Збірник наукових праць. Галузеве машинобудування, будівництво
Academic journal. Industrial Machine Building, Civil Engineering
http://journals.nupp.edu.ua/znp
https://doi.org/10.26906/znp.2025.64.4052

UDC 624.07:692:725

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Results of the Inspection and Technical Condition Assessment of the Multi-level Load-Bearing Roof Structures of a Supermarket before the Installation of a RoofTop Solar Power Plant

Abstract. A comprehensive detailed inspection and technical condition assessment of the multi-level load-bearing roof structures of a supermarket was conducted to determine the feasibility of installing photovoltaic elements on the building's roof. The work included analysis of technical documentation, visual and instrumental inspection of the building structures, and verification calculations. During the visual inspection, the structural features of the building and the technical condition categories of the building structures based on characteristic signs were established. During the instrumental inspection, non-destructive testing methods were used to determine the concrete strength and reinforcement parameters for reinforced concrete structures, and the steel strength and element thicknesses for the roof beam elements. Verification calculations established the load-bearing capacity of the reinforced concrete slab and metal roof beams. In the event of installing a rooftop solar power plant, a limitation on the building's service life was recommended. The research carried out underscores the necessity of conducting building and structure inspections when installing rooftop solar power plants.

Keywords: inspection, load-bearing capacity, rooftop solar power plant, technical condition assessment.

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Received: 16.05.2025 Accepted: 10.06.2025 Published: 26.06.2025

Introduction

Modern energy policy worldwide, and in Ukraine in particular, is driven by the strategic goals of energy security. Consequently, the global energy market is undergoing a dynamic and accelerated transformation, the main characteristic of which is a fundamental shift from traditional, centralized energy systems to a model that incorporates the broad integration of decentralized energy resources. The development of Renewable Energy Sources, among which solar photovoltaic systems occupy a leading position in terms of growth rates, is a key element of this transition [1].

Review of the research sources and publications

Recently, in light of the increasing volatility and uncertainty of market electricity prices, the deployment of rooftop photovoltaic (PV) elements has acquired the status of a critically important and economically attractive solution. The installation of rooftop solar power plants (RTPVs) on existing buildings is an economically sound decision compared to other options for placing PV elements. It allows for the effective use of developed areas and minimizes the shading of adjacent territories. Furthermore, this technology is strategically valuable for ensuring energy stability, especially during times of increased geopolitical and economic instability (for example, in the context of war). It offers significant benefits for a wide range of consumers, as for large and medium-sized businesses (providing business continuity and reducing operational costs) so for small businesses and private households (achieving lower utility payments and greater energy independence) [2].

Despite the obvious economic and environmental benefits, the integration of rooftop solar power plants onto the roofs of existing buildings – especially those constructed under outdated building codes or having a significant operational lifespan – creates substantial engineering challenges. Photovoltaic modules and their mounting systems introduce new, often significant, constant loads (own weight, ballast) and radically alter the aerodynamic profile of the roof. This alteration leads to an increase in dynamic wind and snow loads [3]. Failure to perform a proper assessment of the load-bearing capacity of the structures may lead to them exceeding their limit states and, consequently, resulting in structural failure.

According to current regulations [4], works involving a change in the loads on existing load-bearing and/or enclosing structures (which is a direct consequence of PV system installation) are classified as either reconstruction or capital repair. This classification mandates the obligatory performance of a technical condition assessment of the building and the provision of a conclusion as a prerequisite for the development of design documentation.

Definition of unsolved aspects of the problem.

The inspected supermarket building was constructed in 2001–2002, prior to the introduction of modern codes regarding loads and actions [5], which increased the design load values for roof structures. Furthermore, the building features multi-level load-bearing roof structures. While this configuration provides certain functionality and esthetic appeal to the building, it necessitates complex engineering calculations to assess the overall structural capacity under increased localized snow loads. This fact underscores the critical importance of the technical condition assessment as a mandatory prerequisite for the safe operation of the building following the installation of a roof-top solar power plant.

Problem statement.

The main objective of the study is technical condition assessment of the supermarket's roof structures to determine the feasibility of installing PV panels on the roof of the building, which features multi-level load-bearing roof structures. In assessing the technical condition of the structure, the following procedures were carried out in accordance with DSTU [6] and the terms of reference:

- analysis of technical documentation (design, executive, and operational documentation);
- visual inspection of building structures and elements;
- field measurements;
- instrumental inspection of building structures and elements to determine actual physical and mechanical parameters;
- verification calculations;
- technical condition assessment based on the results of the analysis of technical documentation, visual and instrumental inspections, and the development of recommendations.

