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THE USE OF METAL-TIMBER STRUCTURES IN THE RECONSTRUCTION OF INDUSTRIAL BUILDINGS FOR THE RENEWAL OF RESIDENTIAL REAL ESTATE

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Summary. The use of modern renovation and reconstruction methods to transform industrial buildings into residential ones, especially in the context of post-war reconstruction efforts in Ukraine, is becoming particularly relevant. To reduce the financial burden of new construction and facilitate the resettlement of refugees from Russian aggression, it is expedient to reconstruct existing decommissioned industrial buildings in ruined cities and migration zones into residential premises. Considering the specific volumetric and spatial solutions of industrial buildings, a significant amount of work is required to reorganize the internal space of such premises for adaptation as residential ones. At the same time, the frames of production premises, due to significant distances between load-bearing structures, allow for more open and spacious premises with modern loft-style interiors. One of the ways to effectively achieve this goal is to install additional floors using metal-timber beams in industrial buildings. The low weight and high load-bearing capacity of such structures make it possible to create additional premises within the existing building volume, with minimal additional loads on the load-bearing frame and building foundations. This approach is not only econo-mically efficient but also offers a unique modern way of organizing the interior for comfortable living.

The aim of the research is to determine the efficiency and feasibility of using metal-timber I-beam profiles in the process of transforming indu-strial buildings into residential spaces. The study analyzes both domestic and foreign experience in the renewal and reconstruction of industrial buildings. The conclusions indicate that various functional adaptations of industrial buildings or complexes are possible depending on the project goals, as well as their further integration into the existing city infrastructure. However, the implementation of this concept faces the challenge of the limit of the structural load that can be applied to existing load-bearing frame structures.

The reconstruction project must ensure the sustainability (or minimization) of additional loads, which allows reducing the required scope of work, project implementation time, and minimizing investment. Taking into account the industrial nature of the original interior of production premises, the loft style is best suited to the concept of renovating industrial buildings into residential ones. The

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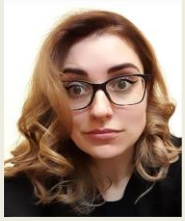

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application of the loft style for the reconstruction of industrial zones is recommended as an economically advantageous option, supported by global experience. Special attention should be paid to the format of transforming production premises into residential ones using lightweight metal-timber roofs, which can become an organic part of the interior space.

Scientific novelty. The reconstruction of industrial buildings for residential purposes is a complex and multifaceted process that requires thoughtful decisions and a competent approach. In this article, we will explore the advantages of using structures made of combined metal-timber systems to create technical solutions that meet the requirements of economic viability, environmental friendliness, and energy efficiency in the reconstruction process.

Practical significance. The application of metal-timber constructions allows for the rapid and efficient restoration of industrial buildings, transforming them into residential housing to address the shortage of living space due to the displacement of refugees from Russian aggression. These constructions have significantly lower weight and cost compared to traditional materials such as concrete or steel, while ensuring high strength and reliability. Additionally, they are made from environmentally friendly renewable materials and have an attractive appearance, making them an ideal choice for the reconstruction of industrial buildings into residential housing.

Keywords. Reconstruction; loft; industrial buildings; restoration; metal-timber structures; composite structures.

PROBLEM STATEMENT

At the outset of the full-scale invasion by the russian federation, the President of Ukraine emphasized that a special state program for reconstruction would be established for every city affected by the war [13, 17]. No trace of the occupiers would be left in any of the cities. To achieve this, companies and architects with the best projects would be hired.

In July 2022, Deputy Head of the Office of the President of Ukraine, Kyrylo Tymoshenko, confirmed that the rapid recovery plan for the country involves the swift reconstruction of social infrastructure, taking into account modern construction standards and an entirely new level of security. He estimated that as of July 2022, the damage to Ukraine due to Russian aggression [21] amounted to $750 billion.

In early July 2022, the city of Lugano in Switzerland hosted a conference where the Ukrainian government presented the Recovery Plan for Ukraine. Over 3000 experts and international consultants from various fields contributed to its development. UN Secretary-General Antonio Guterres is confident that the country's recovery is a lengthy process and must be initiated with the formula "start now," meaning immediately, without waiting for the end of the war.

