (Vapheides, 2021). At the same time, Western elements that penetrated the region through Venice and other European centres became part of the local artistic tradition. Stylistically, Vithkuq's frescoes demonstrate a synthesis of canonical post-Byzantine features with creative innovations reflecting the influence of local artists. The use of the "buon fresco" technique, which involves applying pigments to fresh, wet plaster, ensured the brightness and durability of colours. Thanks to this, the artists created multi-layered compositions, each element of which harmoniously interacted with the others. Unlike the Athos frescoes, which were often executed in the "a secco" technique (on dry plaster), this allowed for greater harmony between the saturation of colours and their depth (Jiménez-Desmond *et al.*, 2024).

In addition to their aesthetic and theological function, frescoes also served an educational role. They served as a kind of means of religious education, conveying the moral values of the Orthodox tradition. Of particular importance in this context are the images of local saints, such as Saints Sava, Naum and Clement, who symbolised spiritual authority and supported the unity of the community. These images combine traditional iconography with local details, which gave them special authenticity and cultural value. Vithkuq's frescoes not only preserved the sacred heritage, but also reflected the daily life of the community, creating a unique connection between the past and the present. They are evidence of the complex interaction of spiritual and socio-cultural processes that shaped the identity of the local population. Thanks to this, the frescoes have become a "living archive", which not only preserves the memory of the past, but also forms the foundation for future generations. However, the process of their preservation faces a number of challenges that require a comprehensive approach and coordinated efforts.

The main factors affecting the condition of the frescoes in the Vithkuq churches are the environment, insufficient care and anthropogenic impact. The humid climate,



temperature changes and ultraviolet radiation contribute to the destruction of the surface through microorganisms, cracks and moisture penetration (Çota *et al.*, 2020). The remoteness of the churches makes regular maintenance difficult, which leads to the progression of damage. Uncontrolled access by visitors often causes mechanical damage and vandalism. To protect the frescoes, it is necessary to implement strict access control, information campaigns and apply modern technologies and scientific methods in cooperation with the local community.

Creating a stable microclimate inside churches is a key factor in the preservation of frescoes, as humidity, temperature fluctuations and insufficient lighting cause cracks to form, the development of microorganisms and the discoloration of pigments (Fabbiano *et al.*, 2022). To minimise these risks, microclimate control systems are implemented that maintain a constant level of humidity and temperature. Passive ventilation systems ensure natural air exchange, while modern sensors allow real-time monitoring and automatic activation of dehumidifiers when necessary (Ranesi *et al.*, 2021). Innovative technologies, including the use of nanomaterials, create an invisible protective layer that protects frescoes from moisture, ultraviolet light, and mechanical damage, preserving their colours and textures (David *et al.*, 2020). Additionally, digital scanning allows for the creation of 3D models of frescoes, documenting their condition, analysing damage, and developing restoration solutions (Montusiewicz *et al.*, 2022). Such models become accessible to a wide audience, contributing to the preservation of cultural heritage even in the event of the loss of the original.

The experience of other countries, including Greece, Italy and Serbia, has demonstrated the effectiveness of an integrated approach to fresco restoration, combining modern technologies, scientific analysis and traditional methods. At the Hilandar Monastery on Mount Athos, the introduction of modern monitoring systems was a key step in the preservation of the unique frescoes (Traparić, 2023). These systems allowed for real-time monitoring of changes in humidity, temperature and other microclimate parameters, preventing the emergence of conditions that could contribute to the degradation of works of art. In addition, the installation of dehumidifiers and the modernisation of ventilation systems made it possible to maintain a stable microclimate, minimising the risk of mold formation and physical damage to the plaster.

In Italy, in particular in St. Peter's Basilica, the use of laser technology has been a real breakthrough in the field of restoration (Costanzo *et al.*, 2022). This technique allowed for the delicate cleaning of fresco surfaces, removing years of dirt, soot and microorganisms without damaging the paint layer. The uniqueness of laser cleaning lies in its precision, which allows for the selective removal of contaminants without affecting the original pigments. A similar approach was also used in the restoration of the Sistine Chapel frescoes, where the technology was combined with careful analysis of the chemical composition of the paints

and the substrate, ensuring the gentlest approach possible (Rosebrock, 2020). This successful experience highlights the importance of innovation in restoration and can serve as an example for the conservation of the murals in Vithkuq, where similar technologies could significantly improve the effectiveness of conservation efforts. The results not only reveal the artistic and cultural value of Vithkuq's frescoes, but also emphasise the need to integrate traditional and innovative methods for their preservation.

DISCUSSION

The results of this study have highlighted the unique iconographic features of the wall paintings in the Vithkuq churches, highlighting their cultural, religious and artistic significance in the broader context of post-Byzantine art. By examining specific iconographic motifs, stylistic innovations and cultural influences, this discussion aimed to explore the broader implications of the study findings and their alignment with existing research. The integration of Byzantine and local artistic traditions significantly shaped the wall iconography in the churches of Vithkuq, creating a unique artistic style that combined elements of sacred art from different eras. The results of the study showed that images such as the "Three-Faced Christ" and the "Communion of the Apostles" demonstrate both traditional Byzantine compositional schemes and innovative iconographic approaches that reflect local cultural influences and the creative pursuits of the masters.

This hybrid style is consistent with patterns identified by Y. Tzedopoulos (2023), who discussed similar religious-artistic syntheses in other Balkan regions under Ottoman rule. Artistic adaptations in iconography reflect the complex sociocultural realities of the time, when spiritual values were preserved through revisions of established canons and creative interpretations of traditional subjects. The stylistic fusion was crucial, as it showed how local artists negotiated religious identity while taking into account external influences. The use of themes inspired by Western European art, such as the Coronation of Mary, demonstrated an ability to adapt iconographic motifs to a new cultural context. These images, while atypical for the traditional Byzantine heritage, organically woven into the local artistic language, giving religious art a renewed meaning. The inclusion of Western subjects was not only a result of contacts with the Catholic world through trade and political ties, but also a response to the aesthetic demands of the local community (Skakandi, 2023). The unique combination of Western and Byzantine stylistic features indicates an attempt to overcome cultural boundaries and create a new form of artistic expression that reflected the multifaceted identity of the Orthodox community.

This synthesis reflected broader regional artistic trends, consistent with K. Kirchhainer (2007) findings on cross-cultural exchanges in Balkan church art. The researcher emphasised the interpenetration of styles as a characteristic feature of the art of a region that was at the



crossroads of different empires and cultural influences. Similar examples of cultural exchange can be found in the church paintings of the Western Balkans and the Carpathians, where the influence of the Italian Renaissance and South Slavic traditions is felt. Furthermore, the inclusion of regional saints, such as Saints Naum, Sava, and Clement, emphasised the churches' spiritual and political affiliation with Orthodox centres such as Ohrid. This iconographic emphasis strengthened community identity while asserting spiritual autonomy. For remote communities such as Vithkuq, these images served as a visual confirmation of a shared religious heritage, fostering a sense of belonging amidst external pressures.

The innovative use of colour, composition, and symbolism also reflected a cutting-edge artistic sensibility. In Vithkuq's wall paintings, a bold combination of rich shades of red, blue, and gold is observed, creating dramatic contrast and enhancing the expressiveness of the images. This colouristic approach, which goes beyond the strict Byzantine canons, testifies to the development of local aesthetic ideas and openness to innovative artistic practices. In The Communion of the Apostles, the colour symbolism emphasises the spiritual struggle: the dark shades around the figure of Judas hint at his spiritual fall, while the light and radiant colours around Christ emphasise his divine nature. The psychological depth depicted in the scene of The Communion of the Apostles, where Judas is shown burdened by the devil, demonstrates a narrative sophistication that can be compared to works found in Ohrid and Mount Athos, as noted by M. Mihaljević (2021). The inclusion of a demonic figure as a visual representation of evil enhances the drama of the scene and the emotional impact on the viewer. Such emotionally charged images were probably intended to enhance religious participation by making the sacred narratives more accessible and immediate. Thanks to this, the paintings performed not only a decorative but also a didactic function, helping parishioners to understand spiritual truths more deeply through artistic interpretation of biblical stories.

The artistic creativity of Vithkuq's frescoes goes beyond religious narrative, demonstrating complex interrelationships between spiritual and secular motifs. The dynamic compositions, characterised by multi-figure scenes, as well as the expressive gestures of the characters, indicate the influence of itinerant artists, whose mobility facilitated stylistic exchanges in the Balkans (Bardik, 2023). The influence of different artistic schools, including Macedonian and Epirus, is traced in the expressive faces of the saints and the sophisticated ornaments. This is consistent with A. Belba (2019) findings on the movement of master painters between Albania, Macedonia and Greece, which contributed to the development of a common but locally adapted artistic tradition. Vithkuq became an important node of this cultural dialogue, enriching the local artistic heritage with innovative figurative solutions.

Despite their historical and cultural significance, the Vithkuq frescoes face numerous conservation challenges.

Environmental factors such as high humidity, temperature fluctuations and biological damage significantly threaten the longevity of these unique artistic treasures (Ivashko *et al.*, 2020). Furthermore, limited funding and a shortage of qualified restorers often make it difficult to implement large-scale conservation projects. Comparative studies by L. Fabbiano *et al.* (2022) and D. Traparić (2023) have shown that the implementation of advanced technologies such as 3D scanning, climate control systems and digital archiving can significantly reduce the risks of damage and ensure the long-term preservation of the frescoes. Conservation efforts should be prioritised to preserve this unique cultural heritage for future generations, promoting deeper research and international cooperation in the field of cultural heritage protection (Shumka, 2019).

Digital documentation and international collaboration can facilitate further research, allowing scholars to explore understudied aspects of Vithkuq's iconography. J. Montusiewicz *et al.* (2022) suggested that interdisciplinary research that integrates art history, theology, and conservation science will provide a full understanding of the cultural and spiritual dimensions of these artworks. The discussion emphasised that the frescoes in the Vithkuq churches are more than religious artifacts; they are visual records of the historical, spiritual, and cultural journey of a community. Their iconographic richness reflects the dynamic interplay of tradition, innovation, and resilience. This study has contributed to a broader understanding of the post-Byzantine artistic heritage and highlights the importance of preserving and studying these cultural assets.

CONCLUSIONS

This study has analysed the iconographic features of the wall paintings in the Vithkuq churches, providing a substantial understanding of their religious, cultural, and artistic dimensions. The findings contributed to a deeper understanding of how local traditions, external influences, and theological concepts were integrated into the visual language of Vithkuq religious art. A key finding of this study was the discovery of a unique hybrid style in the Vithkuq frescoes, combining Byzantine, post-Byzantine and local artistic traditions. This fusion is particularly evident in iconographic motifs such as the Trinity of Christ and the Communion of the Apostles, which combine both traditional and innovative elements. The analysis showed that these frescoes were not simply reproductions of established iconographic types, but adaptations and reinterpretations that reflected the local context and theological considerations of the Vithkuq community. Another significant result was the recognition of the high artistic sensitivity demonstrated in the frescoes, particularly in the use of colour, composition and symbolism. The psychological depth of scenes such as the Communion of the Apostles, where Judas is burdened by the devil, reflects a sophisticated approach to narrative. This not only enhances the emotional impact of the scenes, but also makes the sacred stories more accessible and appealing to local audiences.



However, the study revealed certain limitations in fully understanding the artistic and theological significance of the frescoes. While key iconographic features and stylistic trends were identified, further research is needed to uncover the full theological and social context of these works. The lack of comprehensive historical documentation makes it difficult to understand the full motivations and intentions of the artists. Additionally, the physical condition of some frescoes, with areas of damage obscuring important details, limited the scope of iconographic analysis. Future research should explore the connections between these frescoes and the broader religious, cultural, and social dynamics of the post-Byzantine region. Archival research and modern conservation methods, such as digital imaging and 3D scanning, could provide further insight into the original form and meaning of the frescoes.

The study emphasises the importance of preserving these frescoes not only as works of art but also as key cultural artifacts that offer a glimpse into the religious and artistic life of the Vithkuq community. Given the threats posed by environmental factors and insufficient

restoration efforts, it is crucial that future conservation projects prioritise the protection of these frescoes, using modern technologies to prevent further damage. In conclusion, this study has provided valuable insights into the iconographic features of the wall paintings in the Vithkuq churches, revealing how local and external artistic traditions intersected in the creation of these religious artworks. The research highlights the role of these frescoes not only as sacred representations but also as cultural and historical documents, reflecting the complex social and theological dynamics of the region during the post-Byzantine period.

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<https://orcid.org/0009-0006-6044-1766>**Деякі іконографічні особливості настінних розписів у церквах Віткука**

Анотація. У цьому дослідженні розглянуто іконографічні особливості настінних розписів у церквах Віткука в Албанії з метою дослідити походження, еволюцію та значення іконографічних особливостей фресок. Дослідження зосередилося на виявленні гібридного стилю цих фресок, які поєднують візантійські, поствізантійські та місцеві традиції, а також проаналізувало конкретні іконографічні теми, такі як «Трійця Христова» та «Причастя апостолів». Дослідження також показало, як місцеві традиції та зовнішні впливи вплітаються у візуальну мову цих релігійних творів мистецтва. Аналіз показав, що ці фрески були не просто репродукціями усталених іконографічних типів, а радше адаптаціями, які відображали місцевий богословський і культурний контекст. Дослідження також підкреслило високу художню чутливість фресок, особливо з точки зору використання кольору, композиції та символіки. Дослідження виявило вплив мандрівних художників, які принесли в регіон нові стилістичні елементи, сприяючи динамічному обміну мистецькими традиціями на Балканах. Результати дослідження висвітлили проблеми збереження цих фресок, пов'язані з екологічними факторами та недостатніми реставраційними зусиллями. Дослідження запропонувало цінну інформацію про те, як місцеві та зовнішні мистецькі традиції перетиналися у створенні цих розписів, і сприяє глибшому розумінню соціальної, релігійної та мистецької динаміки поствізантійського періоду на Балканах. Зроблено висновок, що фрески у церквах Віткука є не лише важливими релігійними творами мистецтва, але й ключовими культурними артефактами, які відображають складність історичного та богословського розвитку регіону в поствізантійську епоху.

Ключові слова: фрески; візантійський вплив; балканське релігійне мистецтво; художня еволюція; культурна спадщина



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Restoration of sepulchral plastic works made of cement compositions

Abstract. The restoration of sepulchral sculptures made of reinforced concrete is becoming increasingly relevant, as the issues of physical preservation of monuments are exacerbated by the lack of proper care and natural factors that are aggressive to this material. Timely professional restoration is important for keeping monuments in proper condition. Among professionals, it is usually more common to handle ancient works of art, however, artworks made of cement compositions, which were first used by architects and sculptors at the end of the 19th century, also need preservation. The study aimed to analyse modern methods and provide examples of their implementation, which were applied in restoration practice and tested on specific artworks. The authors' experience of handling sepulchral plastic, obtained during the 2019-2024 restoration work at the Department of Architecture and Restoration of Lviv Polytechnic National University, was analysed in the study. The history of the appearance of plastic cement compositions has been analysed. The methods, techniques and technologies of working with various damage to monuments were discussed in detail on three practical examples. The research results described in the study have practical value for a wide range of art restorers, as they will help practitioners preserve the integrity of sculptural and architectural objects made of cement compositions from the late 19th and early 20th centuries. The methods described in the study can also be applied to monuments made of reinforced concrete during the 20th century if similar technologies were used in their manufacture

Keywords: memorial plastic; artificial stone; conservation; destruction causes; monuments preservation

INTRODUCTION

The restoration of sepulchral plastic artworks from cement is relevant since under the influence of time, atmospheric influences and human action, all researched monuments require restoration. Restoration of this type of monument requires a detailed study of their state, and manufacturing technology, as well as knowledge of modern materials and techniques that can be applied in restoration. According to researchers of architectural history T. Klymeniuk *et*

al. (2019), Roman concrete, which was invented in ancient Rome and widely used in construction, was made from a mixture of slaked lime and pozzolana mixed with water. Researchers claim that pozzolana is volcanic ash, the deposits of which were mined in the vicinity of Puteoli, now Pozzuoli, in the Campania region, Italy. Other components of this ancient concrete were crushed and whole stones and organic additives (such as eggs).

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Concrete of the late 19th and early 20th centuries significantly differed both in terms of ingredients and manufacturing technology. Furthermore, sepulchral sculptures made using this technology do not often become the subject of research and practical restoration. This is determined by the complications in restoration, caused by destruction due to damage and neglect. In such a case, a customer prefer reconstruction, replacing it with a copy. Importantly, this approach is incorrect from the point of view of restorative science, since instead of an original artwork, even damaged, a copy is constructed, which has no historical or artistic value. A study by O. Kyrlyuk (2020), which argued that the destruction of sacred places of Ukrainian memory by assimilators is a substantial step in the enslavement process, is noteworthy. The coloniser always seeks to destroy the memory carriers on the territory of the people to enslave, to replace the “sacred space” with the “abstract”, and to erase the graves of heroes from both physical and memory realms. An illustration of this thesis can be the example of the destruction by Soviet functionaries in 1950 of a reinforced concrete cross that was created in 1938. The history of the cross’s creation, destruction, and discovery was described by N. Datsko (2022). The cross was dedicated to the 950th anniversary of the baptism of Rus’ and Ukraine and was installed in the Holy Dormition Univ Lavra and is a beautiful example of Ukrainian modernism.

Reinforced concrete structures were actively introduced as structural and decorative elements in buildings constructed in the style of Ukrainian architectural modernism at the beginning of the 20th century. The famous architect and entrepreneur Ivan Levynskyi used many such elements. In particular, R. Hnidets & M. Yasinskyi (2021), studying the architect’s work, noted that “the characteristic and obligatory features of these buildings were the harmonious combination of folk architecture and art forms, translated into stone or concrete, decorating the facades with bright ceramic tiles, in the colours and patterns of which the stylisation of Ukrainian traditional embroideries or ornaments was notable”. Despite the folkloric decoration of the facades, their construction was made of the latest materials, often specifically reinforced concrete.

As for the use of reinforced concrete in memorial tombstones, many such monuments of sepulchral sculptures were present in western Ukrainian territories between the First and Second World Wars. As O. Mykhaylova (2022) noted, the traditions of honouring fighters for independence in Western Ukraine were more prominent. In the interwar period, memorials to Sich riflemen were already present. The author mentioned memorials at the Yaniv cemetery in Lviv and in Berezhany, Ternopil region. However, the author also noted that in almost all cases these memorials were destroyed by the Soviet authorities.

Military burials in Halych have become the subject of research, as the city and its surroundings have repeatedly become the centre of hostilities. Three locations of military burials in the territory of Halych have been preserved in varying conditions. Military burials were also done in the

church cemetery near the church of St. Dmitry in Halych. According to A. Chemerynskyi (2019), in 2011, one military concrete cross was found on the western side of this church cemetery, and during the landscaping of the territory in 2022, another one (both from the 1920s) was found. Notably, a local historian stated that the above-mentioned burials of fallen soldiers from the First World War were marked with “concrete military crosses”. The author also stated that “...in some places, the bases of broken crosses are still visible from the ground” (Chemerynskyi, 2023).

As for the monuments in the military cemeteries of Volhynia, they are closely correlated with historical events of Galicia, being a part of thereof. S. Havryliuk (2022) in a study on the military cemeteries of Volhynia stated that “...time and objective circumstances have hidden many places where those who died in this war rest. The region currently has 34 cemeteries and mass graves from the First World War, which have signs of military necropolises”. Many of these burials were also made of reinforced concrete and were destroyed primarily due to the policy of the Soviet government. As for restoration measures for such monuments, they primarily require scientific study. For instance, the tombstones in the cemetery of the village of Tobolya in Volyn were first arranged in the interwar period. The existing cemetery in the centre of the village has two large concrete structures resembling a memorial complex. This is a unique monument that requires more detailed study and determination of ways of its restoration. A large proportion of these memorials are made of concrete or reinforced concrete. Technological problems of preserving such monuments rarely become the subject of separate research, although the causes of destruction and the means to eliminate them are of key importance in this case.

