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STRESS-STRAIN STATE OF THE ELEVATOR WORKING TOWER FLOOR UNDER DYNAMIC LOADS

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Abstract. *This paper examines the performance and stability of steel–concrete composite systems used in the working towers of grain elevator facilities, subjected to dynamic effects originating from grain cleaning equipment. The research centers on evaluating the structural response of elevator towers with separator floors formed either from steel-only frameworks or composite slabs incorporating concrete and profiled sheeting. Particular attention is given to resonance susceptibility and methods to enhance structural integrity under operational conditions.*

Purpose. *The aim of the study is to analyze and compare the dynamic performance of different flooring systems in grain elevator towers – steel-only structures versus steel–concrete composite slabs – and to assess their susceptibility to resonance caused by grain cleaning equipment.*

Methodology. *The study employed modal analysis of two flooring configurations using computational modeling tools. Natural frequencies and corresponding mode shapes were determined via LIRA-FEM for both static and dynamic analysis. Autodesk Revit was used to develop the structural models. Resonance risk was evaluated by comparing computed natural frequencies with the known 5 Hz operational frequency of grain cleaning machinery.*

Results*. The analysis revealed that composite floor systems using profiled steel decking and concrete slabs significantly reduce vibration intensity compared to steel-only floors. Variations in concrete slab thickness and shear connector dimensions were tested, resulting in improved dynamic behavior and structural stability. The natural frequencies of both systems were benchmarked to evaluate resonance potential. Composite floors showed better alignment with safety requirements and machine stability under dynamic loads.*

Scientific novelty*. The study introduces the application of steel–concrete composite floor systems with profiled decking as permanent formwork in grain elevator towers, highlighting their effectiveness in minimizing resonance effects. The research presents an original configuration that enhances structural performance and operational safety, laying the groundwork for further optimization of slab parameters in future investigations.*

Practical significance*. The results of this research can be used to improve the design of grain elevator tower floors by selecting appropriate composite configurations. The tested systems showed better vibration damping and structural stability, which*

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contributes to safer and more reliable operation of grain cleaning equipment. These findings support engineers in making informed decisions when designing dynamically loaded agricultural facilities.

Keywords: composite structures, grain elevator, dynamic loads, modal analysis, resonance, LIRA-FEM, steel–concrete systems, structural safety.

INTRODUCTION

Today, Ukraine's agro-industrial sector plays a vital role in the national economy and remains a significant contributor to the state budget. Historically, agriculture has been central to daily life in Ukraine. However, recent challenges – including infrastructure damage from military conflict, occupation of certain regions, and disrupted grain export logistics – have severely impacted the industry [5]. As a result, there is a considerable shortage of grain storage facilities. To address this, agricultural producers are working to expand storage capacities, build new elevator complexes, and modernize existing infrastructure through technical upgrades [10].

The primary function of a granary is to maintain the quality of grain for further processing. This involves several technological steps: receiving, preliminary cleaning, drying, storage, final cleaning, and shipment. One of the most important operations is cleaning the grain, which is carried out using modern separators. These machines function by passing grain through sieves of various sizes while applying controlled vibrations, allowing separation of grain and waste into different outlets.

These separators are housed in specialized structures – working grain-cleaning towers [15]. These towers are multi-level, steel-frame buildings with columns spaced 6×6 m, supporting the primary and secondary beams of operational platforms. The separator floor (Fig. 1) carries the heaviest loads, including the weight of the machine, grain, and dynamic forces [16]. Due to these stresses, designers increasingly favor the use of reinforced structural solutions, particularly steel-reinforced concrete floor systems.

Steel-reinforced concrete structures combine reinforced concrete with structural or cold-formed steel sections, connected by shear-resistant links that prevent slippage or separation between the materials [4]. This composite approach merges the strength of steel with the rigidity of concrete, offering improved performance under various load conditions [7].