The Recovery Plan for Ukraine is designed for a duration of 10 years. The first stage, from 2023 to 2025, includes 580 National Projects. The second stage, from 2026 to 2032, comprises 270 National Projects. Among the 17 programs, the most expensive is the program for the restoration and modernization of housing and infrastructure in regions, requiring $150-250 billion. However, these estimates are not final, as the war is ongoing, and destruction continues. The exact amount needed for recovery will be understood upon the conclusion of hostilities.

The Recovery Plan for Ukraine is based on five principles:

- Immediate initiation and gradual development.
- increasing fair prosperity.
- integration into the EU.
- Reconstruction better than it was on national and regional scales.
- stimulating private investments.

Additionally, in the spring of 2022, the non-governmental organization "Urbanina" initiated the development of the "Guide to the Reconstruction of Cities." Over 50 experts, the NGO "Accessibility," and the Office of the President joined this initiative. In turn, the Architectural Chamber of the National Union of Architects of Ukraine (NSAU) established a special coordination headquarters for post-war recovery of cities and communities.

Since the era of urban industrialization, cities have inherited large industrial facilities. Factories, manufactories, and thriving ports attracted new residents and permanently altered urban landscapes. Subsequently, new favorable spaces for production emerged, and extensive

industrial zones became abandoned wastelands [7, 17, 18, 24].

To transform these territories into urban spaces, developers and municipal authorities resort to their revitalization and reimagining in a new environment. Enormous factories are repurposed into modern housing, and water towers become art objects.

In the process of rebuilding the housing stock in post-war conditions, key requirements include architectural expressiveness, authenticity, enhanced quality, and durability of buildings, as well as the reduction of material, labor, and energy costs for their construction and operation [6, 9, 10, 11, 12, 19].

It is crucial to consider the priority implementation of green technologies, as buildings overall account for 40% of energy consumption and approximately 47% of CO2 emissions throughout their life cycle. In 2022, the National Standard of Ukraine DSTU 9171:2021 "Guidance on Ensuring Balanced Use of Natural Resources in the Design of Structures" was released. It approves the reuse and secondary recycling of materials and products at a level not less than 70%, as part of compliance with the EU agreement.

The standard describes criteria for the rational use of natural resources in the reconstruction of architectural and construction systems, methods to reduce financial costs for building maintenance, outlines a methodology for considering the ecological efficiency of using building materials at various levels of analysis during design, and provides a methodology for determining the effects of implementing measures for balanced use of natural resources [1, 2, 8, 14, 15, 16].

The introduction of mandatory life cycle environmental and economic assessment for buildings necessitates a reassessment of traditional structural solutions and adaptation for increased efficiency.

An effective solution in this context is the reconstruction of industrial buildings into residential spaces using metal-timber constructions. The advantages of such constructions include:

- the ability to implement complex architectural solutions.
- freedom in planning spaces within existing buildings and structures.
- metal-timber constructions can be manufactured separately and assembled on-site in a very short time, using low-capacity lifting mechanisms due to their low weight.
- metal-timber constructions are lighter than traditional materials, creating less load on the foundation.
- high environmental performance of metal-timber materials.
- use of local renewable materials.
- reduction of dependence on production bases for metal and concrete constructions.
- the ability to combine the functions of load-bearing structures and elements of interior design with minimal interior finishing.
- quick reconfiguration and recyclability of constructions at the end of the lifespan or when there is no longer a need for residential spaces.

The uniqueness of metal-timber constructions lies in the synthesis of the working properties of thin corrugated metal walls and belts made of solid or laminated timber. This combination allows for constructions that are lighter than both steel and solid timber.

For a reliable connection between the steel profiled sheet and timber belts, mechanical compression of the rigid corrugated steel wall into the timber belts or bonding using a two-component epoxy adhesive, which adheres well to both metal and timber surfaces, can be employed. The use of corrugated steel walls in timber I-beams results in increased load-bearing capacity, profile stiffness, reduced required section height, and reduced weight of the beams. All of these significantly expand the range of applications of I-beams with timber belts and enhance their efficiency.