Main material and results.

The supermarket building is a rectangular in plan, freestanding structure, featuring varying varying heights. Based on its structural features, the building was divided into two blocks.

Block No. 1 is the single-story section of the building. The structural scheme is a framed system. Foundations – reinforced concrete pile foundations utilizing cast-in-place bored piles with monolithic reinforced concrete grillage. Columns are constructed as monolithic reinforced concrete with a square cross-section of 500×500 mm; monolithic reinforced concrete within stay-in-place formwork made of steel pipes with a diameter of 219 mm; locally, columns are made of welded steel I-beams with a cross-section of 200×220 mm (flange and web thickness: 10 mm). External walls constructed from sandwich panels 150 mm thick, fastened to the frame columns, and, in some areas, as vitrage glazing fastened to the frame columns. Vertical bracing consists of paired bent channels welded into a "box" section, with a cross-section of 140×140 mm. Load-bearing roof structures – a multi-level beam grid system utilizing welded steel I-beams. The main beams are supported by the frame columns via steel plates secured with bolts. The secondary beams are supported by the main beams via vertical ribs on the main beams. In axes "А-Б/1-13" an entrance canopy is constructed using continuous cantilever beams supported at axes "Б" and "В". Roofing – low-slope, insulated roof with an internal internal gutter. The waterproofing layer is a PVC membrane. The roof is built over a load-bearing profiled steel decking of type RAN113/T113 with a thickness of 0,9 mm, following a two-span support scheme.

Block No. 2 is the two-story section of the building. The structural scheme features longitudinal and transversal load-bearing walls. Foundations – reinforced concrete pile foundations utilizing cast-in-place bored piles with monolithic reinforced concrete grillage. Walls – monolithic reinforced concrete walls, 200 mm thick. The external surfaces of the walls are insulated with mineral wool slabs 100 mm thick and clad with profiled sheeting. Floor slab - monolithic reinforced concrete beamless slab 200 mm thick. Load-bearing roof structures – monolithic reinforced concrete beamless slab 200 mm thick. Roofing – low-slope, insulated roof with an internal internal gutter. The waterproofing layer is a PVC membrane.

The overall view of th supermarket roof is presented in Fig. 1.

Figure 1 – Overall View of the Supermarket Roof

During the analysis of the technical documentation, it was established that the building was constructed in 2001–2002. The design documentation from the start of construction is unavailable. It was also established that during a reconstruction in 2013, the insulation thickness was increased by 100 mm over the existing roll-out bituminous roofing, followed by the installation of a PVC membrane roof.

During the visual inspection of the structure's elements, the following procedures were carried out in accordance with regulations [6, 7]:
- inspection and dimensioning of structures to determine the actual structural scheme; - determination of the condition of element and joint conditions;
- identification of deficiencies and poor workmanship from construction and repairs that lead to a reduction in the load-bearing capacity of the structures;
- assessment of the actual operational conditions of the structures and identification of violations of normal operating conditions;
- determination of areas with damages and defects.

The results of the dimensioning and field measurements are presented in the form of a layout plan of the load-bearing roof structures in Fig. 2.