As for the reasons for the mass use of reinforced concrete in sepulchral sculpture, functionality and the possibility of mass copying of similar monuments were important. This thesis can be confirmed by the article by G. Twardowski (2023), dedicated to the use of concrete in early 20th-century architecture in Poland. The study noted that “a lifeless, monotonous geometry of repetitions, devoid of radical accents – often arose from purely functional reasons, but was also an artistic demonstration of modern achievements”. Furthermore, the very nature of the material and its strict aesthetics often led memorial creators to choose this material.

The study aimed to highlight problems during search, identification and restoration of monuments of sepulchral plastic made of concrete, as well as to determine ways to solve them based on theoretical research and practical experience of the authors of the article on the example of the study and restoration of three monuments.

MATERIALS AND METHODS

Traditional methods of reinforced concrete monuments research included visual inspection, as well as scientific methods of historical analysis. Complex studies of the technological aspects of their creation were also conducted to



determine the components, means, materials and features of each artwork. The inventory and accounting methodology was used in compiling documentation during the study of monuments made of historical concrete (Stasyuk, 2022).

From the first reinforced concrete products their widespread use, sepulchral plastic was primarily used to construct artworks. The study described three monuments of sepulchral plastic made of reinforced concrete, which underwent the restoration process as part of the diploma works developed at the Department of Architecture and Restoration of the Institute of Architecture and Design of the Lviv Polytechnic National University (Bevz *et al.*, 2022). The study authors participated in the research of all three monuments, as well as advised the executors of the works. The studied monuments are: the first half of the 20th century reinforced concrete gravestone cross of the Ukrainian People's Republic diplomat Volodymyr Mursky, from the city of Istanbul; a commemorative reinforced concrete cross from the collections of the Museum of the Holy Assumption Univ Lavra, which was made and installed in honour of the 950th anniversary of the baptism of Ukraine-Rus' in 1938 and a cross preserved in the city cemetery of Belz on the grave of eight unknown riflemen of the Ukrainian Galician Army. In the example of these monuments, both positive and negative technological features, which are inherent in reinforced concrete structures, are considered.

Unconditional advantages are the relative ease of creating structures made of this material, their strength and ability to carry large loads (provided the proper construction technology), the possibility of creating a wide variety of forms (thanks to the use of iron reinforcement and the possibility of pouring concrete mixture into the form), the monolithic nature of monuments (Sanytsky *et al.*, 2002). However, reinforced concrete has its technological limitations, as well as several features that can cause damage or destruction of a monument made of this material. Usually, when creating certain works from reinforced concrete, it is difficult to achieve ideal conditions, the use completely appropriate materials, and sometimes there is non-compliance with the technology (Gralińska-Grubecka, 2019). Tharticle study addressed these problems and, thanks to the conducted research and acquired practical experience, a certain section of the problems was presented and the ways of their solution during restoration were indicated.

The main goal of restoration with reinforced concrete monuments is to stop destruction and stabilise the construction of reinforced concrete objects, conservation, replenishment of losses and preservation of the authenticity of monuments. Therefore, in all three cases, the prominent issue was reinforcement. During the restoration process, stainless steel was used as reinforcement, as the most optimal material. This steel was used in additions and reconstructions to replace corroded material as necessary. When performing additions and reconstructions, historical technologies for making wooden formwork were used as a form. This was used to recreate the historical texture of the finished product. As for the cleaning of all types of

contamination, strengthening, and glueing, modern chemical materials were used here with the obligatory performance of samples of each of the applied materials on each of the objects with which they worked.

RESULTS AND DISCUSSION

All three monuments described in the article were made of reinforced concrete at the beginning of the 20th century. All were admitted for restoration in unsatisfactory condition. Notably, each of these monuments was damaged differently and each required a different method of restoration. The first of the monuments is the reinforced concrete tombstone cross of the Volodymyr Murskyi Ukrainian People's Republic diplomat (Fig. 1), a cross of the early 20th century from the city of Istanbul. The work performed by the Student Zhala Zakhar, within the framework of the diploma, was successfully defended in 2021 at the Department of Architecture and Restoration of the Lviv Polytechnic National University (Bevz *et al.*, 2022).



Figure 1. Reinforced concrete tombstone cross of the Volodymyr Murskyi view before restoration
Source: authors' photo

The tombstone cross was submitted for restoration in an unsatisfactory condition. It was on the brink of destruction. However, at first glance, the cross did not appear in poor condition. It was practically intact, with almost no damage. During the initial inspection, washing out of the front surface of the concrete and the marble memorial slab, numerous biogrowths on the surface of the cross and the marble slab, minor losses of concrete around the perimeter of the cross, and many cracks on the concrete surface was notable. That is, a wear and tear caused by age, which does not cause alarm initially. However, after a detailed inspection, it was noted that the cracks on the concrete surface were primarily caused by the corrosion of



iron fittings, which changed the appearance of iron oxide inside the monument to appear “swelling”, the loss of the integrity of concrete and metal, as a result of which a cavity was visible in the middle of the cross. Such destruction of reinforced concrete structures is dangerous as they are, as a rule, hardly noticeable, have a progressive nature and require urgent emergency restoration works.

After a detailed study of the object, a decision was made to clean the monument from biogrowths and metal from corrosion; to prevent the recurrence of these processes by the method of preservation of the metal and concrete cross; to glue the preserved, but damaged fragments to the object in its original place; to paste the lost parts with a complementary mass that is not aggressive to the authentic material (Ciabach, 1998); to fill the cracks on the concrete surface and the cavity in the middle of the cross, and tint the addition. As a result of the measures carried out, the monument was stabilised, it was given an exhibition appearance and transferred to the Lviv Museum of the History of Religion for safekeeping (Fig. 2).



Figure 2. Reinforced concrete tombstone cross of the Volodymyr Murskyiv after restoration

Source: authors' photo

Another destroyed object that was sent to the Department of Architecture and Restoration of the Lviv Polytechnic National University for restoration is a memorial reinforced concrete cross from the Saint Assumption Univ Lavra museum's collections (Vuitsyk, 1997). The memorial cross was made and installed in honour of the 950th anniversary of the baptism of Ukraine-Rus'. The construction was done on October 2, 1938. During the communist occupation, in 1954, the cross was toppled and broken by order of the communist authorities. The villagers hid the fragments of the cross by burying them under a linden tree. After the Ukrainian Greek-Catholic Church returned to

normal operation, fragments of the cross were found, and a few years later they were processed for restoration (Fig. 3).



Figure 3. Memorial reinforced concrete cross from the Saint Assumption Univ Lavra museum's collections before conservation

Source: authors' photo

In 2020-2021, Student Volodymyr Petryshyn conducted restoration at the Department of Architecture and Restoration of Lviv Polytechnic National University under the supervision of Doctor of Architecture O. Rybchynskyi and PhD in Architecture V. Melnyk. At the time restoration, the condition of the object was unsatisfactory. The monument lacked structural integrity. The cross consists of three main large parts and many debris and fragments. The main part is the upper half of the cross with two arms and two separate parts of the lower arm. The cross was soiled with earth, splashes of paint, and moss. The cross is made of reinforced concrete, which includes different fractions of sand, crushed stone, and bricks, which is another destructive factor since ceramics (brick fragments) are porous materials that accumulate moisture. The monument required mechanical cleaning, preservation of metal elements, glueing of existing parts into a monolith, reinforcement, and restoration of lost elements by pouring concrete into formwork. Moreover, measures had to be taken, which involved pouring concrete to form a monolithic structure, which lost its integrity when destroyed.

The first step in the preservation and reconstruction was to expose the lower arm to its current position, keeping the arms parallel. The next step was the manufacture and installation of the armature. The armature was made of stainless-steel rods. The reinforcing bars were glued to the concrete with epoxy resin in drilled holes. A two-component epoxy resin was used alongside sand as a filler. In this case, sand was used to reduce fluidity and increase strength. Missing parts were patched with a filler compound that is not aggressive to the authentic material, cracks on the concrete surface and a cavity in the middle of the cross were filled, and the addition was tinted (Fig. 4). As a result of the measures taken, the monument was stabilised, restored and transferred to the Saint Assumption Univ Lavra museum for safekeeping.



Figure 4. Memorial reinforced concrete cross from the Saint Assumption Univ Lavra museum's collections after conservation

Source: authors' photo

The third memorial is a cross preserved in the city cemetery of Belz on the grave of eight unknown marksmen of the Ukrainian Galician Army who died in battles with the Polish army for Belz in 1919. The cross was transferred for restoration as a result of the expedition of the teachers of the Department of Architecture and Restoration, Vasyl Petryk, Olena Stasyuk, Viktor Melnyk, Serhiy Siry, as well as the Student Vladyslav Lelitka, who conducted further restoration of the cross as part of a diploma thesis. When it was received for restoration, the cross was in an unsatisfactory condition (Fig. 5). During the initial inspection of the object, it was established that the cross was exposed and substantially damaged. The cross was separated from the pedestal. The body of the cross was broken into pieces, parts of which were missing, the armature was twisted and covered with rust. The memorial required mechanical cleaning, conservation of metal elements, reinforcement, restoration of lost elements by pouring concrete into the formwork, and addition of lost parts from concrete to form a monolithic structure that lost its integrity when destroyed.

As a result of the measures, the lost parts were pasted with a complementary mass that is not aggressive to the authentic material, and the cracks on the concrete surface were filled. As a result of the measures taken, the monument was stabilised and given a proper appearance. As of 2024, it is located at the Department of Architecture and Restoration of Lviv Polytechnic National University (Fig. 6) and is awaiting transfer to the State Historical and Cultural Reserve in the city of Belz.



Figure 5. Reinforced concrete cross rifleman of the Ukrainian Galician Army from the city of Belza before the conservation

Source: authors' photo



Figure 6. Reinforced concrete cross rifleman of the Ukrainian Galician Army from the city of Belza after conservation

Source: authors' photo

All three reinforced concrete monuments described in the article constructed made at the beginning of the 20th century. Each has been restored, received a proper appearance. In the context of the different nature of the damage, a different method of restoration was applied to each of the monuments, which was described in detail in the article. Description of restoration accounted for special problems of each of the monuments and ways of solving them. The results of the restoration were illustrated in detail with photographs.

Cement is an artificial inorganic viscous substance. Artificial stone is one of the main modern-day building materials. On an industrial scale, was first produced in the 19th



century. This new material was strong and cheap. The oldest objects made of reinforced concrete are over 100 years old, many of them are monuments that need preservation and restoration. Restorers of both Europe and America are faced with the problems of restoration of historical reinforced concrete. For example, in 2017-2018, conservation of large-scale reinforced concrete sculptures took place in Canada. Conservation efforts addressed three different objects built at different times from the beginning to the middle of the 20th century. The Centre Street Bridge Lions (1916), Dinny the Dinosaur (1934) and the Maurice Savoie Mural (1966). They are three examples of large-scale outdoor artworks that adorn the roadways and buildings of Canada. Despite the difference in age, size and scale of these works of art, they share similar challenges associated with old historic concrete (Caldwell *et al.*, 2018).

The same large-scale reinforced concrete sculptures decorate the roads and squares of European cities. The statue of an African elephant opposite the Africa Museum in Brussels is a notable example. The sculpture was created by Albéric Collin in 1935. As of 2023, the sculpture was severely damaged, cracked, with many gaps, chips, and substantial corrosion (Chini, 2023). The restoration was initiated to preserve the historical value, structural integrity and appearance as well as to strengthen the structure and remove current damage.

Large-scale concrete sculptures, which were on city streets in the 70s of the 20th century, also often require restoration. An example of such a sculpture can be the congratulatory modernistic compositions of the city Hojneec (Poland) created by Norbert Jażdżewski in 1973-1975. These objects were in bad condition, cracked, lost their original colouring, and visible corrosion of metal elements (Conservation of a set..., 2022). The restoration recovered their original shape, texture and colour, and strengthened them as much as possible.

The Iwo Jima Monument conservation is an example of historical reinforced concrete memorial plastic conservation. Iwo Jima Monument is located on Parris Island South Carolina. This monument holds significant value to the Marine Corps representing all Marines who bravely died in service to their country. Based on the technical analysis and detailed visual inspection, all cracks, defective fittings and areas of the base material were identified (Chemello, 2019). Conservation of this monument preserves not only its physical materiality but also its rich historical, spiritual value and emotional connection with the Marines.

In Ukraine the Tula Bridge was the first reinforced concrete object. O. Noha (1993) defined it as the first curved product of this material in the world. Notably, Lviv Polytechnic was among the pioneers in the introduction of reinforced concrete structures into mass use. An example of this is the Tula Bridge, which has been preserved to the left of the Main Academic Building of the Polytechnic.

Restoration of reinforced concrete structures was substantially addressed in the literature on building structures of the late 19th and early 20th centuries. As of 2024,

buildings constructed using this material are already showing "age-related issues" that often require urgent and radical solutions, such as partial replacement of reinforcement, strengthening of concrete structures, etc. An example is the comprehensive restoration of the Hall of the Century in Wrocław, which has been on the UNESCO World Heritage List since 2006 (Ilkosz, 2006). The building was constructed in 1911-1913 by architect Max Berg. In 2009-2011, the reinforced concrete structure and the interior decoration was repaired, restored and reconstructed (Laska, 2010). After the restoration was completed, a conference was held in Wrocław, where reports were made, including information on the restoration of reinforced concrete structures. Comparing the methods of reinforced concrete structures restoration of the Hall of the Century and monuments of sepulchral plasticity, which was conducted at the Department of Architecture and Restoration, certain common features can be noted, namely: in both cases, the conservation of metal structures was done using agents containing corrosion inhibitors.

The problem of conservation and the implementation of additions to lost details is related to restoration philosophy and ethics. Decisions about additions are preceded by extensive theoretical research. This includes the identification of the object, detailed study, search and study of archival and photographic documents, analogues, etc. After theoretical research, a clearing, strengthening and addition methods can be selected. The sequence of all these stages must be followed.

CONCLUSIONS

The professionalism restoration, among other things, is based on knowledge of the tools and materials used in modern restoration. As a result of the activities conducted at the Department of Architecture and Restoration, monuments were stabilised and saved from destruction. Despite the variation in size and degree of preservation of the three artworks discussed in the study, each demonstrates similar problems associated with old historic concrete. The primary issue is the corrosion of reinforcing steel, which is associated with the water accumulation by concrete and its cyclical freezing-thawing, which is highly destructive for concrete. The performed activities also demonstrated the importance of a detailed, in-depth, comprehensive study of the monument for the correct identification of problems and the choice of a restoration concept. Among other things, methods of stabilisation, strengthening, addition, arrangement and toning were tested on each of the artworks. The technical methods and technologies described in the article, in combination with practical skills and various techniques for sepulchral plastic artwork preservation, can be beneficial in the restoration of this type of artwork. Notably, such problems are present in restoration efforts globally. The study described the processes of restoration and conservation of cement artworks, as well as those materials and restoration technologies that were tested by the authors in practice, which can be valuable for other





restoration works on similar objects. Monitoring of the completed restoration is an important stage. Monitoring of the restored monuments described in the article demonstrated a successful choice of materials and technologies. All objects demonstrate structural stability and no new damage. The only aesthetic defect is a little change in colour in the areas of additions and reconstructions. This problem remains for further research and experiments.

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Реставрація надгробних пластичних творів з цементних композицій

Анотація. Реставрація сепульклярної пластики із залізобетону набуває все більшої актуальності, оскільки проблеми збереження фізичної субстанції пам'яток посилюються відсутністю належного догляду та агресивними для цього матеріалу природними факторами. Важливе значення для збереження пам'яток у належному стані мають своєчасно проведені фахові реставраційні роботи. Серед професіоналів зазвичай більш поширена робота зі старовинними творами мистецтва, однак і твори з цементних композицій, які увійшли в практику архітекторів і скульпторів наприкінці XIX століття, також потребують збереження. Метою дослідження було проаналізувати сучасні методики роботи з цементними композиціями в реставраційній практиці та навести приклади їх реалізації, апробовані та застосовані на конкретних пам'ятках. У дослідженні проаналізовано авторський досвід роботи зі сепульклярною пластикою, набутий під час реставраційних робіт у 2019-2024 рр. на кафедрі архітектури та реставрації Національного університету «Львівська політехніка». Проаналізовано історію появи цементних композицій. На трьох реальних прикладах детально розглянуто методи, прийоми та технології роботи з різними пошкодженнями пам'яток. Описані в статті результати досліджень мають практичне значення для широкого кола реставраторів мистецтва, оскільки допоможуть практикам добитися збереженості скульптурно-архітектурних об'єктів із цементних композицій кінця XIX – початку XX століття. Методи, описані в цій роботі, також можуть бути застосовані при реставрації пам'яток із залізобетону створених протягом всього XX, а також початку XXI століття, якщо при їх виготовленні були використані такі ж технології

Ключові слова: меморіальна пластика; штучний камінь; збереження; причини руйнування; охорона пам'яток

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Optimising the construction process through digitalisation: Case studies of projects under unstable resource supply

Abstract. This study aimed to investigate the impact of digital technologies on the optimisation of the construction process under conditions of unstable resource supply and to formulate practical recommendations for their effective implementation. The research methodology included an analysis of current trends in the field of digital solutions, including Building Information Modelling, Internet of Things technologies, artificial intelligence, digital twins, and cloud platforms. The possibilities of integrating these technologies to improve the planning, construction, and operation of facilities were considered, as well as their impact on increasing the efficiency of resource management. An analysis of real-world case studies was conducted, including the implementation of Building Information Modelling in the ASTON HALL project by the company DEHAUSS, which confirmed the significant potential of digital technologies. The Crossrail project

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was also considered, where BIM technologies ensured effective coordination between contractors, as well as digital twins in Singapore, which are used for the management of urban resources. The research showed that Building Information Modelling contributes to reducing errors in design and construction, improving coordination between project participants, and lowering costs. Internet of Things technologies provide real-time monitoring of the condition of building materials and equipment, which increases the level of safety and reduces the risks of downtime. The use of artificial intelligence enables the prediction of potential delays, the optimisation of logistics, and the automation of management processes. Digital twins allow for the testing of different construction process scenarios, which positively impacts the quality of the final outcome. The main challenges of construction digitalisation remain the high cost of technology implementation, the need for staff training, the difficulties of integrating software platforms, and cybersecurity issues. At the same time, the advantages, such as process automation, increased accuracy of load and energy efficiency calculations, optimisation of resource supply, and improved control over construction projects, confirm the strategic importance of digital solutions in the development of the construction industry. The results of the research demonstrated that a comprehensive approach to the implementation of digital technologies, the adaptation of construction processes, and the effective integration of digital platforms can significantly increase the productivity of construction projects, especially under conditions of unstable resource supply.

Keywords: blockchain; building information modelling; geoinformation technologies; cloud computing; remote sensing

INTRODUCTION

In the 21st century, the construction industry faces several challenges, including unstable resource supply, complex logistics for material delivery, the impact of external factors (economic, environmental, political), and the need to increase the efficiency of construction processes. Traditional approaches to construction management can no longer fully ensure process optimisation and loss reduction, which necessitates the implementation of innovative technologies. One of the key solutions for increasing construction efficiency is digitalisation, which allows for the optimisation of processes at all stages of project implementation. Digital technologies, such as Building Information Modelling (BIM), Artificial Intelligence (AI), Internet of Things (IoT), and cloud computing, enable effective resource planning, cost forecasting, and risk minimisation (Shults & Annenkov, 2023). The use of these technologies is particularly relevant in conditions of unstable resource supply, where it is necessary to quickly adapt construction processes to changes in material supply, price fluctuations, and logistical constraints. The relevance of the research topic is driven by the increasing challenges in the construction sector related to the instability of material supplies, the rising cost of resources, and the need to ensure the resilience of construction processes. The implementation of digital solutions can significantly improve resource management, shorten construction times, and enhance the quality of work execution.