To ensure high corrosion resistance, galvanized metal sheets are used. By incorporating timber and thin corrugated walls, the weight of combined beams is 2-3 times less than that of equivalent solid timber or metal beams with a rectangular cross-section. The application of combined metal-timber beams is

a promising direction for further improving the efficiency of load-bearing structures by combining the positive properties of two materials.

ANALYSIS OF PREVIOUS RESEARCH

Military aggression by the russian federation has caused significant damage and destruction in Ukraine, leading to the decline of key enterprises and leaving numerous industrial sites unused [13, 17, 21]. These factors have had a negative impact on the economic, social, cultural, and psychological development of cities and their residents. In light of this, it is essential to actively engage in the renovation and reconstruction of decommissioned industrial facilities with the aim of transforming them into residential buildings. This is a rational and necessary step in ensuring sustainable urban development and improving the quality of life for the population, especially those forcibly displaced due to the ongoing armed conflict.

One example of the renovation and reconstruction of industrial areas, buildings, and structures is the gas holders in the Zimmering area of Vienna, Austria (Fig. 1).

Fig. 1. Renovation of the gasholders in Vienna
Рис.1. Ремонт газгольдерів у Відні

The gas holders, constructed between 1896 and 1899, consist of four cylindrical telescopic gas reservoirs, each with an approximate volume of 90,000 m³. Each gas holder has a height of 70 m and a diameter of 60 m. Originally operational until 1984, they fell into disuse thereafter. Leaving only the walls, architects transformed them by adding transparent domes by 2001. Each building was divided into residential (upper), office (middle), and commercial-recreational (lower) zones, connected by transitions.

Examples of large-scale reconstruction of industrial zones in Ukraine, including Kiev, were observed even before the onset of the war. One such project in Kiev is the extensive reconstruction of the Kiev Motorcycle Plant on Simyi Khokhlovykh Street to accommodate the innovation park (UNIT CITY) – a complex of residential and public buildings and structures (Figure 2).

Fig. 2. Reconstruction of the Kyiv Motorcycle Plant to accommodate the UNIT CITY innovation park
Рис.2. Реконструкція Київського мотоциклетного заводу під інноваційний парк UNIT CITY

The Kiev Motorcycle Plant operated on the site from 1945, producing heavyweight motorcycles, including popular models such as "Dnepr" and "Kyivlianin." In the 2000s, the plant ceased operations, and the 24 hectares of land remained abandoned. At the start of the reconstruction in 2016, the buildings were available for lease, and the area was neglected

The first step towards implementing the innovation park was the construction of the business campus with the UNIT Factory IT school. The school's curriculum was built on student initiative, offering young specialists the opportunity to work in nearby IT offices after three years of study or even during their studies. The infrastructure of the innovation park later expanded with public dining establishments and residential areas.

The main goal of UNIT.City's innovation is to create a modern, convenient platform for attracting and developing the IT community.

Residents of the innovation park can freely exchange ideas and implement ambitious projects without leaving the premises. During the reconstruction, additional floors were installed inside the buildings using metal beam ceilings and lightweight profiled concrete slabs.

An excellent example of the conversion of an industrial building into residential housing is the development of the residential complex "SMART HOUSE" in a multi-story building at 39-41 Mashynobudivelna Street in Kyiv (Figure 3).