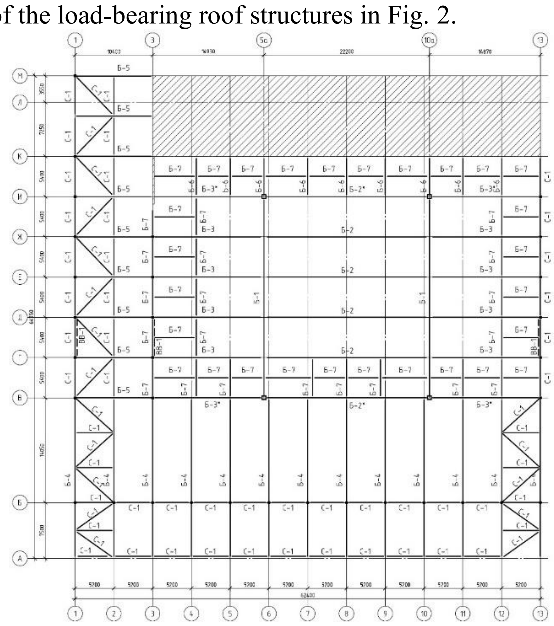


Figure 2 – Layout Plan of the Load-Bearing Structures

Based on the results of the visual inspection, the technical condition categories of the building structures were established according to characteristic signs:
- foundations (indirect signs) – normal technical condition (Category I);
- columns – normal technical condition (Category I);
- walls and partitions – normal technical condition (Category I);
- floor structures – normal technical condition (Category I);
- vertical and horizontal bracing – normal technical condition (Category I);
- roof structures – normal technical condition (Category I);
- roofing– normal technical condition (Category I).

The following procedures were included within the framework of the instrumental inspection of the building structures:
- determination of concrete strength using non-destructive testing methods;
- determination of reinforcement parameters using non-destructive testing methods;
- determination of steel hardness;
- determination of the thickness of metal elements.

The methodology for the instrumental inspection of reinforced concrete structures was adopted in accordance with the requirements of DSTU [8]. The concrete strength of the structures was determined using the ultrasonic method with the use of the «Novotest IPSM» device. The ultrasonic method is based on the dependence between the velocity of ultrasonic wave propagation in concrete and its strength. Ultrasonic measurements of sound wave propagation in concrete were performed using indirect method. At each control area, no less than five measurements of the ultrasonic pulse transit time were taken using the surface transmission method. The concrete strength in the area was determined by the average value of the obtained results of the ultrasonic pulse transit time measurements.

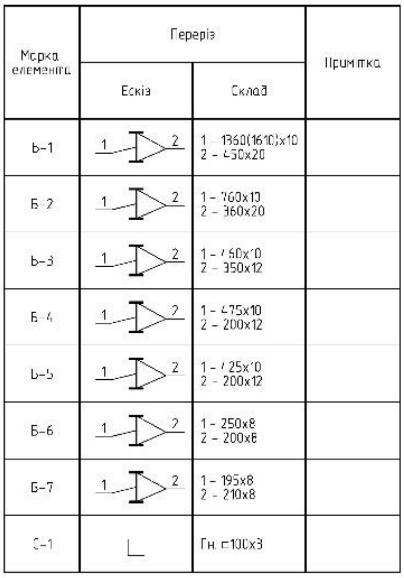
The reinforcement parameters of the slabs were determined using the magnetic method in accordance with the requirements of DSTU [9] and the «Novotest Armaturoscop» device.

The steel hardness of the elements of the metal structures was determined using a «Novotest» hardometer in accordance with DSTU [10] by the ultrasonic contact impedance method. During the instrumental inspection of the metal structures, the Brinell hardness (HB) of the steel elements was measured, after which the mechanical characteristics of the steel were determined.

The thickness of the steel elements was determined using a «Novotest» ultrasonic thickness gauge, the operating principle of which is based on the ultrasonic pulse-echo signal – a measurement method that utilizes the properties of ultrasonic vibrations as they reflect off the boundary between media with different acoustic impedances.

The following was established based on the results of the instrumental inspection:

- the average concrete strength of the reinforced concrete roof slabs is 27,5 MPa with a coefficient of variation of 9,6%, which corresponds to concrete class C20/25;
- along the bottom face of the slab, reinforcement bars with a diameter of 12 mm were detected in both directions at a spacing of 200 mm. The concrete cover of the slab is 15–20 mm;
- the tensile strength of the steel is 370 MPa, the yield strength is 245 MPa, and the relative elongation is 25%, which corresponds to steel grade C255;
- the thicknesses of the webs and flanges of the beams are presented in the element schedule in Fig. 3.



Марка елемента	Переріз		Примітка
	Ескіз	Склад	
Б-1		1 – 1360(1610)x10 2 – 450x20	
Б-2		1 – 760x10 2 – 360x20	
Б-3		1 – 460x10 2 – 350x12	
Б-4		1 – 475x10 2 – 200x12	
Б-5		1 – 425x10 2 – 200x12	
Б-6		1 – 250x8 2 – 200x8	
Б-7		1 – 195x8 2 – 210x8	
С-1		Гн. ⊏100x3	

Figure 3 – Element Schedule of Load-Bearing Roof Structures

The results of the visual and instrumental inspections were used in the verification calculations.