Main types of steel-reinforced concrete systems include [20]:

– Reinforced concrete slabs on profiled steel decking;
– Composite slabs with steel beams;
– Rigidly reinforced concrete systems;
– Concrete-filled steel tube structures.

ANALYSIS OF PREVIOUS RESEARCHES

Numerous Ukrainian researchers have contributed to the study of steel-reinforced concrete systems. L.I. Storozhenko, founder of the scientific school of steel-reinforced concrete structures at the National University «Poltava Polytechnic named after Yuriy Kondratyuk,» made significant advancements in this field. O.V. Semko and O.P. Voskobiynik [12] explored the probabilistic aspects of design, construction, operation, and strengthening of such systems. F.E. Klymenko, M.Yu. Izbash, A.M. Bambura, O.B. Golyshev, and O.F. Yaremenko [7] led comprehensive experimental and theoretical work focused on strength and deformation analysis of beam and slab elements.

In agriculture, the adoption of steel-reinforced concrete structures is growing, particularly in the design of separator floors within elevator towers. During separator operation, dynamic loads arise from the parallel motion of sieves. These loads are periodic and may cause resonance and vibrations – especially when multiple machines are installed on the same level. This can lead to microcracking in concrete, reducing floor stability and overall structural durability [9; 10].

Thanks to their combination of stiffness and damping, steel-reinforced concrete floors effectively resist dynamic forces, significantly reducing vibration amplitudes and minimizing resonance. This enhances both the stability of the equipment and the longevity of the structure [11].

PURPOSE

The aim of this study is to analyze and compare the dynamic performance and resonance susceptibility of steel-only and steel–concrete composite flooring systems in grain elevator towers, with the goal of enhancing structural stability and operational safety under dynamic loads generated by grain cleaning equipment.

Research methodology. When designing working towers, metal engineering structures with a dimension in plan up to 12,0x18,0m, a height of the above-ground part up to 45,0 m and a depth of the underground concrete part of 6,0 m are used. As an example of application, let's consider the working tower of an elevator in the Kyiv region (Fig. 1).

At the specified construction site, the separator floor located at an elevation of +12.500 m is designed using a steel-concrete composite slab based on profiled steel sheeting, as described in [13; 1]. A grain cleaning separator is mounted on this floor, which introduces significant dynamic loading and raises the possibility of resonance effects. The key technical parameters of the installed equipment are summarized in Table 1.

Resonance refers to a sharp rise in the amplitude of forced vibrations that occurs when the frequency of an external periodic force matches the system's natural frequency. In structural engineering, if this effect is not properly considered during the design phase, it can result in serious deformations or even structural failure.

Table 1

Main Technical Characteristics of Grain Cleaning Machines

Overall dimensions, mm	
length	3300
width	4090
height	4000
Mass, kg	7000
Electrical power, kW	7,0
Frequency of circular oscillations of the sieve body, s-1 (num/min)	5 (300)
Radius of circular oscillations of the body, mm	up to 11

RESULTS AND DISCUSSION

To assess the likelihood of resonance within the structure, a modal analysis was performed to identify its natural vibration frequencies. These frequencies were then compared with the operational frequency of the grain cleaning machine to determine the risk of resonance. In addition to frequency values, the modal analysis provides insight into the specific