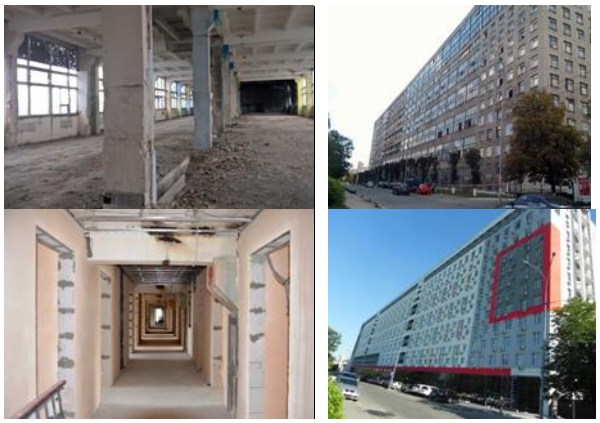

Fig. 3. Arrangement of the SMART HOUSE residential complex in Kyiv

Рис.3. Облаштування житлового комплексу SMART HOUSE в Києві

During the reconstruction of the industrial building, a full-fledged complex comprising a thirteen-story building with three sections was constructed. The initial floors of the new structure were designated for commercial purposes, hosting coworking spaces, a family medical center, dry cleaning services, cafes, a laundry, supermarket, fitness center with a pool, pharmacy, etc. From the fourth to the top floor, modern smart apartments and fully equipped one-bedroom apartments were designed, already offered with completed renovations and furnishings. Inside the building, additional floors were created for residential spaces using metal structures attached to load-bearing columns, effectively doubling the usable area of the interior premises.

The revitalization of the former Kyiv Rubber Goods Factory on Amurska Street has been completed, transforming the old buildings and workshops into a Class B business center known as City Garden. The restored and modernized premises are actively utilized for leasing by both Ukrainian and international companies.

The project authors have successfully created an open area for guests, featuring abundant greenery and recreational spaces. The territory also hosts various open infrastructure facilities such as cafes, restaurants, bank branches, etc. Another distinctive feature of the new business center is the utilization of all the roofs of the buildings. For the residents, barbecue areas and relaxation terraces have been equipped. There are plans to create a multi-court training area on one of the rooftops in the future.

Fig. 4. Revitalization of the buildings of the shoe factory for the construction of the City Garden business center in Kyiv

Рис. 4. Ревіталізація корпусів взуттєвої фабрики для будівництва бізнес-центру City Garden у Києві

During the implementation of reconstruction measures, it is advisable to identify and preserve the most valuable aesthetically pleasing fragments of the urban environment. This approach allows for the development of its positive individual characteristics and the creation of a new aesthetic for the industrial area based on the already formed architectural ensemble.

A realization of a modern approach to residential design is the loft style. This design trend originated in America in the 1950s. The lack of available space and new constructions compelled the creative population to set up their studios directly in the attics of industrial buildings (Figure 5).

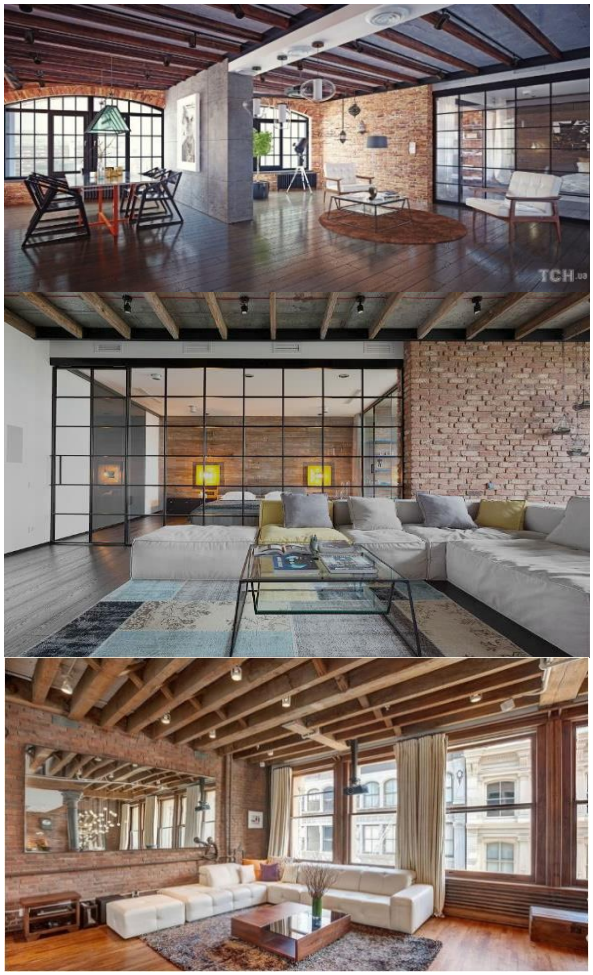

Fig. 5. Examples of loft-style interiors with timber beams

Рис.5. Приклади інтер'єрів в стилі лофт з дерев'яними балками

The main features of the style include:

– a large open space, where neither furniture nor walls take the forefront, but rather the space itself. The premises should be open, requiring the demolition of certain walls or door openings and the merging of rooms with different purposes to implement this solution in typical apartments. For industrial buildings, this is already a starting point, and it is sufficient to organize the internal space correctly.