The development of digitalisation in the construction sector is actively being researched by academics. Analysis of academic studies allows for the identification of the main approaches and prospects for using digital technologies to optimise the construction process under conditions of unstable resource supply. For example, T. Goncharenko (2021) investigated how BIM affects resource management and the planning of construction projects. He noted that the implementation of BIM is capable of reducing material waste and improving the efficiency of building

resource supply. V. Shcheglov & O. Morozova (2022) analysed the use of IoT technologies for real-time monitoring of the condition of building materials, which is critically important under conditions of unstable supply. In their study, A. Kuzior *et al.* (2023) considered the role of AI in improving management decisions and optimising innovative processes. The authors emphasised that the application of artificial intelligence contributes to accelerating the development of new solutions, increasing the efficiency of collaboration between participants in innovative ecosystems, and reducing risks at the implementation stage. R. Krishnan *et al.* (2024) noted that intelligent algorithms of artificial intelligence help to improve logistics processes and enhance coordination in supply management.

In turn, W. Li *et al.* (2021) emphasised the role of cloud computing in ensuring flexible management of construction processes. They noted that the implementation of cloud platforms allows for the centralised management of resources and the integration of data from various sources, which is critically important in unstable supply conditions. The study by S.N. Pargoo & M. Ilbeigi (2022) focused on cybersecurity issues in the digitalisation of the construction sector, pointing out the risks of data leaks and potential attacks on automated management systems. They proposed the use of blockchain technologies to increase the security of data and transactions in construction management. In their research, K. Lavrukina *et al.* (2024) argued that the challenges of globalisation contribute to the accelerated development of innovative and information processes, which positively impact the competitiveness of the construction industry. S.V. Mhaskey (2024) pointed out the importance of integrating automated management systems with enterprise resource planning (ERP) systems for the effective allocation of resources and the monitoring of supply. He emphasised that digital solutions can reduce logistics and procurement costs. The study by N.H. Pan & N.N. Isnaeni (2024) considered the application of augmented reality





(AR) in construction, which allows engineers and project managers to make more accurate decisions regarding the use of materials and the optimisation of work processes. J.M.D. Delgado *et al.* (2019) focused on the use of autonomous robotic systems in construction, which can reduce dependence on the human factor and ensure the continuity of work even in difficult resource supply conditions.

Despite significant progress in the digitalisation of construction processes, several important aspects remain insufficiently studied. In particular, most research focuses on the implementation of individual technologies (BIM, IoT, AI), but comprehensive models for the integration of digital solutions under conditions of unstable resource supply are rarely considered. Furthermore, insufficient attention is paid to the analysis of the effectiveness of digitalisation in real-world projects, especially in the context of adaptive resource management and risk forecasting. The question of the economic feasibility and potential return on investment of digital technologies in the construction sector also requires further study. Considering these aspects, this study aimed to evaluate the effectiveness of the digitalisation of the construction process under conditions of unstable resource supply and to develop recommendations for optimising the use of digital technologies to enhance the flexibility and resilience of resource management. To achieve this aim, it was necessary to analyse existing digital technologies and their impact on the optimisation of the construction process and to investigate adaptive models of resource management based on digital solutions.

MATERIALS AND METHODS

The research methodology was based on a comprehensive analysis of academic sources, specifically works focusing on the implementation of BIM in residential building projects, the use of digital twins in urban planning, and the application of virtual reality (VR) technologies to optimise costs in construction. Particular attention was paid to the case study of BIM implementation in the ASTON HALL residential complex project by the company DEHAUSS. This example was chosen due to its relevance to the Ukrainian context, the public availability of information, the presence of a digital strategy, and its execution in conditions of unstable resource supply, which allows for tracking the effectiveness of digitalisation in a real-world setting. The case study of BIM usage in the large-scale infrastructure project Crossrail in Great Britain was also analysed, where digital models significantly reduced errors, optimised change management, and accelerated implementation (BIM and GIS integration..., n.d.; Walker, 2023). Another important example was Singapore's practice of implementing digital twins for urban infrastructure management, demonstrating the effectiveness of digitalisation at the national planning level. A comparison of regulatory approaches in different countries, particularly Great Britain and Singapore, allowed for the identification of best practices, the assessment of the degree of regulatory readiness for digitalisation, and the determination of areas for improving national regulation.

The research encompassed an analysis of the functionalities of BIM 360, Revit, ArchiCAD, and Tekla Structures software, as well as energy efficiency calculation tools such as DesignBuilder and EnergyPlus. Particular attention was paid to a comparative analysis of digital technologies: BIM, IoT, AI, AR/VR, GIS, blockchain, cloud platforms, and automated control systems. Their application in the processes of design, logistics, energy management, monitoring, and cost control was considered. To assess the effectiveness of digital solutions, comparative analysis and case study analysis were used. This allowed for the comparison of different technologies based on criteria such as the reduction of design and implementation time, the decrease in the number of errors, the saving of financial and material resources, the improvement of calculation accuracy, as well as the enhancement of energy efficiency and the overall manageability of construction processes.

The focus was on evaluating the challenges and prospects for the development of digital technologies in construction. Key barriers were identified, such as the high cost of implementation, the need to adapt the regulatory framework, the complexity of integrating digital solutions with traditional construction methods, and the insufficient level of digital competence among specialists. Possible ways to overcome these barriers were analysed, including the updating of regulatory documents, the stimulation of investment in digital technologies, the development of training programmes, and the international exchange of experience. The prospects for the development of digitalisation in the context of global trends in sustainable construction, increased efficiency of resource use, and the automation of construction process management were also investigated.

RESULTS

The digitalisation of construction is the process of implementing digital technologies across all stages of the life-cycle of building projects, aimed at increasing efficiency, reducing costs, and minimising risks. It encompasses the use of automated control systems, artificial intelligence, the Internet of Things, cloud computing, and other digital solutions that allow for the optimisation of the planning, construction, and operational processes of buildings. One of the key technologies of digitalisation is BIM – Building Information Modelling – which involves creating a digital three-dimensional representation of a building with all its characteristics. BIM enables the integration of all stages of design, construction, and operation into a single system, which reduces errors, shortens project implementation time, and improves the accuracy of material calculations. The use of BIM ensures better coordination between contractors, clients, and engineers, which is critically important in conditions of unstable resource supply.

The implementation of BIM allows for a significant increase in the accuracy and speed of drawing coordination by creating a single digital model of the building that integrates all necessary data in one place. This enables all project participants (architects, engineers, contractors) to



work with up-to-date data in real time, which minimises the risk of errors and simplifies the process of approving design decisions. Thanks to the ability to integrate different disciplinary models (architectural, structural, building services, etc.), all changes are automatically reflected in all relevant parts of the documentation. This means that any changes made to one element of the model instantly update the linked drawings, ensuring their synchronisation.

Thus, the process of drawing coordination becomes significantly faster and more accurate, as the need for manual document updates and making changes in different files is eliminated. Thanks to model integration and automatic data updates, the number of repeated checks and adjustments is reduced, which also shortens the time spent on coordinating project documentation. This ensures a faster transition to the construction phase, which is critical when projects have tight deadlines. Within BIM, each stage of design automatically integrates changes into all other elements of the model and the corresponding drawings. This allows for maintaining the relevance of documentation without the need to manually make changes in different files. For example, changing the dimensions of doors or windows in the 3D model immediately updates all related drawings, which significantly reduces the time spent on correcting errors and coordinating changes between different project participants.

Furthermore, automatic updating helps to reduce the likelihood of errors when manually transferring changes between different parts of the project, which, in turn, improves the overall quality of the documentation and lowers the risks associated with inconsistencies in the building's elements. Revit and ArchiCAD are among the most popular platforms for BIM, widely used in the construction industry. Revit is a leading platform for Building Information Modelling. This software integrates various design disciplines (architecture, structural engineering, and building services) into a single digital model, ensuring effective collaboration between different project participants. A key advantage of Revit is its ability to automatically update all project components when model parameters are changed. This helps to reduce the likelihood of errors and simplifies the process of coordinating drawings. ArchiCAD, in turn, also offers a wide range of features for model integration and automatic updating, but with a greater emphasis on flexible work with 2D and 3D elements. This platform allows for more convenient work with drawings, has a large set of tools for creating detailed plans, and enables users to customise them according to project requirements. Both programs, Revit and ArchiCAD, offer powerful capabilities for automatically updating documentation and integrating changes into the BIM model. They have similar features for collaboration and error reduction; however, Revit is more geared towards integration with other engineering disciplines, while ArchiCAD offers a more user-friendly and intuitive workflow for architects and designers. The choice between these platforms often depends on the specific needs of the project, the budget, and the existing expertise of the team.

In any case, both systems significantly enhance the speed and accuracy of creating and coordinating project documentation in the process of digitalisation in construction.

The IoT allows for the use of network-connected devices to collect and process data in real time. IoT sensors can monitor the condition of equipment, the level of construction material stocks, environmental conditions, and the safety level on the construction site. This enables automatic adjustments to workflows, helps to avoid downtime, and increases the efficiency of resource management. The application of AI and machine learning in the construction sector helps to predict potential delays, analyse risks, and optimise logistical processes (Shults *et al.*, 2023). AI algorithms are capable of analysing large volumes of data obtained from IoT devices and BIM models to ensure effective resource planning. Furthermore, AI is used to control the quality of construction and automate routine processes, which helps to reduce the impact of human error. Digital Twin technology is a virtual representation of a physical object or process that allows for the analysis, simulation, and optimisation of the construction process. The use of digital twins allows for the testing of different construction scenarios, predicting the behaviour of structures and optimising the use of resources. Cloud technologies provide centralised data storage and simplify access to information for all participants in the construction process. This enables real-time updating of documents, tracking of changes in projects, and ensuring management transparency (Visartsakul & Damrianant, 2023). Blockchain technologies are used to enhance the security and transparency of transactions in construction, ensuring the reliability of financial operations and control over the execution of contracts. Thus, the digitalisation of construction is based on the implementation of comprehensive technological solutions that allow for the automation of processes, the improvement of resource management, and the enhancement of the efficiency of construction projects, especially in conditions of unstable resource supply (Kim *et al.*, 2020).

The digitalisation of the construction process offers significant advantages; however, its implementation is accompanied by several challenges, particularly in conditions of unstable resource supply. The main focus is on the key challenges and benefits associated with the practical aspects of construction activities – specifically, the processes of preparing project documentation, conducting geodetic surveys, using specialised software for creating drawings and visualisations, as well as performing calculations of material loads and assessing their energy efficiency. Challenges in implementing digital solutions in construction include the high cost of implementation and staff training, as the use of modern software for creating project documentation, geodetic and geological surveys, calculating material loads, and assessing their energy efficiency requires significant financial expenditure. Additionally, staff must undergo training, which increases the timeframes for technology implementation (Demirkesen & Tezel, 2021). The alignment of data formats between these systems is a





complex task, especially when it comes to integrating load calculations, energy efficiency assessments, and geodetic surveys. Insufficient digital literacy within the industry is also a significant obstacle, as many construction companies are slow to adopt digital technologies due to resistance to change. Traditional management methods, paper-based documentation, and manual calculations are still widely used, which complicates the transition to automated processes. Furthermore, reliance on stable resource provision and infrastructure becomes an issue, as digital solutions require reliable electricity supply, internet connectivity, and computing power, and in conditions of unstable resource supply, such as when building in remote or crisis regions, this becomes a significant problem. Cybersecurity and data protection are also important, as the use of cloud technologies and digital platforms for project management increases the risks of unauthorised data access. This is particularly important when storing geodetic surveys, structural calculations, and drawings, which can be critical for the safety of structures.

The successful implementation of digital technologies in the construction industry is only possible with a strategic approach and the integration of innovative solutions at all stages of a project. Digital methods, such as Light Identification, Detection and Ranging (LIDAR), drones, and GIS, have significantly changed approaches to geodetic and geological surveys in construction. These technologies allow for the collection of data with high accuracy and in shorter timeframes compared to traditional methods. LIDAR is one of the most effective technologies for mapping and measuring the Earth's surface, using laser beams to create detailed three-dimensional models. This makes it possible to measure distances to objects more accurately, as well as to determine surface characteristics with an accuracy of up to a few centimetres. Due to its high scanning speed, LIDAR can quickly cover large areas, making it ideal for use in geodesy and geology, particularly for studying landscapes, construction sites and for investigations in areas where traditional measurements are not feasible.

The accuracy of measurements obtained using LIDAR can reach a few centimetres, ensuring high data reliability. In the case of drones, the accuracy of measurements depends on the type of camera and sensors used, but it typically also amounts to a few centimetres for height and a metre for horizontal distances, making them highly accurate for mapping. GIS, in turn, allows for the integration of data from various sources and provides their spatial analysis with an accuracy of up to a few metres, depending on the input data (Golinko & Nedosnovanyi, 2024). Overall, these digital methods provide a high level of accuracy and efficiency in geodetic and geological surveys, which is important for the successful planning and implementation of construction projects. The use of drones in geodesy also allows for obtaining high-precision images and maps of the terrain. With the help of drones, aerial photography can be carried out from altitude, which enables effective mapping of large areas, as well as obtaining 3D models of

the terrain for further analysis. The application of drones in combination with the Global Positioning System and geodetic instruments allows for achieving high accuracy in measurements, which is important for design and engineering. Drone technology makes it possible to conduct investigations in hard-to-reach places, such as mountainous terrains or marshy areas, where traditional methods are impractical or extremely expensive.

The advantages of implementing digital solutions in construction include the optimisation of project documentation creation, as the use of digital platforms such as BIM significantly reduces the time for developing and approving documentation. Automated drawing updates and instant access to information ensure more effective project management. Increased accuracy in geodetic and geological surveys is also an important advantage, as drones, LIDAR, satellite technologies, and GIS allow for the highly accurate determination of topographical features of the terrain, which reduces the likelihood of errors during construction. The automation of material load calculations and energy efficiency analysis is also a significant advantage, as specialised software (e.g., SCAD Office, Tekla, ETABS) allows for the quick and accurate calculation of loads, optimising the use of materials (Abdelalim *et al.*, 2025). Energy efficiency analysis tools (EnergyPlus, DesignBuilder) help to assess the effectiveness of insulation materials and predict the energy consumption of buildings. The optimisation of resource provision and supply chain management allows for the use of digital technologies to control material costs and minimise downtime due to unstable supply. IoT sensors can track the status of warehouses in real time, and artificial intelligence algorithms can predict optimal delivery routes. Improved visualisation and project coordination through 3D modelling, AR, and VR allow clients, architects, and contractors to view the future building at a real scale even before construction begins, minimising the risks of discrepancies between expectations and actual execution. Waste reduction and improved environmental safety are further advantages, as digital resource management helps to optimise the use of materials and reduce construction waste. Automated planning enables a decrease in surplus material orders and, consequently, their wastage (Anh & Pásztor, 2021). The use of software for creating drawings and visualisations has significantly transformed the construction process, particularly through the integration of the latest VR and AR technologies. These technologies allow for a significant increase in the efficiency of project coordination, as they provide the opportunity to visualise the future construction project in a real-world environment. In VR, using special headsets and devices, the user can immerse themselves in a virtual environment where they can fully explore the building project or structure, viewing it from different angles and scales. This significantly improves the understanding of the project and also helps to identify potential problems at the coordination stage that might not be noticed in 2D drawings. AR, in turn, allows for the superimposition of virtual models onto the real world,



making it possible to see how the future project will look in a specific location. This is particularly useful for planning construction work, as it allows for a comparison of the project with the actual parameters of the site in real-time, live conditions. This use of technologies helps to reduce the number of errors in design and decreases the need for expensive and labour-intensive adjustments at later stages.

In the context of 3D visualisation, programs like Navisworks, Unity, and Unreal Engine have powerful capabilities for creating detailed building models and their visualisations. Navisworks provides the integration of different data types and allows for the creation of complex models that help to identify potential clashes between structural elements before work begins on site. This program allows not only for viewing 3D models but also for checking how different construction phases will look in practice. Unity and Unreal Engine offer even greater possibilities for creating interactive visualisations. Unity allows for the development of interactive applications where the user can navigate through 3D models, explore different work execution scenarios, and interact with building elements. Unreal Engine provides high-quality graphics and realistic

visualisations, enabling the creation of impressive visual effects for presentations and real-time project testing. The use of these platforms allows not only for demonstrating projects but also for conducting simulations, analysing various aspects of energy efficiency, and even testing the building's interaction with the surrounding environment (lighting, weather, etc.). These technologies create new opportunities for project development and coordination, as they provide interactivity and realism, allowing all participants in the construction process (from architects to clients) to gain a complete understanding of the future building. This significantly reduces the risk of misunderstandings at the design stage and allows for more effective planning and execution of construction work. Modern construction is actively implementing digital technologies to increase efficiency, reduce costs, and optimise resource provision. The adoption of BIM, GIS, automated control systems, and other digital solutions allows for a significant improvement in the quality of planning, construction control, and facility operation. Table 1 demonstrates the main digital technologies in construction, their areas of application, advantages, and challenges.

Table 1. Impact of digital technologies on construction processes: areas of application, advantages, and challenges

Digital technology	Area of application	Main advantages	Implementation challenges	Software examples
BIM	Design, construction management, cost optimisation	Accurate modelling, automatic drawing updates, coordination between project participants, error reduction	High software costs, need for staff training, difficulty transitioning from traditional methods	Autodesk Revit, ArchiCAD, Tekla Structures, Navisworks
LIDAR scanning and 3D scanning	Geodetic surveys, object condition assessment, reconstruction	High measurement accuracy, possibility of creating digital twins of buildings	Expensive equipment, need for specialised software, large data volumes	Leica Cyclone, Faro Scene, Autodesk Recap
GIS	Site analysis, construction planning, infrastructure management	Visualisation of spatial data, integration with geodetic surveys	Need for high-quality input data, the complexity of analysing large volumes of information	ArcGIS, QGIS, Bentley Map
IoT	Monitoring the condition of construction sites, resource control, safety	Real-time control, cost reduction, prediction of material wear	High dependence on a stable internet connection, risks of cyberattacks	Smart Construction Dashboard, Trimble Connect, Autodesk Forge
VR/AR	Project visualisation, staff training, construction monitoring	Improved client coordination, error detection at the design stage	High equipment costs, content adaptation is required	Unity, Unreal Engine, Fuzor, IrisVR
Cloud platforms for document storage	Project documentation management, team collaboration	Access to data from any location, fast information exchange, protection against data loss	Risks of cyberattacks, stable internet connection is required	BIM 360, Procore, Aconex
Automated construction management systems	Monitoring work progress, logistics, resource planning	Increased efficiency, accurate cost forecasting, minimisation of delays	Need for integration with other systems, need for staff training	Primavera P6, Buildertrend, PlanGrid, Microsoft Project
Automated systems for calculating loads and energy efficiency	Assessment of structural strength, optimisation of energy costs	High accuracy, reduction of calculation time, decrease in energy consumption	Complexity of modelling, need for high-performance equipment	SCAD Office, ETABS, EnergyPlus, DesignBuilder
Drones (UAVs) in construction	Construction site monitoring, geodetic surveys, safety assessment	Reduction of geodesy costs, speed of data acquisition	Need for qualified operators, legislative restrictions	DroneDeploy, Pix4D, Propeller Aero
3D printing in construction	Printing of building elements, construction of low-rise buildings	Reduction of construction time, decrease in material costs	Need for qualified operators, legislative restrictions	COBOD, ICON, WASP

Source: compiled by the authors based on L.D.H. Anh & Z. Pásztor (2021), A. Yasinska *et al.* (2023), D. Bondarenko & K. Kalashnikova (2024)



The development of digital technologies significantly impacts the efficiency of the construction process, reducing risks, optimising costs, and promoting the sustainable development of the industry. However, the implementation of digital solutions requires significant investment in staff training, equipment modernisation, and data protection. Despite these challenges, the use of digital technologies in construction is key to increasing the productivity and resilience of the construction industry. The methodology for implementing digitalisation in construction involves a comprehensive approach that includes several key stages. First, there is an analysis of the current state and the definition of digitalisation goals. This involves assessing existing business processes, and technological provision, identifying key problems, and formulating specific goals, such as optimising load calculations, automating geodetic surveys, or improving document management. The next step is the selection of appropriate technologies and tools, which may include BIM modelling for accurate design, GIS and LIDAR scanning for spatial analysis, software packages for creating drawings and visualisations, automated construction management systems for process monitoring, as well as energy efficiency analysis systems for assessing the impact of materials and structural solutions on energy consumption.