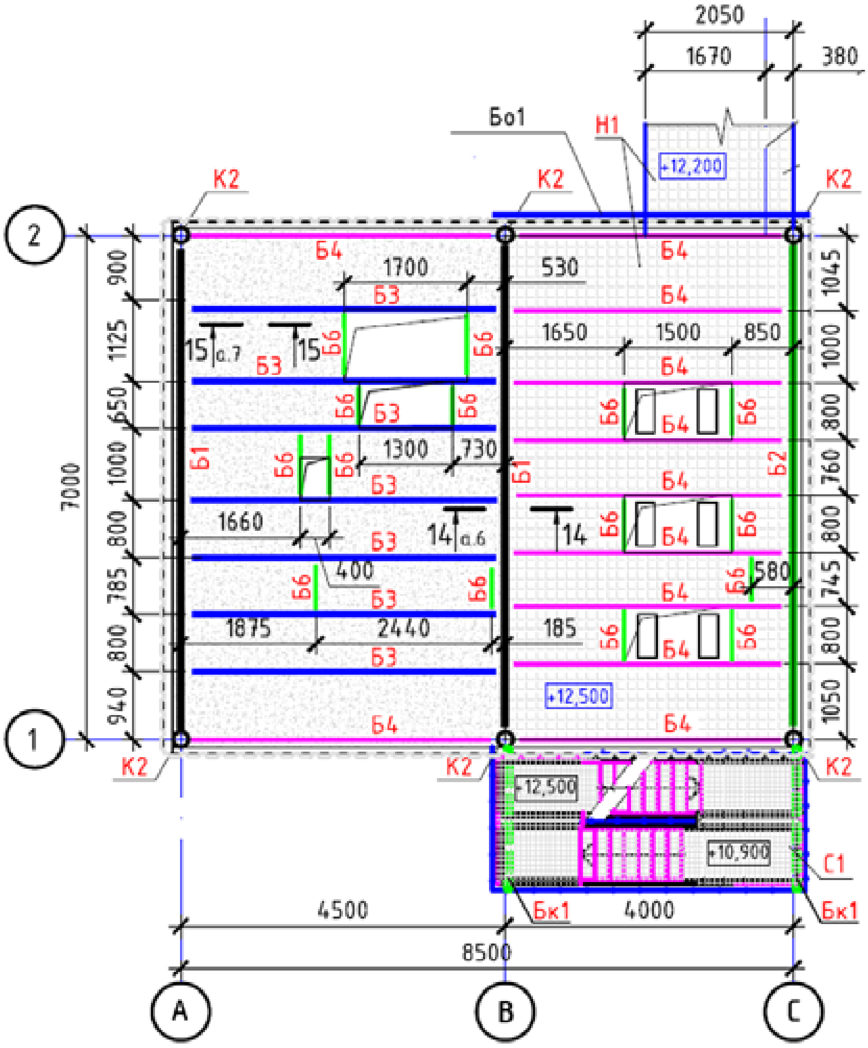

Fig. 1. Fragment of the layout of the structural elements of the working tower at elevation +12500

vibration modes of the structure [6; 13; 16], offering a deeper understanding of how the structure responds to dynamic loads. These vibration modes are illustrated in Figures 2 and 3. The numerical values of the natural frequencies obtained through the analysis are summarized in Tables 2 and 3, which are essential for evaluating the structural performance.

Figure 2 illustrates one of the natural vibration modes observed in the working tower structure that features steel beams combined with corrugated metal decking used as the separator floor. This construction method is widely adopted in agro-industrial facilities because it provides a balance of strength, ease of assembly, and material efficiency. Figure 3 shows a natural vibration mode of a working tower that utilizes a steel-concrete composite floor system, where profiled metal decking serves as permanent formwork. This approach enhances structural rigidity and vibration resistance, making it particularly suitable for supporting machinery that generates dynamic loading. The use of composite slabs in this configuration is gaining traction due to their improved performance under operational loads and their ability to reduce vibration amplitudes, thereby increasing the durability and reliability of both the structure and the installed equipment.

Analyzing the frequency values from Table 2 (structure with steel beams and corrugated metal decking), the closest natural vibration frequencies of the tower to the machine vibration frequency of 5 Hz are vibration mode **№34 – 4.818 Hz**. Modes of natural vibrations with modal masses less than 2% are conventionally neglected, as these values have an insignificant impact on the structure due to their negligible mass.