– presence of raw and rugged finishes, with characteristics provided by materials such as brick, concrete, exposed pipes, and other elements.

– minimalism, characterized by the absence of numerous accessories and decorations, emphasizing strict forms.

– industrial furniture and decor elements, where all furniture and decorations should be strict, functional, and practical.

Timber elements seamlessly integrate into such interiors, adding a sense of naturalness and environmental friendliness to the industrial style (Figure 5).

PRINCIPAL RESEARCH

Why should we prefer structures made of metal-timber profiles? The current state of the construction market, amidst damage and destruction of industrial and logistical infrastructure, demands the development of new effective structural forms. These forms should have less dependence on production bases, allow the use of local renewable materials, and ensure the quick and easy construction of buildings while maintaining reliable and safe operation over an established period

One of the most readily available materials in this context has always been timber [1, 23, 25]. To enhance load-bearing capacity, modern technological capabilities allow for the production of massive composite timber structures: glued laminated timber (GLT) structures and cross-laminated timber (CLT) structures, composed of an odd number of layers of boards arranged perpendicularly in adjacent layers. CLT panels are used in panel and panel-frame construction for structures of various architectural complexity and height [2, 11, 12]. The challenge is to further reduce the weight of the structures while increasing the free span, improving sound absorption between floors, and enhancing the thermal insulation of roofing structures. This is achieved by replacing solid timber with a composite I-beam cross-section with a thin corrugated steel wall and flanges made of solid or glued timber (Figure 6).

The effectiveness of the structure is achieved through the synthesis of the properties of the corrugated metal wall, which effectively absorbs transverse forces in beams, and the flanges made of solid or glued timber, capable of withstanding significant normal stresses along the fibers and contributing to the safe

flexural-torsional stability of the beams [15, 20, 22].

Fig. 6. Construction of a metal-timber beam and cutting of a metal wall for insertion.
Рис. 6. Конструкція металево-дерев'яної балки та вирізка металевої стінки для вставки.

The task is solved by milling a longitudinal groove in timber belts, into which a steel profiled sheet is glued or pressed. The width of the groove equals the height of the corrugation of the profiled sheet. The thickness of the wall, the height of the corrugation of the steel sheet, and the dimensions of the timber belts should be determined through calculation. For reliable bonding of the steel profiled sheet and timber belts, a two-component epoxy adhesive with good adhesion to both metal and timber surfaces can be used.

Assembly, pressing, or gluing takes place on specialized production lines, the length of which can be adjusted depending on the required length of the elements (Figure 7).

Fig. 7. The technological line of connecting metal mesh with timber belts
Рис. 7. Технологічна лінія з'єднання металевої сітки з брусовими стрічками

In this process, elements of a constant cross-section can be manufactured, as well as structures with variable wall height or face width.

The application of a metal profiled sheet in timber I-beams results in an increase in load-bearing capacity, profile stiffness, and a reduction in the required cross-sectional height and the weight of the beams. To ensure high corrosion resistance, galvanized metal sheets made of S550 GD + Z steel according to DIN EN 10147 are used. Due to the lower density of timber and the use of a thin corrugated sheet, the weight of the combined beams is 2-3 times less than that of a comparable all-metal counterpart, reducing construction costs. Currently, in Europe, structures made of metal-timber constructions are frequently used for the construction of warehouse and industrial premises (Figure 8).

Fig. 8. Frames of warehouses made of metal-timber I-beams
Рис. 8. Каркаси складських приміщень з металево-дерев'яних двотаврів

But besides new construction, such constructions prove to be extremely effective, especially in the reconstruction of buildings, when additional structures are added to expand the usable area of existing premises (Figure 9).

Fig. 9. The use of metal- timber beams during reconstruction
Рис. 9. Використання металево-дерев'яних балок при реконструкції

The weight of a metal-timber beam with a span of 6m and a height of 230mm under the load from the floor of a residential building is approximately 36 kg. This means that such a structure can be assembled even without the use of lifting mechanisms. The weight of a metal beam under identical conditions will be at least

110 kg, and for a reinforced concrete beam, it will be no less than 160 kg.