There is also staff preparation and training, which involves conducting training sessions for designers, engineers, geodetic surveyors, and managers, familiarising specialists with the use of digital tools and providing consultancy support. This is followed by pilot implementation and testing on a specific project, which allows for the identification of potential problems, the assessment of the economic efficiency of the technologies, and the adjustment of the integration of new tools with existing systems (Hasegawa *et al.*, 2020). After successful testing, digital solutions are integrated into the overall construction process,

covering all its stages: design and documentation preparation, execution of geodetic and geological surveys, logistics optimisation, calculation of material needs, control of energy efficiency, and operational characteristics of building structures. The final stage is the monitoring of effectiveness and the adjustment of strategy, which includes assessing cost reductions, increasing the speed of project execution, and improving the quality of construction and the level of integration of new technologies into work processes. Thus, the implementation of digitalisation in construction requires careful planning, the adaptation of staff to new technologies, and the continuous analysis of results to increase the efficiency of the construction process in conditions of unstable resource supply (Nikmehr *et al.*, 2021).

In modern construction, the implementation of digital technologies is becoming not just a trend but a necessity, driven by increased demands for the quality, speed, and efficiency of construction work. Traditional methods, based on paper documentation, manual calculations, and physical inspections, are gradually being replaced by digital tools that provide greater accuracy, reduce the risks of human error, and significantly speed up processes. The use of BIM modelling, automated resource management systems, laser scanning, sensor technologies, and other digital tools allows construction companies to manage projects more effectively, minimise costs, and improve quality control (Turner *et al.*, 2020). At the same time, the digitalisation of the construction process is associated with certain challenges, such as the need for staff training, high initial investments, and the integration of new technologies into existing workflows. However, the experience of many companies demonstrates that the long-term benefits of digital solutions significantly outweigh the costs of their implementation. To better understand the differences between traditional and digital methods in construction, comparative Table 2 highlights the key aspects of these two approaches.

Table 2. Comparison of the effectiveness of traditional and digital methods in the construction process

Stage of the construction process	Traditional methods	Digital methods
Design and documentation	Manual drawing, paper-based documentation, complex process for making changes	Use of BIM, AutoCAD, Revit, rapid drawing adjustments, and centralised document storage
Geodetic surveys	Manual measurements, traditional theodolites, high probability of errors	LIDAR scanning, drones, GIS systems, high data accuracy
Geological surveys	Costly and time-consuming process, physical sampling	Digital soil modelling, automated data analysis
Load calculations	Use of standard calculation tables, risk of errors	Software for engineering calculations (SAP2000, ANSYS, SCAD), automation of processes
Cost estimation and cost management	Manual cost estimation, difficulty in accounting for changes in material costs	Automated cost estimation systems (ABC 4, AVK-5), integration with supplier databases
Construction work	Lack of centralised control, paper-based reports	Use of digital construction logs, quality control sensors
Logistics and resource management	Manual supply planning, risk of delays	Intelligent resource management systems, IoT for monitoring material status
Quality and safety control	Visual inspection, risk of human error	Digital monitoring, drones for inspections, AI image analysis
Energy efficiency of buildings	Limited methods for calculating heat loss, reliance on standard designs	Software modelling of energy efficiency, digital sensors for energy consumption
Operation and maintenance	Manual record-keeping, difficult access to data about the building	Digital building logbooks, predictive maintenance using IoT

Source: compiled by the authors based on O. Bashynskiy (2018), V.V. Vapnichna (2020), C.J. Turner *et al.* (2020)



An equally important aspect is quality and safety control. Traditional methods are often limited to visual inspections and periodic checks, whereas digital solutions, such as monitoring sensors and augmented reality, allow for the detection of deviations in real time. This is particularly relevant in conditions of unstable resource supply, where it is important to respond promptly to changes in material costs, workforce availability, and logistical difficulties. Despite the significant advantages of digitalisation, its implementation requires substantial initial investments, the adaptation of work processes, and the training of qualified specialists. However, in the long term, digital methods provide significant cost savings, increased productivity, and reduced project completion times (Urbach *et al.*, 2018).

The Crossrail project, the largest infrastructure project in the United Kingdom, is a prime example of the use of BIM technology for coordinating construction processes (Elizabeth Line, n.d.). For this project, a single digital model of the entire rail transport system was created, including tunnels, stations, and infrastructure. The implementation of BIM allowed for the reduction of errors, the simplification of communication between project participants, and ensured accuracy in the execution of drawings and calculations. Thanks to BIM, effective management of changes that arose during construction was ensured, as well as improved integration with other digital tools. This made it possible to shorten construction time and reduce costs.

In Singapore, digital twins have become a key tool for managing infrastructure projects. By using digital copies of the city's infrastructure, the Singaporean authorities have been able to optimise resource use, monitor the condition of engineering networks, and plan urban development. Digital twins allow for the real-time monitoring of the condition of construction sites, the prediction of resource needs, and the early detection of potential problems. This has helped not only to increase the efficiency of the construction process but also to ensure the sustainability of infrastructure in the long term, which is particularly important in the context of urbanisation and climate change (Muruganandan *et al.*, 2022).

Analysis of the implementation of digital technologies in construction in Ukraine also shows significant potential for increasing the efficiency and quality of construction projects. The company DEHAUSS (2017) actively implements BIM in its projects in Ukraine, which allows for a significant increase in the efficiency of design and construction. Thanks to the use of BIM 360, transparent control of the construction process has been ensured, the quality of work execution has been improved, and logistics have been optimised. However, to achieve wider adoption of BIM, state support, the development of appropriate standards, and the encouragement of the use of these technologies at all levels of the construction sector are necessary. One of the key projects is the ASTON HALL residential complex, located in Odesa. DEHAUSS carried out the conversion of the project from 2D to BIM, covering all stages of the life-cycle: design, construction, and operation. The implementation of BIM allowed for the identification and elimination of design errors and clashes even before the start of construction, which helped to avoid rework, material overruns, and additional work, as well as ensuring adherence to construction completion deadlines.

The implementation of information technologies in construction varies significantly depending on the country, the level of development of digital infrastructure, and the availability of government support. In the United Kingdom, digital solutions, particularly BIM and IoT, are actively used to improve coordination between contractors and optimise the management of construction processes, as evidenced by the experience of the Crossrail project. In Singapore, digital twins and artificial intelligence are used at the level of public administration, which allows for the effective monitoring of urban infrastructure. In Ukraine, the digitalisation of construction is still in its early stages: the company DEHAUSS, in the ASTON HALL project, demonstrated the effectiveness of BIM in reducing costs and increasing design accuracy. However, the widespread adoption of digital technologies is hindered by the lack of unified standards and financial barriers. A comparison of these approaches is presented in Table 3.

Table 3. Comparison of the implementation of information technologies in construction in the United Kingdom, Singapore, and Ukraine

Criterion	United Kingdom (Crossrail)	Singapore (Digital Towns)	Ukraine (ASTON HALL, DEHAUSS)
Key technologies	BIM, IoT, digital twins	Digital twins, IoT, AI	BIM, design automation
Main advantages	Coordination between contractors, change control, optimisation of construction processes	Management of urban resources, forecasting infrastructure loads	Cost reduction, error minimisation, reduction of construction timeframes
Use of IoT	Real-time monitoring of construction processes	Monitoring the condition of urban infrastructure and loads	Limited use (focus on BIM)
Use of AI	Risk analysis, forecasting potential deviations	Automated management of urban processes, adaptive planning	Initial stage of development, used for design optimisation
Level of digitalisation	High, widespread adoption of BIM standards	Very high integration of digital twins at the state level	Partial implementation, lack of unified national standards
Main challenges	High complexity of data integration between contractors	Large data volumes, powerful computing infrastructure is required	Lack of regulatory framework, need for staff training, financial constraints
Economic effect	Cost reduction of 10-15% due to process optimisation	Effective management of urban resources, minimisation of accidents and failures	Cost savings due to the elimination of errors at the design stage

Source: compiled by the authors





The experience of the United Kingdom and Singapore demonstrates a high level of implementation of information technologies in construction, which contributes to resource optimisation, increased forecast accuracy, and cost reduction. In the United Kingdom, the emphasis is on BIM and IoT to improve construction management, while in Singapore, digital twins are used at the state level for comprehensive urban infrastructure management. In Ukraine, digitalisation is only gaining momentum: individual companies, such as DEHAUSS, actively implement BIM to minimise errors and reduce costs, but the overall level of digitalisation remains fragmented due to the lack of unified standards and financial constraints. For the successful development of digital technologies in construction, Ukraine needs to adopt international experience, introduce state support, and standardise processes.

DISCUSSION

The digitalisation of construction is becoming a key factor for the optimisation and efficiency of construction processes, particularly in conditions of unstable resource supply. Digital twin technologies offer significant advantages in the planning, execution, and operation of construction projects. At the same time, this process is accompanied by several challenges related to high implementation costs, the need for staff training, software compatibility, and dependence on a stable resource supply. M. Wang *et al.* (2020) noted that the digitalisation of construction has played an important role in increasing the efficiency and optimisation of construction processes, especially in conditions of unstable resource supply. The authors emphasised the importance of integrating technologies such as BIM, IoT, AI, and digital twins to improve all stages of construction projects. However, the authors also pointed out the existing challenges related to high implementation costs, the need for staff training, software compatibility issues, and dependence on a stable resource supply.

One of the main advantages of digitalisation is the significant reduction in the time taken to develop project documentation and the increased accuracy of calculations. The use of BIM allows for the integration of all stages of the construction process into a single model, which significantly improves coordination between project participants and reduces the number of errors. The implementation of automated construction management systems allows for the optimisation of resource allocation, which is critical when there are unstable material supplies (Kuznetsov, 2024). Furthermore, IoT systems provide the ability to monitor the condition of construction sites in real time, which allows for a quick response to unforeseen situations and the minimisation of risks. Y. Zheng *et al.* (2021) highlighted the advantages of digitalisation, such as the reduction in time for developing project documentation and improved coordination through BIM, which aligns with the findings here, where the importance of these technologies for increasing accuracy and efficiency is also noted. However, unlike this study, the authors did not focus on challenges such as the

need for staff training and resource supply issues. Their emphasis on automated management systems for optimising resources in unstable conditions partially coincides with this study, although this study focuses more on the integration of IoT for site monitoring. Overall, the authors' results confirm most of the conclusions in this study but differ in their focus on certain aspects of technological implementation.

M. Tetik *et al.* (2019) emphasised in their research that a key factor in the successful digitalisation of construction is the integration of digital technologies at all stages of a project – from design to operation. They noted that while the implementation of digital solutions is accompanied by challenges such as high costs and the need for qualified specialists, the long-term benefits in terms of increased efficiency and reduced costs significantly outweigh these. Their conclusions generally align with this study, particularly regarding the importance of a strategic approach to digitalisation. At the same time, the authors placed a greater emphasis on the management aspects of digital transformations in construction, whereas the current study focuses more on the technical tools and methods of their application in conditions of unstable resource supply.

Through the use of digital technologies, such as LIDAR laser scanning and GIS, it has become possible to conduct geodetic and geological surveys more accurately. This enables the determination of site characteristics and the selection of the most optimal construction materials, taking energy efficiency into account. For example, energy efficiency calculation programs such as EnergyPlus and DesignBuilder allow for the prediction of the energy consumption of buildings, as well as the selection of materials that maximally reduce energy costs during the operation of the facility (Sukhodub & Serdechnyi, 2024). L. Jones & P. Hobbs (2021) emphasised the importance of using LIDAR laser scanning and GIS for geodetic and geological surveys, which aligns with this study regarding the application of digital technologies in these processes. However, the authors focused on the selection of materials for energy efficiency using programs such as EnergyPlus and DesignBuilder, which is not present in the current study. Overall, the authors' ideas are consistent with the current ones but include additional specific examples of software.

However, the implementation of digital technologies in construction is associated with several challenges. One of the biggest is the high cost of software and equipment. The expenses for licences for BIM, LIDAR scanners, or specialised load calculation programs significantly exceed the budget of traditional methods. In addition, there is a need for staff training to effectively use these tools, which further increases time and financial expenses. On the other hand, even after the implementation of technologies, problems arise with their integration and compatibility with other platforms, such as AutoCAD or Revit. In the absence of a unified standardised platform for storing and exchanging data, working with different systems can complicate interaction between the various participants in the construction



process. S.A. Hendrawan *et al.* (2024) noted that the main problems with the implementation of digital technologies are the high costs of software and equipment, as well as the need for staff training for the effective use of tools, which aligns with this study. However, this study did not raise the issue of compatibility between different software platforms such as AutoCAD or Revit, unlike this author, who considered the integration of different systems in detail. Overall, the authors' results confirm the findings here regarding financial and training challenges but add specifics regarding software compatibility.

Another significant challenge is the dependence on a stable resource supply. Digital solutions require a reliable electricity supply and internet access, which can be a serious problem for construction in remote or crisis-stricken regions. Power outages or low internet speeds can lead to delays in the execution of work and disable digital monitoring and management systems. J. Wang *et al.* (2022) emphasised the importance of a stable resource supply for the effective implementation of digital technologies, noting that a reliable electricity supply and internet access are critical factors for working with digital systems. These results align with the findings of this study, as this study also highlights the dependence on a stable resource supply as one of the main problems of construction digitalisation. However, the authors described the potential consequences of low internet speeds or power outages in more detail, which was not emphasised in this study.

Furthermore, data security is an important aspect of implementing digital technologies. The use of cloud platforms for storing documentation and managing projects increases the risks of unauthorised access to critical data, such as drawings, load calculations, and geodetic surveys. In this regard, it is necessary to develop and implement strategies to protect data from cyber threats. S. Somanathan (2023) noted that with the development of digital technologies in construction, there is a need to ensure data security. The use of cloud platforms for storing project documentation and managing projects can increase the likelihood of unauthorised access to important data, such as drawings, calculations, and research results. In this regard, it is important to develop measures to protect data from cyber threats and ensure reliable information security. This aligns with the findings of this study, which also addressed data protection in the context of digitalising construction, although it did not focus on cloud technologies and cybersecurity aspects, which emerge as critical in the research by this author.

Despite the challenges, the digitalisation of construction offers significant advantages in increasing efficiency, reducing costs, and improving the quality of construction work. Through the integration of the latest technologies, it is possible to significantly shorten construction time, increase the accuracy of work execution, and optimise resource expenditure. In particular, the ability to carry out automatic documentation updates, real-time monitoring of the construction status, and accurate energy efficiency calculations allows for the creation of more sustainable

and economical buildings (Schults *et al.*, 2016). J. Berlak *et al.* (2020) investigated the impact of digitalisation on construction efficiency, focusing on increasing the accuracy and speed of work execution. Their article noted that the integration of new technologies allows for a significant reduction in construction time, an increase in the accuracy of design calculations, and the optimisation of costs. Particular attention was paid to monitoring and the automatic updating of documentation, which allows for more effective project management at all stages. The results of the authors' study align with this research in certain aspects, particularly in highlighting the advantages of digitalisation for increasing efficiency, reducing construction time, and improving the quality of work through the integration of the latest technologies. However, their article places more emphasis on the automatic updating of documentation and the real-time monitoring of the construction status, while this study focuses more on the use of specific tools for energy efficiency calculations and resource allocation. Also, the authors paid less attention to the challenges associated with digitalisation than in this study.

For the successful digitalisation of construction, it is necessary to address several problems, particularly those related to cost, training, and ensuring data security. However, provided there is a strategic approach and the integration of innovations at all stages of construction, digital technologies can significantly improve resource management and ensure high efficiency of construction processes, even in challenging conditions of unstable resource supply. In their study, F. Elghaish *et al.* (2021) noted that for the successful digitalisation of construction, it is necessary to address several key problems, such as the high cost of technologies, the need for staff training, and data security issues. At the same time, they indicated that with a strategic approach and the integration of innovations at all stages of construction, digital technologies are capable of significantly improving the efficiency of resource management and ensuring high performance of construction processes, even in challenging conditions of unstable resource supply. These conclusions correspond to the results of this study, as it is also noted that for the implementation of technologies, it is important to address issues of funding, security, and staff training. However, the authors placed more emphasis on strategy and the integration of innovations into the overall process, while this study also considered specific aspects of using the latest technologies for energy resource management and the monitoring of building conditions.

In their study, K. Guo & L. Zhang (2022) noted that the digitalisation of construction can significantly improve resource management and optimise construction processes. However, the successful implementation of technologies requires a comprehensive solution to problems associated with the high cost of software, the need for staff training, and ensuring cybersecurity. They emphasised that a strategic approach to the integration of digital solutions allows for the minimisation of risks and the increase of efficiency, even in challenging conditions. Their conclusions partially





align with the findings presented here, as this study also emphasises the importance of addressing these challenges. However, unlike this study, the authors focused more on cybersecurity issues and the organisational aspects of digital transformation, while this study places a greater emphasis on the technical aspects of resource management and the application of specific digital technologies in construction. Thus, the results of the conducted research not only confirm the key conclusions obtained by other researchers but also supplement them with new details, particularly in the context of the technical implementation of digital solutions in construction under conditions of unstable resource supply.

CONCLUSIONS

This study conducted a comprehensive analysis of the digitalisation of construction, examining key technologies, their advantages, challenges, and implementation methods. The research confirmed that digitalisation encompasses the entire lifecycle of construction projects, from design to operation, using BIM, IoT, AI, digital twins, cloud technologies, and blockchain. It was demonstrated that BIM allows for the reduction of errors, the optimisation of resource management, and the increased accuracy of material calculations, while the integration of IoT provides real-time monitoring of sites, promoting the efficient use of resources. The use of AI in construction helps to analyse risks, predict delays, and optimise logistical processes, while digital twins allow for simulations and the prediction of structural behaviour. It was determined that cloud technologies simplify document management, and blockchain promotes the transparency of financial transactions and ensures data security. Within the scope of the study, real-world case studies of the implementation of digital technologies in construction were analysed. Specifically, in the DEHAUSS project, BIM technologies ensured effective coordination between contractors, and digital twins were used for the management of urban resources. In the United Kingdom, in the Crossrail project, BIM facilitated smooth coordination between different contractors and the

optimisation of construction, reducing risks and delays. In Singapore, digital twins are actively used for monitoring and managing urban resources, increasing infrastructure efficiency and improving city development planning.