For frequency №34, the deviation is as follows: In absolute terms:

$$\Delta^f = |f_{machine} - f_{tower}| = |5.0 - 4.818| = 0.182\text{Hz}$$

A comparison between the natural frequency of the structure and the operating vibration frequency of the cleaning machine indicates a significant risk of resonance occurrence, attributable to the relatively small frequency deviation. Such close proximity in frequencies may lead to amplification of vibrational amplitudes, potentially compromising the structural integrity.

Analyzing the frequency values from Table 3 (structures using steel-concrete composite floor

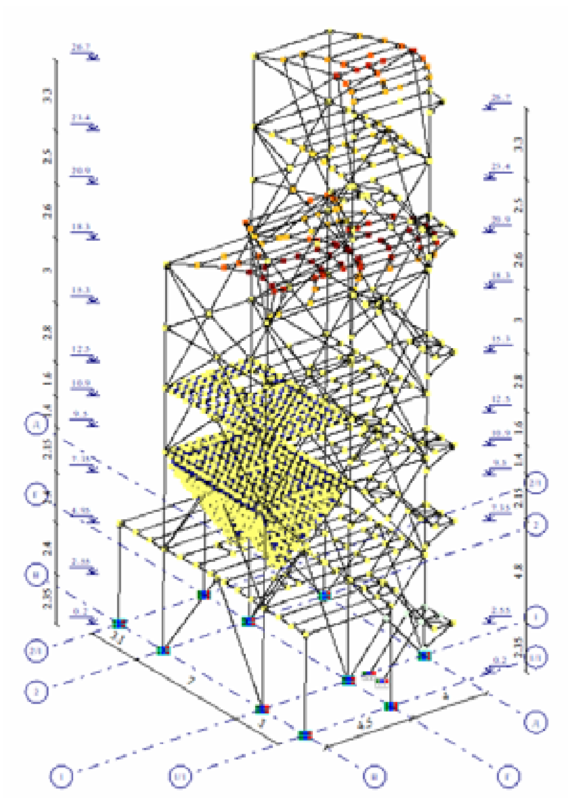

Fig. 2. Forms of natural vibrations of the working tower structure with steel beams and corrugated metal decking

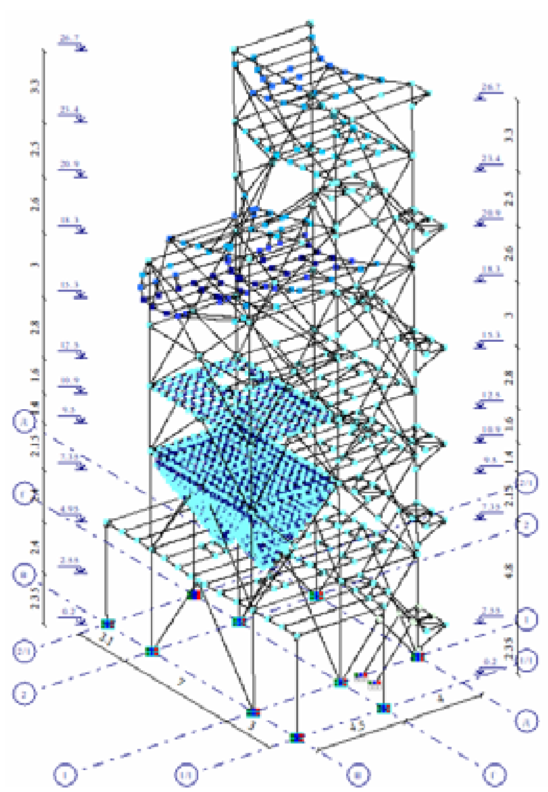

Fig. 3. Natural vibration modes of the working tower structures using steel-concrete composite floor slabs with profiled metal decking as permanent formwork

Table 2

Periods of vibrations of the working tower. Modal analysis. Working tower structure with steel beams and corrugated metal decking