The verification calculations for the steel frame structures were carried out based on a spatial unified finite-element model created using the LIRA-SAPR software package.The structures were modeled using two-node universal bar finite elements (FE 10), the parameters of which correspond to the actual steel beams. The general view of the spatial finite-element model is presented in Fig. 4, and the view of the volumetric model is presented in Fig. 5.

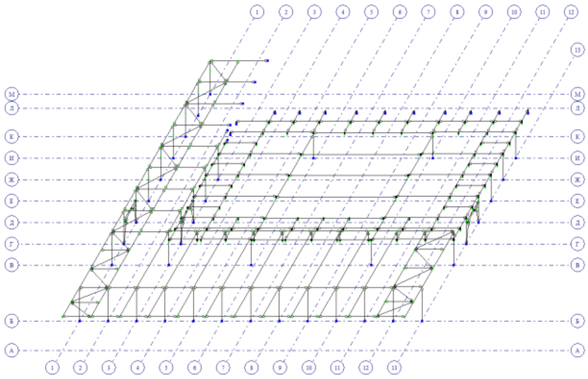


Figure 4 – General view of the spatial finite-element model of the frame structure

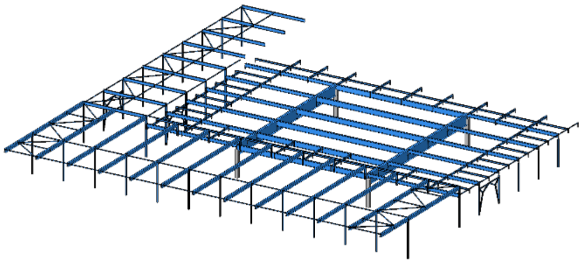


Figure 5 – General view of the volumetric model of the frame structure

When forming the calculation model for the reinforced concrete roof slab, the planar elements were approximated by four-node flat shell finite elements, the thickness parameter of which corresponds to the actual thickness of the structures.

The general view of the spatial finite-element model of the slab is presented in Fig. 6.

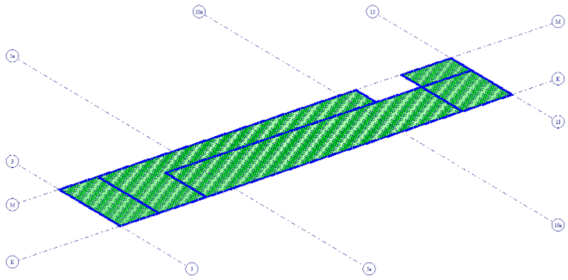


Figure 6 – General view of the spatial finite-element model of the slab

Loads in the calculation models were adopted in accordance with current regulations [5] and included constant and temporary loads, specifically including loads from wind pressure and snow drifts.

The calculation results established that the load-bearing capacity of the monolithic roof slab of the building, when solar PV are installed on the store's roof, is ensured without limiting the operational lifespan of the structure.

However, the load-bearing capacity of the steel roof elements is not ensured within the design operational lifespan when PV elements are installed. The reason for these limitations is the increase in snow loads in the current DBN [5] compared to the codes that were in effect at the time the building was constructed.

The calculation results are presented in the table 1 for operational lifespans of 3 and 1 year.

Table 1 – Results of the structural calculations (at the building service life Tef = 1 and 3 years)

№	Element Name	Utilization Factor (Load-Bearing Capacity)					
		First group of limit states		Second Group of Limit States		Local Stability	
		T_{ef}=3 years	T_{ef}=1 year	T_{ef}=3 years	T_{ef}=1 year	T_{ef}=3 years	T_{ef}=1 year
1.	*Beam Б-1*	0,96	-	0,86	-	0,98	-
2.	*Beam Б-2*	0,91	0,78	1,03	0,98	0,75	0,75
3.	*Beam Б-3*	1,08	0,92	1,09	0,99	0,98	0,96
4.	*Beam Б-4*	0,64	-	0,26	-	0,8	-
5.	*Beam Б4-1*	0,65	-	0,07	-	0,8	-
6.	*Beam Б-5*	0,8	-	0,68	-	0,49	-
7.	*Beam Б-6*	0,81	-	0,69	-	0,65	-
8.	*Beam Б-7*	0,82	0,65	3,31	3,23	0,79	0,7
9.	*Horizontal Bracing*	0,1	-	0,96	-	0,69	-
10.	*Vertical Bracing*	0,1	-	0,38	-	0,69	-
11.	Column К-3	0,15	-	0,29	-	0,34	-
12.	Column К-2	0,31	-	0,29	-	-	-
13.	Profiled Decking	0,95	-	0,62	-	-	-