The practical construction aspects of digitalisation were considered separately, including documentation development, the execution of geodetic and geological surveys, and the use of software for drawings, load calculations, and the assessment of material energy efficiency. It was determined that digital technologies allow for a significant increase in the accuracy of geodetic surveying, improved project modelling using 3D scanning, as well as the automation of design and engineering calculation processes. At the same time, several challenges were identified, including the high cost of implementing digital solutions, the need for staff training, software compatibility issues, and the complexity of data integration between different systems. The problem of an unstable resource supply, which affects the stability of digital solutions, especially in remote or crisis-stricken regions, was also investigated. The results of the study confirmed that the digitalisation of construction is a key factor in increasing the efficiency of the industry. However, its successful implementation requires a comprehensive approach, investment, and the resolution of several technical and organisational challenges. Promising directions for further research include the development of adaptive digital solutions for conditions of unstable resource supply, the improvement of methods for integrating BIM and IoT, as well as the evaluation of the effectiveness of artificial intelligence in predicting risks in construction projects.

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Оптимізація будівельного процесу за допомогою цифровізації на прикладах проєктів в умовах нестійкого ресурсозабезпечення

Анотація. Метою роботи було дослідити вплив цифрових технологій на оптимізацію будівельного процесу за умов нестійкого ресурсозабезпечення та сформулювати практичні рекомендації для їх ефективного впровадження. Методологія дослідження включала аналіз сучасних тенденцій у сфері цифрових рішень, зокрема інформаційного моделювання будівель, технологій Інтернету речей, штучного інтелекту, цифрових двійників та хмарних платформ. Було розглянуто можливості інтеграції цих технологій для покращення планування, будівництва та експлуатації об'єктів, а також їхній вплив на підвищення ефективності управління ресурсами. Проведений аналіз реальних кейсів, зокрема впровадження інформаційного моделювання будівель у проєкті ASTON HALL компанії DEHAUSS, який підтвердив значний потенціал цифрових технологій. Також розглянуто проєкт Crossrail, де BIM-технології забезпечили ефективну координацію між підрядниками, і використання цифрових двійників у Сінгапурі, які використовуються для управління міськими ресурсами. Дослідження показало, що інформаційне моделювання будівель сприяє зменшенню помилок у проєктуванні та будівництві, покращенню координації між учасниками проєкту та зниженню витрат. Технології Інтернету речей забезпечують моніторинг стану будівельних матеріалів та обладнання у реальному часі, що підвищує рівень безпеки та зменшує ризики простоїв. Використання штучного інтелекту дає змогу прогнозувати можливі затримки, оптимізувати логістику та автоматизувати процеси управління. Цифрові двійники дозволяють тестувати різні сценарії будівельного процесу, що позитивно впливає на якість кінцевого результату. Основними викликами цифровізації будівництва залишаються висока вартість впровадження технологій, необхідність навчання персоналу, складнощі інтеграції програмних платформ та питання кібербезпеки. Водночас переваги, такі як автоматизація процесів, підвищена точність розрахунків навантажень та енергоефективності, оптимізація ресурсозабезпечення та вдосконалений контроль за будівельними проєктами, підтверджують стратегічну важливість цифрових рішень у розвитку будівельної галузі. Результати дослідження продемонстрували, що комплексний підхід до впровадження цифрових технологій, адаптація будівельних процесів та ефективна інтеграція цифрових платформ можуть суттєво підвищити продуктивність будівельних проєктів, особливо в умовах нестійкого ресурсозабезпечення.

Ключові слова: блокчейн; інформаційне моделювання будівель; геоінформаційні технології; хмарні обчислення; дистанційне зондування



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Classification of agricultural elements used in buildings

Abstract. The study addressed the utilisation of agricultural elements and applied landscaping in buildings, as current research in the field of architecture is either absent or only tangentially related to the topic. The study aimed to classify the agricultural element in the building structure to provide a basis for further research in this area, to identify the main characteristics of agricultural elements and to establish their interaction with buildings. The study used analysis of literary and scientific sources, logical, decomposition, comparative analysis, graph-analytical method, formalisation, generalisation and abstraction, and induction. As a result of the interdisciplinary research, three main possible ways of distinguishing between agricultural elements and/or applied landscaping were identified. These are: “by purpose”, “by use model”, and “by location”. The classification of the studied buildings was conducted based on the aforementioned characteristics. The first category, “by purpose”, denotes the primary function of the agricultural element in the structure of the building and includes the following subtypes: commercial, social, and recreational elements. The second “by use model” category reflects a certain function of an agricultural component: for commercial purposes, it is the food production capacity; for recreation, its visual accessibility, and the number of people it can serve in the case of applied recreation. This category includes subclasses: citywide, district use, and in-building. The third category, “by location” denotes the location of agricultural or landscaping elements in the structure of the building and contains subclasses “in the structure of the plot”, “in the structure of the building”, and “in the structure of the apartment (floor)”. The practical value of this study is that the results complement the conceptual and terminological apparatus and can be used to create recommendations and guidelines for designing agricultural elements in the building

Keywords: housing; apartment; planning; landscaping; agricultural production

INTRODUCTION

New constructions are being formed in architectural practice with the introduction of applied greening and food growth units. This reflects the need and consumer desire for a green natural environment in the conditions of the over-compacted space of modern cities, which, according

to I. Hnes & U. Ivanochko (2019), create a perceptive lack of space. The negative impacts of the urbanisation process in the form of overidentification of the urban environment and lack of necessary social services, which negatively affect health and mental well-being, were studied by

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T. Cheung *et al.* (2024) on the example of Hong Kong and C. Sun *et al.* (2023) on the example of Germany. The existing problems of suburbanisation in urban development were considered by J.B. Kocsis & K. Tomay (2024), namely, bloating and increased traffic. A. Sarzynski & T.J. Vicino (2019) noted the insufficient provision of the necessary resources and services, which increases criminogenic activity.

J.K. Mensah (2023) analysed the potential of urban agriculture in local economic development of cities. The study examined the role of urban agriculture in local urban economies in the developing country of Ghana. The study demonstrated that, with proper support, urban agriculture can improve the local economy through numerous benefits in terms of employment, income, improved livelihoods and food security. S. Barron & E.J. Rugel (2023) explored the correlation between young people, the environment and the impact on future decisions and priorities. In a potentially limited space of green areas, a person may experience a weakened sense of connection with nature, leading to less time spent in the natural environment and less sustainable behaviour.

However, despite the large number of existing buildings, as of 2025, no clear classification of agricultural elements (AE) in the building structure is present, which complicates further research on this topic. The study aimed to develop the classification in the building structure. The task of the study was to classify agricultural elements in the building structure based on the analysis of the existing architectural practice of introducing agricultural elements into the building structure. The study addressed agricultural elements as a physical, structural component of the environment to determine the nature urban agricultural element in the development structure, for which, until 2025, no methodological provisions for their planning and regulation was present in the Ukrainian scientific community.

MATERIALS AND METHODS

At the initial stage of the study, the multilevel nature of the problem and the relevance of the research were determined by analysing literature and scientific sources. Due to the complexity of the issue of growing plants in a building, an interdisciplinary research method was used to determine the characteristics of AEs. Previous studies have identified the main characteristics, which were used to categorise and systematise the worldwide practice of AEs in buildings, based on research by L.J.A. Mougeot (2005), M.M. Herrmann (2015), and S. Barron & E.J. Rugel (2023). Studies that describe methods and ways of AE implementation in buildings were prioritised. After clarifying the prerequisites and scientific basis, a sample of objects was formed using the methods of critical and comparative analysis, as well as the method of generalisation, based on the following criteria: typological diversity of buildings, belonging to different geographical areas and time, purpose, location in the city structure, and variability of use.

The next stage focused on the study of existing objects or concepts with AE in their structure. Among the wide

range of nations whose architectural practice includes the creation of buildings, including residential dwellings with AE, countries with a temperate climate were selected due to beneficial plant growth conditions. The objects were selected from different periods, with descriptions of their original intent and how they were used. A total of 63 examples of buildings with applied landscaping and/or agriculture in their structure were considered (Google Docs, n.d.). Using the method of deconstructive analysis, the location, principle of functioning, and purpose of the elements of landscaping and agricultural production were identified following the previously adopted classification. By combining the methods of reduction from the individual to the general and abstraction, each element was generalised to a broader concept, which was used for the main classification. To simplify information processing, the method of formalisation was used with the help of ArchiCAD 25 and Adobe Photoshop 21. The studied buildings were recorded in the form of a miniature, according to the appearance, description, or commentary from the designer. The use of images of the same size, style, and construction principle demonstrated the difference between different elements of the classification, which simplified the systematisation of building characteristics. The study described in detail the research algorithm using four separately selected buildings representing the sample width: residential, commercial, public, and industrial buildings. Based on the obtained data, a matrix was formed using the method of matrix construction, which reflected the relationship of selected objects from different periods and locations to the developed classification system. Graphic materials for all the projects under consideration were taken from the websites of the object, technology representatives, or the large electronic gallery of modern architectural objects at AchDaily (n.d.). The final stage of the study categorised AE used in the structures of the building. Three main classifications and nine subclassifications were identified and tested using the diachronic and synchronic methods.

RESULTS AND DISCUSSION

The main aspects and principles of the arrangement of an agricultural element in the structure of multi-story housing are similar to traditional means of creating green architecture. Everything that applies to “classical” landscaping is also true for vertical farming in terms of wind, sun, soil, water, and fertilisation requirements. The fundamental difference between the two is that vertical farming involves an end result of being sold or used as self-sustaining production. The principles of functioning of the agrarian element in the city as a whole, as well as the factors influencing its formation, were described by L.J.A. Mougeot (2005). The specifics of the formation of AE and their purpose during the Second World War were studied by M.M. Herrmann (2015), while S. Barron & E.J. Rugel (2023) investigated the importance of the impact of greening on young people in contemporary society. J.K. Mensah (2023) addressed urban agriculture as a key to overcoming



hunger and sustainable food sourcing. D. Chen *et al.* (2024) analysed the importance of agricultural production near cities. D. Starr (2021) addressed the impact of fresh air, and P. Reed (2021) analysed the effect of physical labour on health. I. Panțiru *et al.* (2024) also noted the impact of agriculture on health. Based on the above, four key characteristics of AEs were identified: purpose, use (capacity for commercial production), technology, and location.

Based on the primary agricultural element characteristics, the categorisation was conducted during development, particularly, in building. The purpose determines its main function in the building and its priority goal – recreation, social or commercial. The use model depends on the size and type of the AE, and its functionality. Technology determines the technological process of agricultural production. Location describes how the building interacts with the environment.

In 2014, a residential complex with 213 apartments and eight shops in 7 blocks with 4-7 floors above ground was built in Vienna's 22nd district (Fig. 1). The courtyard, which is the centre of this residential complex, is a semi-enclosed area connected to the pedestrian zone. Each building has its courtyard, which is furnished at the request of the residents – either as a simple recreation or as an agricultural element. The latter is widely used for educational purposes for children or elderly people. It contributes to their socialisation and the creation of hobbies. This neighbourhood is well-planned in terms of high-density, medium-rise buildings combined with privacy and comfort (Komar, 2023). The courtyards are divided into gardens and recreation areas. Residents can manage the space in the courtyard independently, which improves overall well-being via sense of property. R. Waldinger & M. Schulz (2023) noted that strong social ties positively influence cognitive functions.



Figure 1. “Wood Housing” by Seestadt Aspern, Vienna

Source: compiled by the authors based on Wood Housing Seestadt Aspern / Querkraft + Berger+Parkkinen Architekten (2020)

Quarterly development, interior-oriented galleries with access to apartments from the middle of the complex, a large amount of greenery, places for recreation, and common spaces positively affect the socialisation of residents. According to T.H. Tan & W.C. Lee (2023), a well-designed, balanced environment improves quality of life, including for the elderly. Lower levels apartments have access to the green roof of the stylobate. The roof has designated space for the residents to engage in agricultural activities. A notable feature is the transition spaces that connect apartments with shared agricultural elements on each floor (Wood Housing..., 2020).

Given that this is a residential building, the AE is designed as a private, applied recreation for residents. This space is intended to provide a variety of agricultural and landscaping elements for the residents. The location of the AE on the external enclosing structures and summer rooms, alongside a barrier and privacy of the adjacent spaces, further enhances the design's purpose. The impact of

such a structure is exclusively in-house, due to the specifics of the location of the AE and landscaping, most of which is located inside the building. However, the use of certain measures allowed to creation of a green barrier between the street and private space. This allows the AEs to be observed by passers-by, which works as a short-range visual recreation.

Home Farm (Fig. 2) adapts a simple aquaponics system inspired by the system successfully used in Singapore by the ComCrop initiative, which grows crops on rooftops using off-the-shelf components. In the project, aquaponics is adapted for use on the building facade, linear soil farming at the highest levels, and on the roofs of buildings. This concept provides for various types of employment for the elderly: planting, harvesting, sorting, packaging, tours, on-site sales, delivery, and cleaning. The rewards for this include salary payments, reimbursement of rent or utility bills, reimbursement of medical expenses at a local clinic, or free products. This makes the building accessible to



older people, especially those with financial difficulties. All of this together will help to form a sustainable community

and bring people together, which will also improve psychological state and well-being (Rosenfield, 2014).

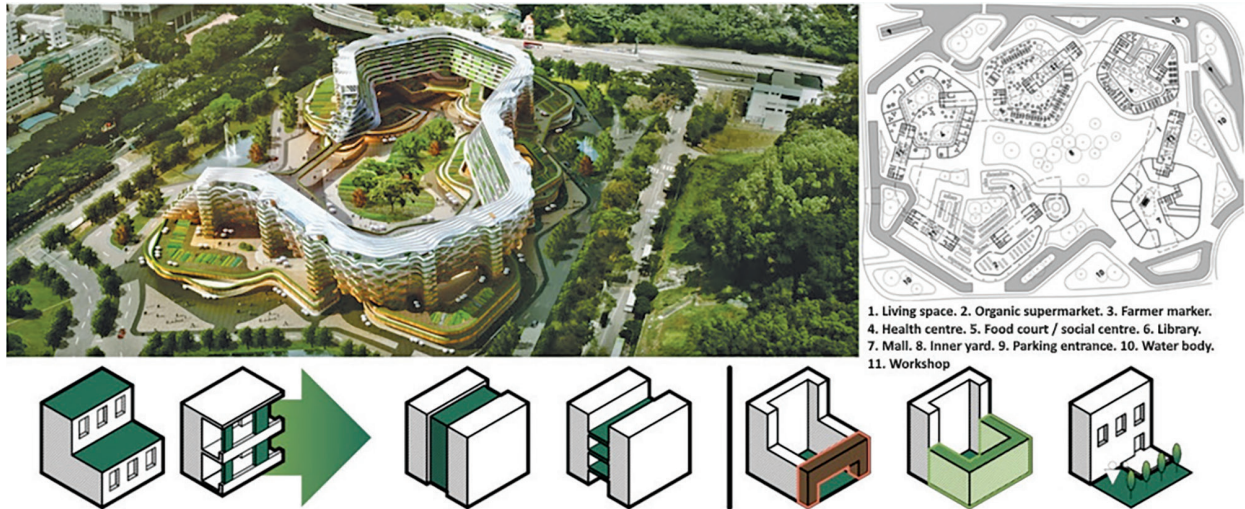


Figure 2. Home Farm by SPARK architects, Singapore

Source: compiled by the authors based on SPARK – HOME FARM (n.d.)

Following the project description, the Home Farm is a private initiative (SPARK – HOME FARM, n.d.). The agricultural element is diverse in terms of technology: hydroponics, linear beds, and planar beds, located on the structure of the building on vertical and horizontal planes. The total area for growing is 14,800 m², an estimated 34.9 tonnes of food per month. Based on the building and its functional content, namely the location of several local retailers and an economic zone with unloading functions, it is possible to conclude that the complex is designed for local production and the prospect of providing food for the surrounding areas. Farm upkeep implies complex physical processes over technology, therefore implementing physical recreation, which, according to T.L. Scott *et al.* (2020), improves well-being, especially among the elderly. C.P. Wen *et al.* (2011) have studied the relationship with increased life expectancy.

This concept has many benefits, including cost-effectiveness, food security, social interaction, health, sustainability, environmental shaping, and healthcare delivery.

The Whole Foods store (Fig. 3) in Gowanus, Brooklyn, opened in 2013, is unique in that it features an 1,860 m² hydroponic indoor farm on the roof, the first commercial-scale greenhouse attached to a supermarket. The retailer serves as a sales outlet for the farm on top. The hydroponics technology and automation of processes enable growth of organic products all year round and for further sale in all nine Whole Foods stores in New York. Moreover, the location in the city addresses the food mileage and shelf-life concerns. Accordingly, from the standpoint of an urban customer, significant improvement of shelf-life is a substantial contribution to quality of life. This generally affects the competitiveness of the business (Gotham Greens, n.d.).

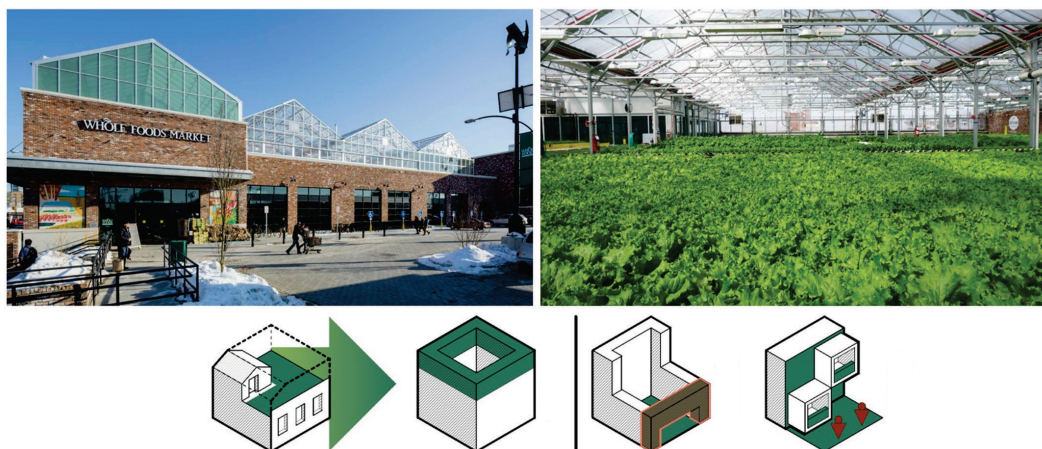


Figure 3. Gotham Greens, on the roof of a Whole Foods store in New York, USA

Source: compiled by the authors based on Whole Foods goes ultra-local with Gotham Greens greenhouse in Brooklyn (2013)



According to the description of the facility, Gotham Greens is an urban commercial project, designed for local production for the affiliated retailer, as well as for export throughout the internal network, which as of 2013 includes six commercial roof farms and more branded retailers, therefore it can be defined as an element of citywide commercial production (Whole Foods..., 2013). From the standpoint of consumers, the facility is a decorative building, prominent for greenery in urban environment.

The Avling Kitchen and Brewery, in addition to the typical elements of such a building, also has a 400 m² roof garden. The garden provides ingredients for business in-house use. The company aims to create a sustainable and organic farm with a wide variety of local plants such as herbs, vegetables, cereals, and hops. Flowers are also grown in the garden, which are an important element for a sustainable ecosystem. The type of crop is also selected to ensure the longest possible harvest period throughout the year (Fig. 4).