Form number	Eigenvalues	Oscillation frequency	Oscillation frequency	Periods	Distribution coefficient	Modal mass	Sum of masses
(№)	(Rad/s)²	(Rad/s)	(Hz)	(s)		(%)	(%)
1	0,112	8,891	1,415	0,707	1,763	10,207	10,207
2	0,105	9,554	1,521	0,658	- 0,369	0,219	10,426
3	0,099	10,123	1,611	0,621	- 1,185	2,518	12,944
4	0,097	10,339	1,645	0,608	- 1,156	0,528	13,473
5	0,077	13,049	2,077	0,482	- 0,058	0,005	13,477
6	0,071	14,141	2,251	0,444	- 2,292	4,140	17,617
7	0,070	14,302	2,276	0,439	3,291	3,892	21,509
8	0,062	16,259	2,588	0,386	- 2,371	7,170	28,678
9	0,059	16,818	2,677	0,374	1,542	9,883	38,561
10	0,051	19,647	3,127	0,320	0,898	0,547	39,108
11	0,049	20,208	3,216	0,311	- 0,846	0,341	39,449
12	0,049	20,270	3,226	0,310	- 0,002	0,000	39,449
13	0,048	21,047	3,350	0,299	2,483	2,081	41,530
14	0,047	21,492	3,421	0,292	3,023	1,290	42,821
15	0,046	21,734	3,459	0,289	- 0,005	0,000	42,821
16	0,045	22,316	3,552	0,282	- 2,072	0,245	43,066
17	0,044	22,756	3,622	0,276	- 3,520	6,435	49,501
18	0,043	23,475	3,736	0,268	- 0,756	0,983	50,485
19	0,040	24,789	3,945	0,253	- 1,748	4,801	55,285
20	0,038	26,270	4,181	0,239	1,809	0,240	55,526
21	0,038	26,381	4,199	0,238	0,524	0,223	55,749
22	0,038	26,568	4,228	0,236	- 1,077	0,111	55,860
23	0,037	27,309	4,346	0,230	0,773	0,350	56,210
24	0,036	27,537	4,383	0,228	0,004	0,000	56,210
25	0,036	27,539	4,383	0,228	0,006	0,000	56,210
26	0,036	27,773	4,420	0,226	0,527	0,027	56,237
27	0,035	28,294	4,503	0,222	- 0,086	0,000	56,237
28	0,035	28,505	4,537	0,220	- 0,772	0,153	56,390
29	0,035	28,624	4,556	0,220	- 6,757	0,114	56,504
30	0,035	28,739	4,574	0,219	- 0,966	0,542	57,047
31	0,034	29,120	4,635	0,216	- 2,324	0,350	57,397
32	0,034	29,737	4,733	0,211	3,402	0,205	57,602
33	0,033	30,031	4,780	0,209	1,319	0,037	57,639
34	**0,033**	**30,274**	**4,818**	**0,208**	**- 2,054**	**4,685**	**62,324**
35	0,032	31,039	4,940	0,202	- 0,155	0,001	62,325
36	0,031	31,863	5,071	0,197	- 0,107	0,009	62,333
37	0,031	32,687	5,202	0,192	- 1,833	0,082	62,415
38	0,030	33,341	5,306	0,188	1,536	0,835	63,250
39	0,030	33,546	5,339	0,187	1,108	0,053	63,303
40	0,030	33,878	5,392	0,185	- 0,015	0,000	63,303
41	0,029	33,904	5,396	0,185	- 1,022	0,039	63,342
42	0,029	34,957	5,564	0,180	- 0,506	0,013	63,355

slabs with profiled metal decking as permanent formwork), the closest natural vibration frequencies of the tower to the machine vibration frequency of 5 Hz are vibration mode №18 – 3.950 Hz. Modes of natural vibrations with modal masses less than 2% are conventionally neglected, as these values have an insignificant impact on the structure due to their negligible mass.