Conclusions

Based on the results of the comprehensive inspection of the supermarket's roof structures, it was established that the adopted space-planning and structural solutions of the building complied with the requirements of the standards and regulations in force at the time of design. No modes with deviations from the normal operation of the structures were detected. No structural failures were recorded. Based on the results of the visual and instrumental inspection, the technical condition categories of the structures were established. The instrumental inspection results determined the concrete class of the roof slabs, the reinforcement parameters of the slabs, the steel grade of the beams, and the thicknesses of the beam elements.

The results of the verification calculations conducted according to current regulatory documents indicate that the load-bearing capacity of the roof structures when PV panels are installed on the roof is ensured without limiting the operational lifespan for the two-story section. However, the load-bearing capacity of the roof structures of the single-story section is not ensured in areas with increased localized snow loads. In other areas, the load-bearing capacity of the structures is ensured only with a limitation on the operational lifespan of the roof structures.

This work confirms the mandatory requirement to conduct an inspection and assessment of buildings and structures when installing photovoltaic elements on the roof, especially for buildings designed and constructed prior to the entry into force of DBN [5]

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Suggested Citation:	
APA style	Matiushenko, I., Kozak, R., Gayda, S., Shchupakivskyy, R., & Kopynets, Z. (2025). Results of the Inspection and Technical Condition Assessment of the Multi-level Load-Bearing Roof Structures of a Supermarket before the Installation of a RoofTop Solar Power Plant. *Academic Journal Industrial Machine Building Civil Engineering*, *1* (64), 96–102. https://doi.org/10.26906/znp.2025.64.4052
DSTU style	Results of the Inspection and Technical Condition Assessment of the Multi-level Load-Bearing Roof Structures of a Supermarket before the Installation of a RoofTop Solar Power Plant/ I. Matiushenko et al. *Academic journal. Industrial Machine Building, Civil Engineering*. 2025. Vol. 64, iss. 1. P. 96–102. URL: https://doi.org/10.26906/znp.2025.64.4052.

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Результати обстеження та оцінки технічного стану різнорівневих несучих конструкцій покриття супермаркету перед встановленням дахової сонячної електростанції

Аннотація. Проведено комплексне детальне обстеження та оцінка технічного стану різнорівневих несучих конструкцій покриття супермаркету з метою визначення можливості встановлення фотовольтаїчних елементів на покрівлю будівлі. Робота включала аналіз технічної документації, візуальне та інструментальне обстеження будівельних конструкцій, перевірні розрахунки. Під час візуального обстеження були встановлені конструкційні особливості будівлі, виконані обмірні роботи, уточнені наявність дефектів та пошкоджень, стан стиків елементів та конструкцій. За результатами візуального обстеження встановлені категорії технічного стану будівельних конструкцій. Інструментальні дослідження будівельних конструкцій проводилися з використанням методів неруйнівного контролю та включали визначення міцності бетону ультразвуковим методом та визначення параметрів армування магнітним методом для плит покриття, визначення міцності сталі для балок покриття та визначення товщин елементів балок ультразвуковим методом. Перевірні розрахунки проводилися на термін служби в діапазоні 1-100 років. Встановлено, що несуча здатність монолітної плити покриття будівлі при встановлені сонячних фотовольтаїчних елементів на покрівлю супермаркету забезпечується без обмеження терміну експлуатації конструкції. Несуча здатність конструкцій покриття одноповерхової частини будівлі на ділянках з підвищеним місцевим сніговим навантаженням не забезпечується, на інших ділянках несуча здатність конструкцій забезпечується лише при обмежені терміну експлуатації конструкцій покриття від одного до трьох років. Проведене дослідження підтверджує обов'язковість проведення обстеження будівель та споруд при встановленні фотовольтаїчних елементів на покриття, особливо для будівель запроектованих і зведених до вступу в дію сучасних норм щодо навантажень та впливів.

Ключові слова: обстеження, несуча здатність, дахова сонячна електростанція, оцінка технічного стану

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Надіслано до редакції:	16.05.2025	Прийнято до друку після рецензування:	10.06.2025	Опубліковано (оприлюднено):	26.06.2025