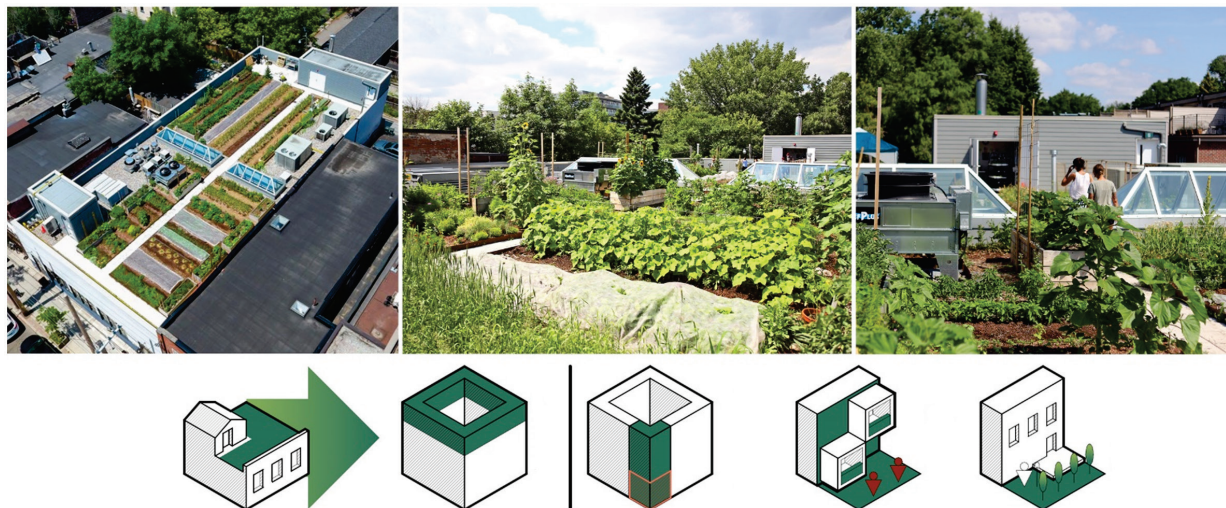


Figure 4. Avling Kitchen and Brewery, Toronto, Canada

Source: compiled by the authors based on Avling Kitchen and Brewery, Toronto (n.d.)

The description of the project annotation to the implementation technology demonstrates that the roof farm is a local autonomous source of food for the establishment. Accordingly, it can be defined as commercial local production. The system is semi-automatic, based on earth masses. Flowers and frequent roof tours for visitors provide visual and applied recreation.

All 63 objects from different periods were studied using the same algorithm of actions, according to the size and purpose of the main building and the use of AE in its structure, using this algorithm of actions with the specified

methods. The results of the objects belonging to the classifier are recorded in a matrix Table 1, subsequently used to draw conclusions. During the study of individual objects, their features were grouped by similarities and common features, and these results were formalised. Due to the number of objects under consideration and the width of their sample, this process was carried out in several stages. This was used to derive subclasses based on the created intermediate groups additionally. The article presents the second matrix dedicated to this study, which includes intermediate groups.

Table 1. Matrix of the objects under study with an analysis of the agrarian element and its features

No.	Period	Object, location	Purpose/function of the building				AE function (greening)							Technology		Placement in the structure			
			Housing	Commerce	Production	Public	for sale	For community	For personal use	Socialisation	Rehabilitation	Visual	Individual						Applied
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	17 th -20 th centuries	Villa Gamberaia Florence, Italy																	
2		Villa Belrespiro Sanremo, Italy																	
3		Villa Borghese Rome, Italy																	
4		Villa d'Este Tivoli, Italy																	



Table 1. Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
5	17 th -20 th centuries	Château de Villandry Villandry, France																	
6		Walmer Castle Welmer, UK																	
7		Château de Chenonceau Endre and Loire, France																	
8		"Schreber Gardens" Leipzig Germany																	
9		Community garden "Quinta da Granja" Lisbon, Portugal																	
10		Peach orchards Gobétue 8 Montreuil, Paris, France																	
11		London's Victory Gardens London, UK																	
12		The Hill (Inverforth House) London, UK																	
13		Barbican Estate London, UK																	
14		St Catherine's College Oxford, UK																	
15		Rooftop farm (social programme of 1970) Chicago, USA																	
16		Residential building "79&PARK" Stockholm, Sweden																	
17		Court-housing Cortingborg Groningen, the Netherlands																	
18		"Edison lite apartment" Paris, France																	
19		"SPARK residential living" Singapore																	
20		"Gotham Greens" at Whole foods store New York, USA																	
21		"Lufa farms" in Quebec, Canada																	
22		Gemeinschaftsgarten Madame Dora Aspern, Vienna, Austria																	
23		"Wood Housing" Seestadt Aspern, Vienna, Austria																	
24		"Parkviertel Giesing" Munich, Germany																	
25		"La Tour Vivante" Paris, France																	
26		"One Central Park" Sydney, Australia																	
27		"Vertical forest" Porta Nova, Milan, Italy																	
28		"ARBORICOLE" Paris, France																	
29		"Living garden" Vienna, Austria																	
30		"Clock House Gardens" Welwyn, UK																	
31		"Origami Housing" Portland, USA																	
32		Rb on Ruben Dario 225 New Mexico, Mexico																	
33		Rb "Sky Villas" Hyderabad, India																	
34		Fira Hotel Barcelona, Spain																	



Table 1. Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
35		Rb "Wooden Mixed-Use Tower" Bordeaux, France																	
36		"Admiralty Kampung" Singapore																	
37		Acros Fukoka Concert Hall, Fukuoka, Japan																	
38		Residential building "SkyTerrace" Singapore																	
39		Residential building "SkyVille" Singapore																	
40		Rb "Puukuokka housing block" Jyväskylä, Finland																	
41		Rooftop Farm in Zuidpark Amsterdam Netherlands																	
42		"Le cordon bleu" Paris, France																	
43		La Serre (Porte de Versailles) Paris, France																	
44		Zinfandel / Field Architecture St Helena USA																	
45		Avling Kitchen and Brewery Toronto, Canada																	
46		"Uncommon Ground" restaurant, Chicago, USA																	
47		"One canal apartments" Boston, USA																	
48	21 st century	"Harvard square roof deck" Cambridge, USA																	
49		"Fenway farms" Boston, USA																	
50		"Whole foods" Linfield, USA																	
51		"Carport roof garden" Brooklyn, USA																	
52		"Boston medical centre" Boston, USA																	
53		"Ester restaurant" Dorchester, USA																	
54		"Sally's rooftop farm" St. Louis, USA																	
55		"Higher ground farm" Boston, USA																	
56		The Inside Home Ammameh, Iran																	
57		Iron Creek Bay Farm Stay Sorel, Australia																	
58		Ushimaru Restaurant Sammu, Japan																	
59		Molí House Balearic Islands, Spain																	
60		Paul and Monique House Gnet, Belgium																	
61		The Corner Building Hegedal, Norway																	
62		"Green Seedling" 6 Tianfu Agricultural Chengdu, China																	
63		The Urban Farming Office Ho Chi Minh City, Vietnam																	

Source: compiled by the authors based on Google Docs (n.d.)



The matrix demonstrates the varieties of the agricultural elements in the structure of the house, meeting the purpose of the study. Accordingly, the classification proposed by the study, based on the newly created matrix, contains three main classifiers, namely, by purpose, by usage model, and by location. The technological characteristic was rejected due to higher relevance to the commercial and industrial sectors. Nine subclasses, three for each of the classifiers, were also created.

Based on the main function (alternative to classic agriculture; creation of new objects of interest for business within the city; influence on the aesthetic of the architectural image and the formation of an attractive environment; creation of new common public spaces capable of contributing to the socialisation of the population, or raising children, or positively influencing the social – unprotected stratum of the population) the agricultural element by purpose can be classified as (Fig. 5):

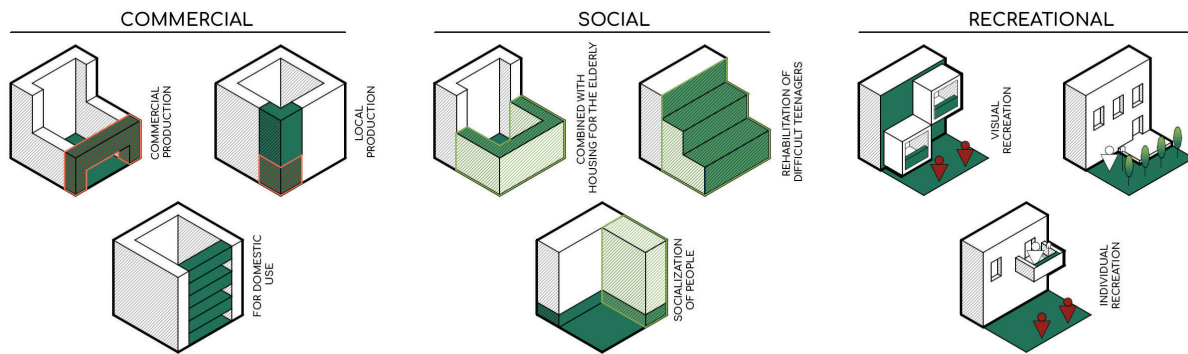


Figure 5. Classification of AE in the structure of the building by purpose

Source: compiled by the authors

1.1. A commercial agricultural element, the main purpose of which is to create alternative sources of food in the city, providing food products to a certain segment of the population. Subclasses:

1.1.1. Commercial production, assumed to be a full-fledged agriculture located in an urban situation. As part of the building and with auxiliary functions, both the production and the product sales centre work.

1.1.2. Local production, represented as the cultivation of a certain type of product with its future sale.

1.1.3. Personal use – a personal or joint place for running one's farm in the structure of an individual, common house or urban space, where the consumer himself decides how to use this plot and what to grow on it.

1.2. The social element, aiming to create a space for passive and/or active socialisation of the population, in particular vulnerable groups, to create open spaces in the city for hobbies with constant interaction with other people. Subclasses:

1.2.1. Socialisation of children from boarding school and child-rearing is an intermediate stage of integration into the social environment, demonstrating simplest social processes on practical examples.

1.2.2. Rehabilitation of troubled teenagers – an opportunity to engage children and teenagers in physical activities, protecting from the negative effects of the environment, providing monetary rewards as additional motivation.

1.2.3. Socialisation for lonely elderly people – creating an environment that helps overcome obsessive thoughts and feelings of loneliness and provides care for the elderly.

1.3. Recreational element. With a high density of buildings in the urban environment, the green areas of

landscaping aim to diversify the architectural and urban planning features of the object, as well as to compensate for the insufficient amount of green areas in the conditions of urban development. The subclasses include:

1.3.1. Visual – a distant aesthetic element of architecture for the enrichment of the visual image and biodiversity of the environment.

1.3.2. Applied – an aesthetic element of architecture with the possibility of direct contact with landscaping.

1.3.3. Individual – in the form of a terrace or a special summer room, as its green cell.

Depending on the capabilities of the city and the resources of the integrated agricultural complex, its functions are adapted and developed according to the needs. This complex can be semi-open, serving a large city region from a commercial point of view, adapt to various social processes, or even have a more psychological nature of recreation for the building's residents. Accordingly, the agrarian element can be divided into (Fig. 6):

2.1. City-wide vertical farms – farms of an industrial type in the structure of buildings, in commerce residential buildings, the capacities of which provide cultivation of food products with a reserve and provide long supply chains.

2.2. Farms of district use (or local) – farms of medium and small industrial capacity, capable of providing products to the surrounding buildings, according to the type of farmers' markets. Agriculture is directly connected to the place of sale, which ensures better turnover.

2.3. Farms for domestic use – small personal or public farms located on free spaces of buildings used as recreation for residents.



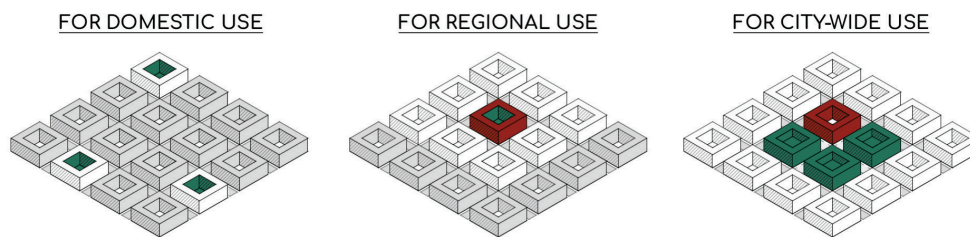


Figure 6. Classification of AEs in the building structure according to the use model

Source: compiled by the authors

A key aspect in planning and architecture is the location of AE in the structure of the building, as it significantly affects the aesthetics of the building and interaction with residents, neighbours, and passers-by through green decoration. This determines how the building interacts with the environment, the development of social processes, the form of recreation, and opportunities for psychological relaxation of the residents. Accordingly, the agricultural elements can be divided by location into (Fig. 7):

3.1. In the structure of the yard – agricultural element is located outside the building itself but integrated into its space.

3.2. In the structure of the house – agricultural element is integrated into the general structure of the building and is a massive part of it.

3.3. In the structure of a floor (apartment) – agricultural element is integrated into the floor structure of the building and exists only within its boundaries.

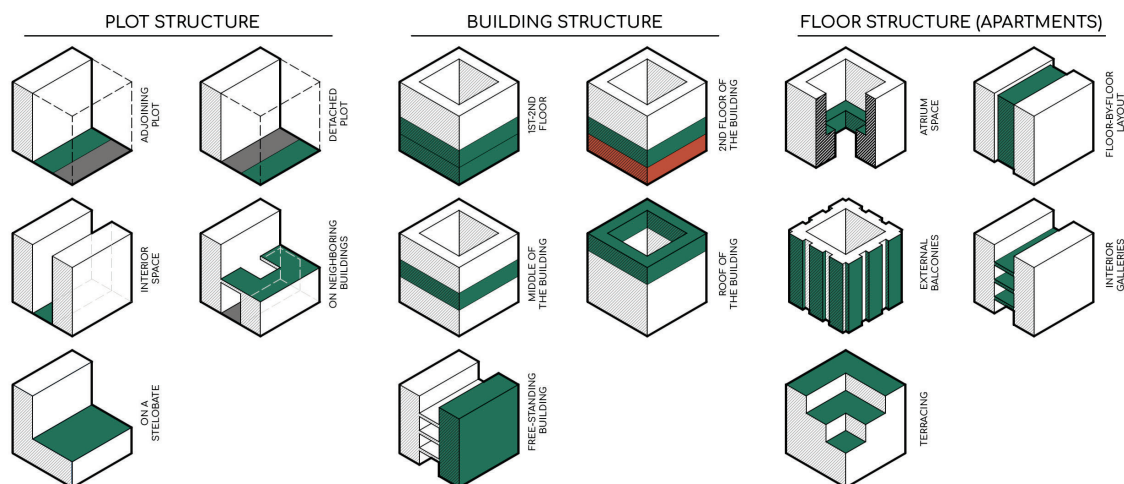


Figure 7. Classification of AE in the structure of the building by location at different levels

Source: compiled by the authors

In general, the feasibility of urban agriculture was described by L.J.A. Mougeot (2005), providing the basis for many researchers in the field of urban agriculture, such as K. Srinivasan & V.K. Yadav (2024). Although current research addresses the technological support of urban agricultural production, the results confirm the statements described in 2005. A. Addas (2024) explored how the introduction of large amounts of urban green space benefits the social fabric of cities. S. Basso *et al.* (2023) examined the convergence of nature and architecture, analysing the phenomenon of vertical trusses as an architectural manifestation of certain modern trends. Specifically, high-rise buildings are functional for agriculture, while demonstrating sustainability features such as reducing supply chains and land consumption. The author conducted a critical analysis of the potential impact of vertical farms on urbanism based on the concept of the right to food.

Analysis of existing experience can be used to compile the possibilities of integration in the structure of buildings of various types. These results correlate with the research conducted by N. Avdieieva & Yu. Zakharov (2021), which addressed the current state of the art of classifying “green structures” in the architectural design and construction of various types of buildings and structures. In addition to the economic characteristics considered in urban agriculture, the differences in classification are in the features of the research objects. AE requires close human contact with the plant to ensure the possibility of farming, which renders variety of AE arrangements in any remote elements of the building impossible, in contrast with the landscaping considered by N. Avdieieva & Yu. Zakharov.

S. Buravchenko *et al.* (2021) investigated ways to solve the problem of a significant reduction in greening in housing construction. The features and types of landscaping on



residential buildings and built-in structures for growing plants are considered. The author examined global trends and features of designing ecological neighbourhoods and residential buildings integrated with greenery. N. Miroshnyk (2023) studied the relationship between urbanisation and ecosystem services of green spaces in the example of the Kyiv urban ecosystem. The author noted that improving the quality of ecosystem services of green infrastructure can be achieved by reducing artificial surfaces, increasing the area of forests and parks within the city is possible through new technologies of vertical gardening, green roofs, rooftop parks, economic incentives for the preservation of large-scale multi-tiered plantations.

Thus, the analysis of integration of agricultural elements (AEs) into urban residential structures created a classification by purpose, usage model, and location. The multifaceted roles of AEs, such as improving food security, fostering social interaction, promoting psychological well-being, and contributing to sustainable urban design were emphasised. The findings demonstrate that well-designed AEs not only address ecological and social needs but also create innovative opportunities for urban communities.

CONCLUSIONS

Based on the existing world examples of the introduction of agrarian elements into the building and the characteristics of the phenomenon of the agrarian element studied in interdisciplinary scientific works, the study highlighted three main classifications in the structure of multi-story housing: 1) by appointment (commercial (full-fledged, local, for personal use); social (socialisation of children, elderly people, teenagers); recreational (visual, applied, individual)); 2) according to the usage model (municipal farms; farms for regional use; for indoor use); by location (in the structure of the yard; in the structure of the house; in the structure of the floor).

The advantages of the agrarian element are an alternative to classical agriculture, the creation of new objects of

interest for business within the city, the impact on the aesthetics of the architectural image and the formation of an attractive environment, and the creation of new common public spaces capable of contributing to the socialisation of the population, or raising children, or positively influencing the socially aggressive segment of the population. Depending on the capabilities of the city and the capacities of the integrated agricultural element, it develops following the needs of users: it works semi-openly, serving a large region of the city from a commercial point of view, or it adapts to various social processes (socialisation and rehabilitation), or it aims at a more psychological nature of recreation for internal use by residents of the building.

The location of the agricultural element is the main architectural and planning characteristic of the AE because it primarily affects the aesthetic values of the building and the ability of residents, neighbours, and passers-by to interact with the landscaping. This changes the interaction of the building with the AE and the surrounding environment, the course of possible social processes, the type of visual or applied recreation, and opportunities for psychological relief of residents. Considering the research results and conclusions, the necessary direction of further research in this area should be the development of specific variations of the integration of agricultural elements into the structure, determination of the most suitable types of AE to be introduced into the existing typology of residential buildings, depending on economic, ecological and social aspects.