For frequency №18, the deviation is as follows: In absolute terms:

$$\Delta^f = |f_{machine} - f_{tower}| = |5.0 - 3.950| = 1.05\text{Hz}$$

A comparison between the natural frequencies of the structure and the operational vibration frequency of the grain cleaning machine shows that the risk of resonance is minimal, as the frequency difference exceeds 20%. This deviation is typically regarded as sufficient to prevent substantial amplification of vibration amplitudes, thus reducing the likelihood of adverse effects on the structural stability and performance.

Several structural design alternatives were evaluated for the tower during the

Table 3

Periods of vibrations of the working tower. Modal analysis. Working tower structures using steel-concrete composite floor slabs with profiled metal decking as permanent formwork

Form number	Eigenvalues	Oscillation frequency	Oscillation frequency	Periods	Distribution coefficient	Modal mass	Sum of masses
(№)	(Rad/s)2	(Rad/s)	(Hz)	(s)		(%)	(%)
1	0,112	8,896	1,416	0,706	- 1,761	10,168	10,168
2	0,105	9,554	1,521	0,658	- 0,371	0,222	10,389
3	0,099	10,123	1,611	0,621	- 1,184	2,517	12,906
4	0,097	10,339	1,645	0,608	- 1,156	0,528	13,434
5	0,077	13,053	2,077	0,481	0,059	0,005	13,439
6	0,071	14,146	2,251	0,444	- 2,307	4,172	17,611
7	0,070	14,305	2,277	0,439	- 3,253	3,797	21,408
8	0,061	16,274	2,590	0,386	2,357	7,020	28,428
9	0,059	16,833	2,679	0,373	1,549	10,059	38,487
10	0,051	19,654	3,128	0,320	0,903	0,551	39,038
11	0,049	20,208	3,216	0,311	0,848	0,342	39,380
12	0,049	20,270	3,226	0,310	- 0,002	0,000	39,380
13	0,047	21,073	3,354	0,298	2,411	1,944	41,325
14	0,047	21,505	3,423	0,292	2,924	1,181	42,506
15	0,046	21,734	3,459	0,289	- 0,011	0,000	42,506
16	0,044	22,804	3,629	0,276	3,430	6,659	49,165
17	0,043	23,496	3,740	0,267	0,747	0,952	50,117
18	0,040	24,816	3,950	0,253	1,722	4,730	54,847
19	0,038	26,394	4,201	0,238	0,623	0,309	55,156
20	0,037	27,310	4,347	0,230	0,765	0,342	55,498
21	0,036	27,537	4,383	0,228	0,005	0,000	55,498
22	0,036	27,540	4,383	0,228	0,007	0,000	55,498
23	0,036	27,784	4,422	0,226	- 0,546	0,029	55,527
24	0,035	28,525	4,540	0,220	0,532	0,073	55,600
25	0,035	28,754	4,576	0,219	- 0,684	0,515	56,116
26	0,033	30,351	4,830	0,207	1,036	0,774	61,090
27	0,031	31,864	5,071	0,197	0,121	0,011	61,101
28	0,031	32,689	5,203	0,192	- 1,773	0,076	61,177
29	0,030	33,355	5,309	0,188	1,471	0,808	61,985
30	0,030	33,878	5,392	0,185	0,049	0,000	61,985
31	0,029	33,905	5,396	0,185	- 0,988	0,036	62,021
32	0,029	34,960	5,564	0,180	0,721	0,017	62,038
33	0,029	34,971	5,566	0,180	0,219	0,002	62,040
34	0,028	35,258	5,611	0,178	0,045	0,001	62,041
35	0,028	35,711	5,684	0,176	- 0,004	0,000	62,041
36	0,028	35,893	5,713	0,175	0,622	0,045	62,086
37	0,026	37,774	6,012	0,166	- 0,701	0,010	62,095
38	0,026	37,936	6,038	0,166	- 0,343	0,016	62,111
39	0,026	38,661	6,153	0,163	0,005	0,000	62,111
40	0,026	38,661	6,153	0,163	- 0,006	0,000	62,111
41	0,026	38,663	6,153	0,163	- 0,001	0,000	62,111
42	0,025	40,109	6,384	0,157	- 1,103	1,490	63,601