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CONFLICT OF INTEREST

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Аспірант

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<https://orcid.org/0000-0003-3459-3636>**Класифікація аграрного елемента в структурі будівлі**

Анотація. Дослідження було присвячене проблемі використання елементів агровиробництва та прикладного озеленення в структурі будівлі, оскільки сучасні науково-практичні роботи в галузі архітектури або відсутні, або лише дотичні до теми дослідження. Метою даного дослідження було здійснити класифікацію аграрного елемента в структурі споруди для створення бази подальших досліджень в даній тематиці, а також визначити основні характеристики аграрних елементів та встановити їх взаємодії з будівлями. У дослідженні використовувалися такі методи, як аналіз літературних та наукових джерел, логічний та декомпозиційний методи, порівняльний аналіз, графоаналітичний метод, формалізація, узагальнення та абстрагування, індукція. В результаті вивчення міждисциплінарних досліджень було виділено три основних можливих способів розрізнення аграрних елементів і/або прикладного озеленення. Це є: «за призначенням», «за моделлю використання», «за розташуванням». Згідно цих характеристик було проведено класифікацію досліджених споруд. Перший клас «за призначенням» позначає основну функцію аграрного елемента в структурі споруди і містить підтипи: комерційний, соціальний та рекреаційний елементи. Другий – «за моделлю використання» – відображає можливості аграрного елемента забезпечувати певну кількість населення своїми зазначеними функціями: для комерції – це потужність виробництва продовольства, для рекреації – її візуальна доступність та кількість людей, що може вона обслужити, у випадку прикладного типу відпочинку. Містить підкласи: загальноміські, районного використання та внутрішньо-будинкові. Третій – «за розташуванням» – вказує на місцезнаходження елементів агровиробництва або озеленення в структурі споруди і містить підкласи «в структурі ділянки» «в структурі будинку» та «в структурі квартири (поверху)». Практична цінність даного дослідження полягає в тому, що отримані результати доповнюють понятійно-термінологічний апарат, та можуть бути використані для створення рекомендацій та методичних вказівок щодо проектування аграрних елементів в споруді

Ключові слова: житло; квартира; планування; озеленення; аграрне виробництво



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Methods of increasing the seismic resistance of metal structures

Abstract. The purpose of the study was to investigate methods to increase the seismic resistance of steel structures to improve their seismic resistance. The research applied dynamic and seismic analysis methods and a comparative approach to evaluate the performance of materials and systems under seismic loads. Various methods of increasing the seismic resistance of metal structures were analysed, including the use of high-strength materials, reinforcement of joints, the introduction of elastic damping elements, and optimisation of design solutions. It was found that the use of modern high-strength steels and alloys significantly increases the resistance of structures to seismic influences, due to their improved plasticity and ability to deform without fracture. Reinforcement of welded and bolted joints helps to increase the overall rigidity and strength of the structure, especially in areas subject to maximum loads. The introduction of damping elements, such as rubber-metal cushions, helps to effectively reduce vibrational oscillations, thereby reducing the load on the structure during earthquakes. It was also confirmed that the use of reinforcing frames and reinforcement

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of the foundation by means of pile structures significantly increases the seismic resistance of buildings and structures. In addition, it was found that the use of earthquake-resistant design technologies, such as load distribution and the use of additional structural elements, significantly increases the stability of metal structures in conditions of strong seismic impacts. The study showed that careful compliance with seismic norms and standards in the design process is a key factor in ensuring the reliability and safety of construction facilities in earthquake-prone regions. As a result of the study, it was concluded that an integrated approach to the design of metal structures is necessary, considering the seismic activity of the region, which will ensure their long-term operation in conditions of seismic risks

Keywords: high-strength materials; reinforcement of joints; damping elements; plasticity; vibrational oscillations; reinforcing frames

INTRODUCTION

With the constant increase in the number of seismically active regions such as Japan, Turkey, Iran, South America, and a number of regions in Central Asia, including Kazakhstan and Kyrgyzstan, and increasing safety requirements for construction sites, the issue of earthquake resistance, which is one of the key characteristics of building structures, is becoming particularly relevant, since earthquakes in earthquake-prone areas may threaten the safety and durability of buildings and structures. Due to their high strength and flexibility, metal structures are often used in construction, however, the use of special methods and technologies is required to ensure their resistance to seismic impacts. Increasing the seismic resistance of metal structures includes a variety of approaches, such as the use of high-strength materials, strengthening joints, the introduction of damping elements, and the improvement of design solutions. These methods are aimed at improving the overall strength and rigidity of structures, and their ability to effectively distribute and absorb seismic loads. An important aspect is also considering the features of the seismic activity of the region when designing, which helps to develop structures capable of withstanding extreme impacts.

The problem of increasing the seismic resistance of metal structures is relevant in the field of construction technologies, since seismic risks can seriously affect the durability and safety of buildings and structures. C. Fang *et al.* (2022) emphasised the importance of using high-strength steels, which provided improved ductility and the ability of structures to maintain integrity under severe seismic impacts. They noted that such materials helped to significantly reduce the risk of destruction under extreme loads. M.M. Kharnoob *et al.* (2021) investigated the impact of the use of modern alloys with improved mechanical properties, which contributed to an increase in structural strength in conditions of seismic activity. They highlighted the role of such materials in ensuring the durability of metal structures capable of withstanding numerous cycles of seismic vibrations without losing their structure. Q. Xu *et al.* (2022) focused on strengthening welded joints, considering them as key elements for increasing the rigidity and stability of structures. The researchers described methods for strengthening joints that improved the ability of structures to withstand dynamic loads caused by earthquakes.

Q. An *et al.* (2024) focused on bolted joints, emphasising their importance for increasing the overall strength of metal structures. The researchers argued that the high-quality processing and reinforcement of these joints increased the rigidity of the entire structure and prevented destruction under severe seismic loads. A.M. Cerapon *et al.* (2023) investigated the use of damping elements, such as rubber-metal cushions, to reduce vibrational oscillations in structures. They came to the conclusion that such elements can significantly reduce the amplitude of vibrations and thereby reduce the load on metal structures during earthquakes, which increases their seismic resistance.

H. Li *et al.* (2021) analysed the role of damping systems in improving structural safety, arguing that their use helped to effectively reduce vibrational oscillations and protect structures from damage. They identified a number of innovative solutions aimed at improving vibration damping, which helped to reduce the load on metal structures in seismically active areas. R. Ridwan *et al.* (2023) considered the use of reinforcement frames to strengthen metal structures, improving their resistance to deformation during earthquakes. They noted that the addition of reinforcement to the structure significantly increased the strength and durability of buildings, and improved their ability to withstand seismic impacts. L. Huang *et al.* (2023) investigated the role of pile structures in improving the earthquake resistance of metal structures, suggesting methods for their integration into the design to strengthen the foundation. They argued that such systems could significantly increase stability and prevent bridge subsidence in conditions of strong seismic fluctuations. I. Iervolino *et al.* (2023) emphasised the importance of observing seismic norms and standards in the design of metal structures to ensure their stability. They emphasised that the integration of such standards into the design helped to significantly improve the seismic stability of facilities and reduce the risks of destruction. J.-L. Zhang *et al.* (2024) proposed an integrated approach to the design of metal structures, including the use of various methods of reinforcement and earthquake-resistant design. The researchers suggested that this combination of solutions allowed increasing the effectiveness of protecting structures from seismic impacts and significantly improving their operational characteristics in conditions of seismic risks.





However, the gaps in these studies include the lack of development of methods for integrating various reinforcements into the design, considering the characteristics of seismic zones, and optimising seismic stability using combined methods. Additional research is needed to develop more effective integrated approaches that consider the interaction of various structural elements and specific operating conditions in various seismic areas. The purpose of the study was to identify the most effective methods of increasing earthquake resistance to ensure the safety and durability of metal structures in earthquake-prone areas. Research objectives:

1. To consider the impact of various joint reinforcement methods, such as welded and bolted joints, on the overall stability of structures.
2. To evaluate the effects of the introduction of damping elements, such as rubber-metal cushions, to reduce vibration and improve seismic stability.
3. To investigate the role of reinforcing frames and pile structures in increasing the strength of the foundation and the overall earthquake resistance of structures.

MATERIALS AND METHODS

The research focused on the use of high-strength steels and alloys with increased ductility to improve the earthquake resistance of metal structures. Materials such as manganese steel, austenitic steels (18Cr-8Ni), and titanium alloys (Ti-6Al-4V), characterised by a high combination of strength, ductility, and resistance to shock and seismic effects, were considered. These materials were selected based on their mechanical characteristics such as tensile strength, ductility, corrosion resistance, and ability to withstand shock and dynamic loads. Their applications in various earthquake-resistant structures were also considered, where durability, reliability and resistance to the effects of seismic waves are the most important requirements.

An important aspect of the study was the reinforcement of the joints of structural elements, which is critically important for preventing damage during seismic loads. Complex mechanical impacts during earthquakes require strong and reliable joints that minimise the possibility of their destruction. The work considered methods for improving the quality of welds, including various types of metal welding. In addition, the possibilities of using additional bolted joints to increase the strength of structures were investigated, where the use of bolts and nuts significantly strengthens the joints and increases their resistance to loads.

The properties of elastic and damping materials, including rubber-metal cushions, vibration dampers, and shock absorbers, were studied using an analysis of their stiffness, damping and energy absorption characteristics. To evaluate the effectiveness of these materials in earthquake-resistant structures, methods of comparative analysis of various types of damping systems were used, with a focus on their ability to reduce vibration. The analysis included studying the behaviour of materials under the influence of seismic waves to assess their impact on the

stability of structures. In addition, the adaptive properties of materials under dynamic loads were analysed.

The study considered methods of dynamic modelling, seismic testing, and vibration monitoring. The technique included seismic load tests, as well as vibration modelling to analyse the behaviour of structures. These methods allowed evaluating the effectiveness of various materials, such as austenitic steels, manganese, and ferritic alloys. In addition, an analysis of the operation of shock absorption and damping systems in real conditions of seismic loads was carried out.

The study provided concrete examples of the application of the investigated technologies in Japan, Turkey, Kazakhstan, Kyrgyzstan, and the USA, where materials and systems were tested to improve seismic stability and strength of building structures. Architectural objects such as Tokyo Skytree (Japan), the Bosphorus Bridge (Turkey) and residential buildings in Kazakhstan and Kyrgyzstan were considered as examples, which illustrate the use of these technologies in different countries to improve the stability of structures.

RESULTS

One of the most effective solutions to increase the earthquake resistance of metal structures is the use of modern high-strength steels and alloys with improved mechanical characteristics. The use of such materials allows structures to significantly increase their ability to withstand dynamic loads, which, in turn, reduces the risk of damage in the event of earthquakes. High-strength steels and alloys have improved ductility, which allows them to withstand significant loads without breaking, distributing stresses throughout the structure. Under conditions of seismic vibrations, buildings and engineering structures are subjected to sudden dynamic impacts, accompanied by repeated impacts, vibrations, and changes in the direction of loads. In such conditions, rigid but brittle materials can crack or collapse, while plastic alloys can temporarily change shape, absorbing the energy of seismic waves and reducing stresses in the bearing elements. This property is especially important for ensuring the stability of structures in seismically active regions, as it reduces the risk of destruction, increases the durability of buildings, and protects their functionality even in severe earthquakes (Shahjalal *et al.*, 2024).

In addition, the use of high-strength materials can significantly reduce the overall weight of the structure, which also improves earthquake resistance. Reducing the mass of the elements leads to a decrease in the inertial forces acting on the structure at the time of seismic impact, which reduces the load on the entire facility and its individual elements. This is especially important for structures that use large spans or other elements that require special attention to strength and stability.

Modern developments in the field of metal science have made it possible to create alloys such as austenitic and ferritic stainless steels, which not only have high strength and ductility, but are also resistant to corrosion and other



adverse external influences. These alloys often include elements such as chromium (12-20%), nickel (8-12%), molybdenum (2-5%), and titanium, which significantly enhance their corrosion resistance and durability, which is especially important for structures in seismically active areas (Hasan & Elmorsy, 2021). The use of high-strength steels and alloys contributes not only to an increase in earthquake resistance, but also to an increase in the durability of structures, which is economically substantiated in the long term. Reinforcing structures using these materials requires additional costs for the purchase and processing of alloys, and the installation of reinforced elements such as additional connections and dampers. However, such investments are justified when one considers the potential damage losses in the event of major earthquakes, which could result not only in the destruction of the facilities themselves, but also in significant reconstruction, evacuation and medical costs.

In the case of seismic disasters, the consequences of which may include damage to infrastructure, human casualties, and environmental disasters, the cost of strengthening structures is significantly lower compared to the possible losses. Thus, investments in high-strength materials and reinforcement of structures are part of a risk reduction strategy, ensuring cost-effectiveness throughout the entire life cycle of the building.

One of the key aspects of ensuring the earthquake resistance of metal structures is to strengthen their joints, such as welds and bolted seams. These structural elements are most stressed during earthquakes, when there is a sharp change in the dynamic effects on buildings and structures. Strengthening the joints helps not only to increase the overall strength and rigidity of the structure, but also to prevent damage that may occur at the joints during strong seismic fluctuations (Table 1).

Table 1. Impact of various joint reinforcement methods on the overall stability of structures

Amplification method	Connection type	Effect on structural stability	Notes
Welded joints	Welding of metals	Increases the rigidity of the structure, improves load resistance	Requires precision welding and quality control
Bolted connections	Bolts and nuts	Increases strength, allows compensating for deformations	Easy to install, but subject to weakening over time
Reinforcement of connections with additional elements	Reinforced seams, additional bolts	Increased strength in key locations, improves ability to withstand dynamic loads	Increases the cost, but is necessary for earthquake resistance

Source: compiled by the authors based on T. Ribeiro *et al.* (2022)

Welded joints play an important role in the distribution of loads throughout the structure, and their strength directly affects the stability of the building during earthquakes. Reinforcement of welds can be performed in various ways, including increasing the thickness of the seam, using stronger welding materials, or using modern welding methods that provide better permeability and joint strength. This prevents the development of cracks and other defects that can lead to the destruction of the structure under the influence of seismic vibrations.

Bolted connections, in turn, are also critically important for maintaining the stability of metal structures in severe earthquakes. Reinforcement of these joints may include the installation of additional bolts or the use of bolts with increased strength that can withstand heavy loads. An important aspect is the correct distribution of bolts throughout the structure to minimise possible loosening at critical points. It is also worth considering the use of materials that are resistant to fracture under dynamic loads, such as high-strength austenitic and ferritic stainless steels, titanium alloys, and carbon fibre-based composite materials. These materials have not only high strength and ductility, but also corrosion resistance, which helps to increase the overall durability of structures, especially in conditions of seismic activity and dynamic loads.

Strengthening compounds is not limited to strengthening individual elements only. An important point is the integrated approach, which includes an analysis of the operation of the entire connection system under seismic loads. The use of more fracture-resistant materials, such as special alloys, such as manganese steel, austenitic steels (18Cr-8Ni) or titanium alloys (Ti-6Al-4V), at the joints increases their resistance to external influences and reduces the likelihood of fracture in the event of earthquakes. These materials are characterised by high strength, ductility, and resistance to fatigue damage, which makes them ideal for use in places where significant dynamic loads occur, such as joints between metal structural elements in seismically active areas. Modern technologies, such as the use of friction bolts or reinforcement of structures with external reinforced frames, also have a positive effect on resistance to seismic loads (Cao *et al.*, 2022).

One of the most effective ways to increase the seismic resistance of metal structures is the use of elastic and damping elements. These elements play a key role in reducing vibrations and absorbing some of the energy generated by seismic waves, which significantly reduces the load on the structure and prevents its destruction. The introduction of such elements helps to significantly increase the stability of buildings and structures to the dynamic effects of earthquakes (Table 2).



Table 2. Effects of the introduction of damping elements to reduce vibration and improve seismic stability

Damping element	Impact on the design	Effect on earthquake resistance	Notes
Rubber-metal cushions	Absorption of seismic vibrations, reduction of vibrations	Reducing the load on the structure, reducing deformations	Easy to install, high efficiency
Vibration dampers	Absorption and dissipation of energy from vibrations	Vibration amplitude reduction, damage prevention	Regular monitoring and replacement is required
Shock absorbers	Absorption of a part of seismic energy and load distribution	Increasing the durability of the structure, reducing impact	Integration with the design can be costly

Source: compiled by the authors based on M. Ghandil *et al.* (2022)

Rubber-metal cushions, which are a combination of rubber and metal, have unique properties that allow them to effectively absorb vibrations. These elements are installed between different parts of the structure, thus reducing the transmission of vibrations from one element to another. They not only reduce the amplitude of vibrations, but also reduce the load on the foundation and walls, which significantly reduces the risk of damage or destruction of construction sites. An important feature of rubber-metal cushions is their ability to adapt to various seismic loads, which makes them versatile in use for structures located in areas with varying degrees of seismic activity.

Vibration dampers, as another damping element, are designed to absorb the energy of vibrations and reduce their amplitude. They can be installed at key points in the structure, such as joints between buildings and foundations, and in places where strong vibrations are most likely to occur. Modern vibration dampers are highly efficient, reducing vibration by several orders of magnitude, which significantly increases the safety of the building during seismic impacts. These devices can be made of various materials such as rubber, polyurethane, and metal, depending on the specifics of the design solutions and operating conditions.

The use of elastic and damping elements helps not only to reduce the amplitude of vibrations, but also to improve the resistance of the entire structure to earthquakes. The absorption of part of the energy generated by seismic waves reduces the intensity of the impact on the elements of metal structures, which prevents their damage and increases the service life of structures. These elements are an important component of modern methods of strengthening buildings, ensuring durability and safety in earthquake-prone areas.

One of the critical aspects of earthquake resistance of buildings and structures is the preparation of the foundation on which they are located. The foundation is the basis of any structure, and its ability to withstand the effects of seismic waves directly affects the overall stability of the entire structure (Lokkas *et al.*, 2021). To ensure reliability in earthquake-prone areas, foundation reinforcement using pile and antiseismic structures is used. These methods are aimed at minimising the displacement and subsidence of the building, and increasing the stability of the foundation to earthquakes, which helps to prevent destruction and reduce risks to life and property.

The most effective method of strengthening the foundation is considered to be the use of pile structures. Piles

are long vertical elements that sink into the ground to more stable layers of soil, where they can effectively transfer the load. They help to distribute the forces generated by an earthquake over deeper and more stable soil layers, which reduces the likelihood of subsidence or displacement of the entire building. This method is especially effective in areas with weak or unstable soils, where conventional foundations may not provide adequate stability.

In addition, to increase seismic resistance, the base is reinforced with antiseismic structures. These devices include various technologies such as dynamic dampers or cushions that are installed between the foundation and the base. They serve to absorb and dissipate the energy generated by seismic vibrations, thereby reducing the amplitude of vibrations that are transmitted to the foundation. This allows significantly increasing the resistance of the entire structure to earthquakes, minimising displacement and damage that may occur in the event of strong seismic impacts.

Strengthening the foundation with piles and antiseismic structures not only increases earthquake resistance, but also improves the durability of the building under intense seismic loads (Waheeb, 2023). These measures provide additional protection against possible shifts, cracks and damage, which makes the structure more stable and durable. Thus, the preparation of the foundation, considering seismic risks, is an important step in the design and construction in earthquake-prone areas.

One of the most important methods of increasing the seismic resistance of metal structures is the inclusion of reinforcement frames or grids in their design. These elements are usually used to strengthen the structure and increase its rigidity, which is of particular importance when exposed to seismic vibrations. During earthquakes, structures are subjected to dynamic loads that can lead to deformation and even destruction. The use of reinforcement helps to significantly reduce such risks, providing the structure with additional strength and stability.

Reinforcement frames typically include metal rods or meshes that are distributed throughout the structure, creating strong and flexible connections between its elements. These frameworks not only strengthen the structure, but also significantly increase its ability to deform without breaking, which is especially important during seismic impacts. When a seismic wave affects the structure, the reinforcement helps to evenly distribute the loads, preventing local damage and cracks that can lead to serious consequences. Due to their high strength and tensile strength, reinforce-



ment frames effectively hold the structure in its original shape, even under strong vibrations (Waqas *et al.*, 2024).

In addition, the use of reinforcement frames improves the connection between metal and concrete elements in the structure, which increases their teamwork. Reinforcement in the form of grids or frames helps to increase not only the strength of the structure, but also its rigidity, reducing the mobility of individual elements, which is especially important in conditions of seismic loads. This allows structures to be more resistant to deformations caused by ground shifts or vibrations that can lead to the destruction of the building.

The use of reinforcement in metal structures also helps to improve their durability. By strengthening key building elements such as columns, beams, or foundations, reinforcing frames help to reduce the effects of corrosion and other external factors, making the structure more durable in the long run. This increases not only safety, but also economic efficiency, since buildings with reinforced structures require less capital repairs and restoration after seismic impacts.

One of the key aspects of increasing the earthquake resistance of buildings and structures is the use of earthquake-resistant design technologies. This includes not only compliance with seismic norms and standards, but also the development of constructive solutions that effectively distribute loads during seismic impacts. Earthquake-resistant design is aimed at creating structures that can withstand earthquakes as effectively as possible, minimising the consequences for buildings, infrastructure and people.