planning phase. The most effective solution was determined to be a composite steel-concrete floor slab constructed on a profiled metal deck [11; 19]. This configuration was selected not only for its cost-efficiency in terms of materials but also for its enhanced ability to resist the dynamic effects generated by the operating machinery. To ensure a reliable connection between the steel framing and the concrete slab, 16 mm diameter stud bolts were used. The principal details of the reinforcement and fastening system are illustrated in Figure 4. A comparison between the natural frequencies of the structure and the operational vibration frequency of the grain cleaning machine shows that the risk of resonance is minimal, as the frequency difference exceeds

20%. This deviation is typically regarded as sufficient to prevent substantial amplification of vibration amplitudes, thus reducing the likelihood of adverse effects on the structural stability and performance.

Several structural design alternatives were evaluated for the tower during the planning phase. The most effective solution was determined to be a composite steel-concrete floor slab constructed on a profiled metal deck [17; 21]. This configuration was selected not only for its cost-efficiency in terms of materials but also for its enhanced ability to resist the dynamic effects generated by the operating machinery. To ensure a reliable connection between the steel framing and the concrete slab, 16 mm diameter stud bolts were used. The principal details of the reinforcement and fastening system are illustrated in Figure 4.

CONCLUSIONS

Through the implementation of modal analysis, the natural frequencies and vibration modes of the structure were identified and subsequently compared with the operational frequency of the grain cleaning equipment. The research considered two flooring systems:

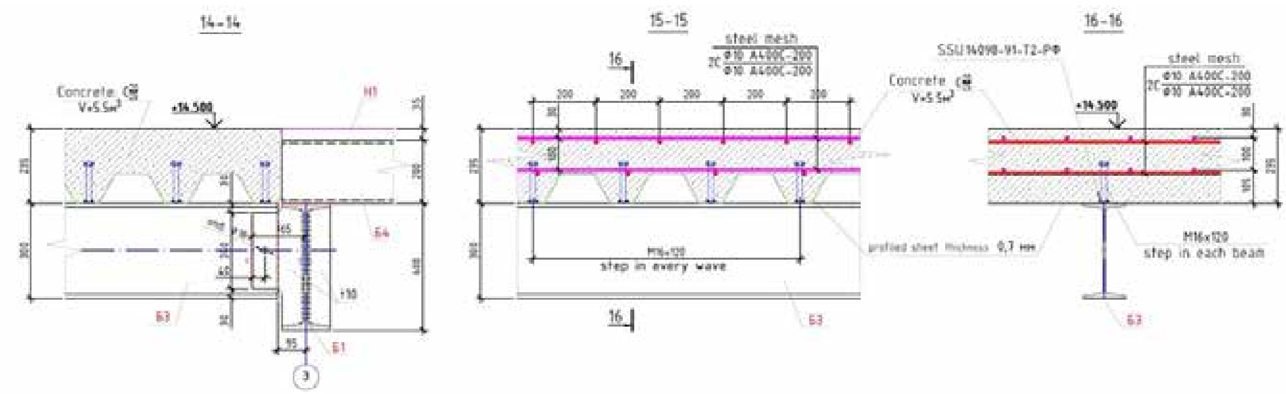

Fig. 4. Fastening and reinforcement nodes of the steel-concrete slab

a composite steel-concrete slab poured over profiled steel decking functioning as permanent formwork, and a conventional steel-framed floor with corrugated metal sheeting. The composite system demonstrated clear advantages in terms of structural stiffness and vibration damping capability. This configuration significantly reduced the amplitude of structural oscillations, eliminated resonance conditions, and contributed to the reliable functioning of the installed equipment. A secure bond between the steel and concrete components was ensured through the use of 16 mm diameter headed stud connectors.