Designing with seismic standards in mind requires a thorough analysis of all possible impacts that may occur as a result of earthquakes. This includes determining the intensity of seismic vibrations, the characteristics of the soils on which the building will be erected, as well as predicting possible structural deformations. Based on these data, architectural and constructive solutions are being developed that minimise the risks of destruction. One such solution is to use flexible structures that can deform without breaking, which helps to reduce the forces exerted on individual building elements (Marti *et al.*, 2023).

The key to earthquake-resistant design is the uniform distribution of earthquake loads. This is achieved by integrating various design solutions such as rigid joints, damping systems, and the use of high-strength materials that can withstand heavy loads. It is important that all the elements of a building or structure work together, effectively redistributing seismic forces throughout the structure. This not only increases the stability of the building, but also contributes to its durability, as such solutions minimise wear and damage that can occur during strong earthquakes.

In addition, the development of earthquake-resistant structural solutions requires the use of innovative technologies and materials. For example, the use of modern high-strength steels, alloys and concretes can significantly increase the strength and flexibility of structures, which plays an important role in preventing their destruction during seismic impacts. Moreover, to increase earthquake resistance, technologies are often used to improve the

interaction between the building and the foundation, such as insulation and damping systems.

One of the most important aspects of earthquake-resistant design is the adaptation of the structure to the features of seismic activity in a particular region. Seismic activity can vary greatly depending on geographical location, and to ensure the reliability of buildings and structures, it is necessary to consider parameters such as the frequency and amplitude of seismic vibrations. The correct approach to adapting design solutions and choosing optimal materials can significantly increase the earthquake resistance of facilities and minimise the risk of damage (Zakian & Kaveh, 2023).

The frequency and amplitude of seismic vibrations play a key role in the design of earthquake-resistant structures. In areas subject to frequent but weak seismic events, the design requirements may be less stringent than in regions with rare but strong earthquakes. In such regions, it is necessary to consider higher oscillation amplitudes, which requires the use of more durable materials and more rigid design solutions. In particular, reinforced reinforcement frames, increased requirements for joint strength and reinforcement of the foundation can be used for such conditions.

To adapt the structure to the type of seismic activity, it is important to choose the optimal materials. In areas with intense earthquakes, it is preferable to use high-strength steels and alloys that have high ductility and are able to withstand large deformations without breaking. In such conditions, materials with improved damping characteristics, such as rubber-metal cushions, are also often used, which help to reduce the impact of vibrations on the structure. In regions with lower seismic activity, less rigid materials can be used, which reduces the cost of construction while maintaining sufficient earthquake resistance.

In addition, it is necessary to consider the specific characteristics of the soils in the region. In areas with seismically active soils, such as sands or clay soils, it is important to consider their behaviour during seismic fluctuations to prevent subsidence or skewing of the building. In such cases, special technologies for strengthening the foundation can be used, such as pile or injection methods, which ensure the stability of the structure, minimising the risk of destruction.

Adapting the structure to the specifics of seismic activity requires an integrated approach that includes not only the choice of materials and structural elements, but also careful design based on local conditions. Such design should include an analysis of possible types of seismic loads, which will allow choosing the most effective ways to strengthen the structure and appropriate materials. This not only increases earthquake resistance, but also contributes to the creation of more stable and safe structures that can effectively withstand earthquakes, ensuring the safety of people and the durability of facilities.

Thus, consideration of the features of seismic activity in the region and adapting design solutions helps to create structures that are as earthquake-resistant as possible. It is important to consider the type of vibrations, the amplitude



and frequency of seismic impacts, and choose the right materials and technologies that meet local conditions. This approach significantly increases the earthquake resistance of buildings and structures, ensuring their safety and

durability. Methods of increasing the seismic resistance of metal structures are widely used in various construction projects, where protection against damage caused by seismic impacts is an important aspect (Figs. 1-4).



Figure 1. Tokyo Skytree (Japan)

Source: Tokyo Skytree (2024)



Figure 2. Bosphorus Bridge (Turkey)

Source: B. Gonultas & M. Ali Gurtas (2016)



Figure 3. Residential buildings (Kazakhstan)

Source: T. Biryukova (2023)

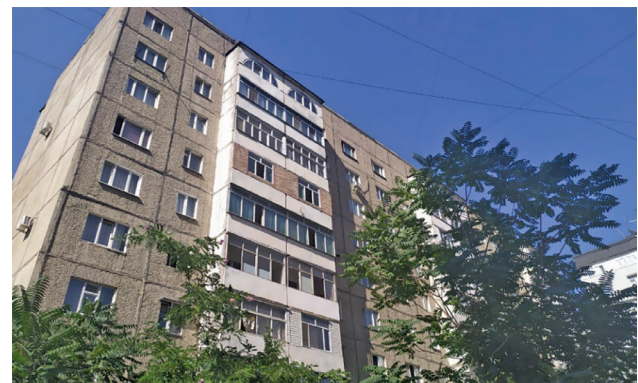


Figure 4. Residential buildings (Kyrgyzstan)

Source: Determination of houses and utilities in Bishkek. Which multi-story buildings are dangerous to live in? (2019)



One of the most famous examples is the Tokyo Skytree in Japan, one of the tallest buildings in the world, located in the earthquake-prone zone of Tokyo. Austenitic steels, which are highly ductile and capable of efficiently absorbing seismic energy, were used in the design of this building. In addition, hydraulic shock absorbers and magnetic dampers using magnetic fluid have been introduced to reduce vibrations. These systems reduced the vibrations of the building by 30-40%, and the maximum vibrations decreased by 50%. Such measures significantly increased Skytree's resilience to earthquakes with magnitudes up to 7 (Kasimzade & Nematli, 2023).

Another important example is the Bosphorus Bridge in Turkey, which connects the European and Asian parts of Istanbul. The bridge is experiencing significant dynamic and seismic loads, as it is located in a seismically active zone. To increase earthquake resistance, the project used manganese steels, which are highly resistant to shock and seismic loads. In addition, rubber-metal cushions and vibration dampers were installed in the joints between the bridge spans to increase flexibility and absorb seismic waves. This reduced the bridge's vibrations by 40%, and manganese steels ensured its strength and stability under dynamic loads, increasing the bridge's service life by 15-20% (Memisoglu Apaydin *et al.*, 2022).

In Kazakhstan, a number of residential complexes have also been reconstructed in Almaty to increase their earthquake resistance, as this region is seismically active. The buildings used high-strength steels and composite reinforcing materials, which significantly increased the strength of the structures. In addition, earthquake-resistant damping systems using carbon fibres for reinforcement were installed at the junctions between the floors. These systems reduced vibrations by 30-35%, and rubber-metal cushions reduced the load on the joints by 20-25%. As a result, the service life of buildings has been extended, and their earthquake resistance has increased significantly (Amirbekova *et al.*, 2023).

In Kyrgyzstan, in the city of Bishkek, work is also underway on the reconstruction of residential complexes located in the seismically active zone. Ferritic steels, which have improved mechanical properties, were used to strengthen the building structures. In addition, rubber-metal cushions and vibration dampers were installed at the junctions between floors and in the foundations of buildings, which reduced the amplitude of vibrations by 25-30%. These measures have improved the earthquake resistance of buildings and extended their service life (Amey *et al.*, 2023).

In Silicon Valley in the USA, titanium alloys, which have high strength and resistance to seismic loads, were used in the construction of a new bridge crossing located in a seismically active zone. Hydraulic shock absorbers and vibration dampers were also used in the bridge project, which effectively absorb seismic energy and reduce vibrations. As a result of these technologies, titanium alloys increased the durability of the bridge by 15-20%, and damping systems reduced bridge deformations by 30% in

earthquakes with a magnitude of up to 7 points (Zhang *et al.*, 2022).

Thus, the use of modern high-strength materials such as austenitic steels, manganese and ferritic steels, carbon fibres, rubber-metal cushions and vibration dampers significantly increases the earthquake resistance of metal structures. The real-world data obtained during the application of these technologies confirms their effectiveness in various construction projects, ensuring the safety of buildings and structures in seismically active areas and increasing their durability.

DISCUSSION

The analysis of the study showed that the use of high-strength steels and alloys such as manganese steel, austenitic steels (18Cr-8Ni) and titanium alloys (Ti-6Al-4V) significantly increases the resistance of metal structures to seismic impacts. It was found that these materials, due to their plasticity, are able to withstand significant deformations without destruction, which is especially important in severe earthquakes. This result confirms the conclusions of previous studies focusing on the role of materials in improving structural reliability.

This issue was also considered by J. Su *et al.* (2021), where the results confirmed that high-strength steels and alloys play a key role in increasing the seismic resistance of metal structures. They have high strength and hardness, which allows structures to withstand large dynamic loads caused by earthquakes. However, an important aspect is also the ductility of these materials, such as manganese steel, austenitic steels (18Cr-8Ni) and titanium alloys (Ti-6Al-4V), which determines their ability to absorb and distribute the energy of seismic waves, reducing the risk of damage.

The studies by A. Mohammadi *et al.* (2023) also showed that the ductility of high-strength materials such as chromium-molybdenum steels, nickel alloys, and aluminium alloys contributes to their ability to deform without breaking, which is especially important in earthquake conditions. This plasticity allows structures not only to withstand intense loads, but also to adapt to shape changes without loss of integrity. This quality significantly increases the durability and safety of buildings and structures, especially in regions with increased seismic activity.

It is worth noting that although high-strength steels and alloys provide excellent structural strength, their high hardness can sometimes limit the ductility of the material (Peleshenko *et al.*, 2017). This, in turn, can lead to a decrease in the ability of structures to deform, which is critical when exposed to seismic loads. Therefore, when developing such materials, it is important to find a balance between strength and ductility to ensure not only resistance to destruction, but also the ability of structures to effectively adapt to dynamic influences.

Strengthening joints, such as welded and bolted ones, has shown its effectiveness in increasing the strength and rigidity of metal structures. Strengthening the welds and adding additional bolts increased the overall stability of





the structures, especially in areas with maximum loads (Sakhno *et al.*, 2024). Such approaches, although they require additional costs for installation and materials, provide a significant reduction in the risk of damage under seismic conditions.

X.C. Liu *et al.* (2021) concluded that reinforcement of welded and bolted joints is an important part of ensuring earthquake resistance of metal structures. Seismic loads can lead to weakening of the joints, which increases the risk of destruction of the entire structure. The reinforcement of these joints can significantly increase the overall strength of the structure, ensuring its ability to withstand dynamic impacts and minimising the likelihood of damage.

The study by Z. Li *et al.* (2021) revealed that key joints, such as welded and bolted joints, play a critical role in transferring forces and loads within the structure. Strengthening these areas helps to improve stress distribution, preventing local damage and increasing resistance to deformation. As a result, reinforced joints allow metal structures to maintain their integrity even when exposed to strong seismic waves, which makes them safer in seismically active regions.

These results confirm the above study, as they demonstrate a significant improvement in earthquake resistance when reinforcing welded and bolted joints. Strengthening these joints allows for efficient distribution of seismic loads, which reduces the likelihood of their destruction and increases the overall strength of the structure. This is consistent with the results of previous experiments, which showed that reinforced joints significantly increase the durability of metal structures in conditions of seismic activity.

Damping elements, including rubber-metal cushions and vibration dampers, have demonstrated the ability to significantly reduce vibrational oscillations that occur during earthquakes. The introduction of such elements helps to effectively reduce the load on structures, which confirms their high efficiency in increasing earthquake resistance. However, their use requires additional monitoring and regular replacement, which must be considered when designing.

It is worth noting the study by W. He *et al.* (2022), who also found that the use of damping elements such as rubber-metal cushions and vibration absorbers is an effective way to reduce vibration effects on steel structures. These elements absorb and dissipate some of the energy generated by dynamic loads such as earthquakes or strong vibrations. This allows significantly reducing the amplitude of vibrations of the structure, increasing its seismic stability, and preventing destruction.

S. Rieß *et al.* (2021) concluded that rubber-metal cushions and vibration dampers play an important role in minimising the impact of vibration loads, reducing the risk of fatigue damage and destruction. They provide additional cushioning by absorbing vibration energy, which helps to protect key structural elements from unnecessary loads. The use of such damping elements is especially important for large industrial facilities located in earthquake-prone areas, where it is important to guarantee long-term stability and safety (Zakharova, 2024).

These data are consistent with the theses given in the previous section, as they demonstrate the effectiveness of damping elements in reducing vibration effects on the structure. Experiments have shown that rubber-metal cushions and vibration dampers significantly reduce the amplitude of vibrations, which confirms their ability to minimise dynamic loads. This confirms the need to use these elements to increase the seismic resistance and overall strength of metal structures in earthquake-prone areas.

Strengthening the foundation using pile structures proved to be a key factor in ensuring the stability of buildings and structures. These methods made it possible to minimise subsidence and displacement of structures, ensuring their stability even under intense seismic loads. In addition, the use of pile systems required consideration of soil features, which underscores the importance of preliminary geotechnical analysis.

This aspect was also investigated by Y. Sawamura *et al.* (2021), who conducted a study that confirmed that pile structures play a key role in strengthening foundations, especially in earthquake-prone regions where high earthquake resistance is required. They can significantly improve the stability of buildings by distributing the load to deeper and more stable soil layers. The use of pile technology helps to reduce the impact of earthquakes by preventing structures from sagging or tilting, which can lead to their destruction (Bannikov *et al.*, 2019).

L. Su *et al.* (2021) also found that the effective use of pile structures requires a thorough geotechnical analysis that considers the characteristics of the soil and its interaction with the foundation. Geotechnical analysis helps to determine the optimal depth and type of piles, ensuring maximum structural stability (Rusho *et al.*, 2024). This is especially important in seismically active areas, where ground conditions can vary significantly, and the wrong choice of pile technologies can reduce the seismic stability of the facility.

Comparing the data obtained during the research, it can be concluded that the correct choice of pile structures significantly affects the stability of buildings in earthquake-prone regions. Geotechnical analysis based on these data allows for more accurate consideration of soil characteristics and prediction of foundation behaviour under seismic loads. This confirms the importance of an integrated approach to the design of pile structures to ensure earthquake resistance and durability of buildings in earthquake conditions.

The use of reinforcing frames and meshes has made a significant contribution to increasing the rigidity and strength of structures. They not only improve resistance to deformation, but also contribute to an even distribution of loads during seismic impacts. These approaches have proven their relevance for ensuring the reliability of structures, especially in areas with high seismic activity.

Research by R.N. Al-Dala'ien *et al.* (2024) confirms that reinforcement frames play an important role in increasing the rigidity and resistance of metal structures to vibrations, especially under seismic conditions. They provide additional reinforcement, allowing structures to withstand



heavier loads without significant deformations. The reinforcement cages help to distribute stresses throughout the structure, which prevents localised damage and failure in earthquakes (Kriukova et al., 2024).

Thus, an integrated approach, including the use of high-strength materials, reinforcement of joints, the introduction of damping elements and the strengthening of the foundation, has proven effective in increasing the earthquake resistance of metal structures. The combined use of these methods allows minimising the risks of destruction, ensuring the durability of structures, and increasing their safety for operation in earthquake-prone regions.

CONCLUSIONS

The research confirmed that the use of high-strength steels, such as austenitic and manganese steels, as well as titanium and ferritic alloys, significantly increases the seismic resistance of steel structures. The introduction of hydraulic shock absorbers, magnetic dampers, and rubber-metal cushions has reduced vibrations and vibrations of buildings and bridges by 30-40%, increasing their durability and resistance to seismic loads. Case studies such as Tokyo Skytree, the Bosphorus Bridge, the reconstruction of residential complexes in Kazakhstan and Kyrgyzstan, and a bridge in Silicon Valley demonstrate the high efficiency of such solutions. These measures confirm the importance of using modern materials and technologies to improve the earthquake resistance of structures. The use of high-strength steels and alloys has shown its effectiveness due to the ability of these materials to withstand significant dynamic loads without breaking. Plasticity and resistance to deformation make such materials a key component for creating earthquake-resistant structures. These properties are especially important for protecting structures in areas of high seismic activity.

The strengthening of welded and bolted joints has demonstrated a significant increase in the strength of metal structures, especially at critical points such as the joints of columns with foundations, the junctions where beams and struts are connected, and in the area of fastening metal elements exposed to high stress during seismic fluctuations. The reinforcement of seams, the use of additional fasteners and the use of fracture-resistant materials helped

to increase the rigidity of structures, improving their overall reliability. The introduction of damping elements such as rubber-metal cushions and vibration dampers has proven its ability to effectively absorb and reduce vibration. This reduces the effect of seismic waves on the structure, minimises deterioration of materials and extends the life of buildings.

In addition, strengthening the foundation using pile structures proved to be an important factor in increasing the stability of structures. Such structures prevent subsidence and displacement, which ensures the stability of buildings even under significant seismic loads. Ultimately, the use of reinforcing frames embedded in metal structures contributed to an increase in their rigidity and fracture resistance. These elements ensured an even distribution of loads, which reduced the likelihood of local damage. The complex application of these methods, including the choice of materials, strengthening joints, the use of damping technologies and proper preparation of the substrate, can significantly increase the reliability and safety of metal structures. These approaches, adapted to the specific features of the seismic activity of the region, are an important step towards the creation of earthquake-resistant structures.

A limitation of the study is the insufficient testing of the proposed methods under conditions of prolonged cyclic loads simulating multiple seismic impacts. It is necessary to investigate the impact of innovative materials and new types of damping elements on the durability and earthquake resistance of metal structures in real-world operating conditions. The prospects for further research lie in the development of new materials and technologies that will ensure an even more effective increase in the seismic resistance of metal structures, based on global climate changes and increased seismic activity in various regions.

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Методи підвищення сейсмостійкості металоконструкцій

Анотація. Дослідження було спрямоване на вивчення методів підвищення сейсмостійкості металоконструкцій для поліпшення їхньої стійкості до сейсмічних впливів. Під час дослідження застосовувались методи динамічного та сейсмічного аналізу, а також порівняльний підхід для оцінки ефективності матеріалів і систем під час впливу сейсмічних навантажень. Проаналізовано різні методи підвищення сейсмостійкості металоконструкцій, включно з використанням високоміцних матеріалів, посиленням з'єднань, впровадженням еластичних елементів, що демпферують, та оптимізацією проєктних рішень. Було встановлено, що застосування сучасних високоміцних сталей і сплавів істотно підвищує стійкість конструкцій до сейсмічних впливів, завдяки їхній поліпшеній пластичності та здатності до деформації без руйнування. Посилення зварних і болтових з'єднань сприяє підвищенню загальної жорсткості та міцності конструкції, особливо в місцях, схильних до максимальних навантажень. Введення демпферних елементів, таких як гумометалеві подушки, дає змогу ефективно знижувати вібраційні коливання, тим самим зменшуючи навантаження на конструкцію під час землетрусів. Також було підтверджено, що використання арматурних каркасів і посилення фундаменту за допомогою пальових конструкцій значно збільшує сейсмостійкість будівель і споруд. Крім того, було виявлено, що використання сейсмостійких технологій проєктування, таких як розподіл навантажень і застосування додаткових конструктивних елементів, значно підвищує стабільність металоконструкцій в умовах сильних сейсмічних впливів. Дослідження показало, що ретельне дотримання сейсмічних норм і стандартів під час проєктування є ключовим фактором для забезпечення надійності та безпеки будівельних об'єктів у сейсмічно небезпечних регіонах. У результаті дослідження було зроблено висновок про необхідність комплексного підходу до проєктування металоконструкцій з урахуванням сейсмічної активності регіону, що дасть змогу забезпечити їхню довгострокову експлуатацію в умовах сейсмічних ризиків

Ключові слова: високоміцні матеріали; посилення з'єднань; демпфуючі елементи; пластичність; вібраційні коливання; арматурні каркаси

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