The scientific significance of this study lies in the novel application of profiled decking as permanent formwork in composite slabs used for elevator working towers, along with the analytical consideration of parameters such as slab thickness and shear connector dimensions. A rigorous modal analysis approach was used to assess resonance risk and enhance dynamic response characteristics. The findings demonstrated that the proposed flooring solutions effectively reduce vibration amplitudes, boost structural resilience, and ensure the safe and uninterrupted operation of grain cleaning machinery.

The dynamic performance evaluation was conducted using advanced structural analysis tools – LIRA-FEM for detailed modal simulations and Autodesk Revit for 3D modeling and coordination. The tested floor systems proved to be efficient in both material usage and dynamic resistance. The integration of steel-concrete composite slabs in the design of elevator towers presents a dependable construction approach, offering long-term durability, effective vibration mitigation, and enhanced structural safety.

Future studies will concentrate on analyzing the influence of concrete slab thickness on the dynamic behavior of composite floors, aiming to further refine vibration control measures and optimize overall structural efficiency.

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АНОТАЦІЯ

Пономарьов П., Костира Н. Напружено-деформований стан перекриття робочої вежі елеватора за дії динамічних навантажень

У статті розглядаються особливості роботи та стійкості сталезалізобетонних перекриттів, що застосовуються у робочих вежах зерносховищ, які зазнають дії динамічних навантажень від роботи зерноочисного обладнання. Дослідження зосереджене на аналізі реакції конструкцій веж із перекриттями сепараторних поверхів, виконаними у вигляді сталевих каркасів або сталезалізобетонних конструкцій по незнімній опалубці у вигляді профільованого листа. Особливу увагу приділено уразливості до резонансних явищ і шляхам підвищення надійності конструкцій під час експлуатації.

Мета. *Метою дослідження є аналіз і порівняння динамічної поведінки різних типів перекриттів у робочих вежах елеваторів – сталевих та сталезалізобетонних – і оцінка їх чутливості до резонансних впливів, спричинених роботою зерноочисного обладнання.*

Методологія. *Виконано модальний аналіз двох варіантів конструкцій перекриттів із використанням обчислювального моделювання. Визначено власні частоти коливань та відповідні форми за допомогою програмного комплексу LIRA-FEM, що використовувався як для статичного, так і для динамічного розрахунку. Для створення тривимірних моделей конструкцій використовувалася система Autodesk Revit. Ризик виникнення резонансу оцінювався шляхом порівняння отриманих власних частот із відомою робочою частотою зерноочисних машин (5 Гц).*

Результати. *Аналіз показав, що комбіновані перекриття з профільованим настилом і бетонною плитою значно краще приглушують коливання порівняно зі сталевими конструкціями. Обидві системи було оцінено за власними частотами для виявлення потенціалу до резонансу. Композитні конструкції продемонстрували кращу відповідність вимогам безпеки та стабільності роботи обладнання.*

Наукова новизна. *У роботі запропоновано застосування сталезалізобетонних перекриттів із профільованим настилом, який виконує функцію незнімної опалубки, для конструкцій робочих веж елеваторів. Доведено їх ефективність у зменшенні резонансних впливів. Представлено оригінальну інженерна конфігурацію, що підвищує надійність конструкції та безпечність експлуатації і може бути основою для подальшого вдосконалення параметрів плит.*

Практична значущість. *Результати дослідження можуть бути використані для покращення проєктних рішень під час вибору конструкцій перекриттів у вежах елеваторів. Перевірені варіанти забезпечують ефективніше гасіння вібрацій і підвищену стійкість, що сприяє безпечнішій та надійнішій роботі зерноочисного обладнання. Отримані дані можуть слугувати основою для прийняття обґрунтованих інженерних рішень під час проєктування динамічно навантажених сільськогосподарських об’єктів.*

<u>Ключові слова:</u> композитні конструкції, зерновий елеватор, динамічні навантаження, модальний аналіз, резонанс, LIRA-FEM, сталезалізобетонні системи, конструктивна безпека.

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