Significant economic benefits can be achieved when using metal-timber beams as individual floor beams or assembled panels with beams fastened with an OSB board (Figure 10). The use of interlocked panels ensures a quick and efficient assembly of structures, significantly speeding up the construction process.

Fig. 10. Metal-timber beams in the frames of floors in the form of individual elements and as part of prefabricated panels

Рис. 10. Металодерев'яні балки в каркасах перекриттів у вигляді окремих елементів і в складі збірних панелей

In addition, the lightweight steel sheet provides such load-bearing systems by reducing the transmission of vibrational oscillations, positively affecting sound absorption when used as interfloor structures. Similarly, the reduction in the weight of the frame and the use of flexible corrugated walls, in combination with timber characteristics, provide metal-timber frames with increased seismic resistance.

Due to the individual manufacturing of structures, production waste is minimized. Thus, when developing a project from hundreds of possible variations, an optimal economic solution is implemented. Moreover, the ability to use simple joints in structures is preserved, as in structures made of solid or laminated timber. The technological simplicity of metal-timber beams is also a significant advantage since traditional manual construction tools, such as timber, can be used for processing - timber allows for easy processing, and the steel used in the wall has a thickness of 0.5-0.8 mm and can be processed with manual disc cutters.

The wall is made of carbon steel, hot-dip galvanized, most often of grade S550 GD+Z, with a zinc layer of not less than 275 g/m2 (approximately 40 μm). Under conditions of high humidity and a medium degree of air aggressiveness (such as industrial or urban atmosphere or coastal climate with low chloride content), the expected service life of the protective zinc coating is 20-30 years.

In the case of operation within residential premises with a mildly aggressive environment, a service life of 50 to 100 years can be expected. Compared to painted coatings, hot-dip galvanizing has significantly better resistance to mechanical influences due to the cathodic protection effect, even with minor surface damage

A very thin steel sheet (0.5 mm) gives metal-timber beams excellent properties in the production of thermal insulation building elements (Figure 11). The insulation properties are much better than when using beams made of solid or laminated timber if the formation of a thermal bridge is not allowed. If the insulation is installed correctly, condensation in the sheet zone will not occur. Additional reliability can be ensured by protecting against corrosion at the intersection of belts with a steel wall when used in aggressive operating conditions [3, 4, 14].

Fig. 11. Therm al insulation of panels with metal-timber beams

Рис. 11. Теплоізоляція панелей з металево-дерев’яних балок

Transparent coating can be applied to the visible lower shelves in the elements of floor structures or the lower part of roofing constructions of single-story buildings while preserving the texture, transforming them into a vivid and distinctive interior feature.

CONCLUSIONS AND PERSPECTIVES FURTHER RESEARCH

The research conducted has identified a series of advantages of metal-timber beam structures compared to traditional construction solutions: increased rigidity and low self-weight due to a rational distribution of material along the cross-section height, high vibration and noise absorption characteristics, resistance to seismic and other dynamic impacts, technological simplicity, low thermal conductivity, and high corrosion resistance. Additionally, the aesthetic appeal of the natural material, which can seamlessly integrate into the interior, enhances the overall qualities. These properties are achieved through the harmonious combination of the benefits of a thin steel corrugated wall with robust timber. Metal-timber I-beam structures undoubtedly deserve attention both from engineers and designers, as well as architects, in the realization of modern, economical, and energy-efficient buildings.

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ВИКОРИСТАННЯ МЕТАЛОДЕРЕВ'ЯНИХ КОНСТРУКЦІЙ ПРИ РЕКОНСТРУКЦІЇ ПРОМИСЛОВИХ БУДІВЕЛЬ ДЛЯ ВІДНОВЛЕННЯ ЖИТЛОВОГО ФОНДУ

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Анотація. Використання сучасних методів реновації та реконструкції для перетворення промислових будівель на житлові, особливо в умовах післявоєнної відбудови України, набуває особливої актуальності. Для зменшення фінансового навантаження на нове будівництво та сприяння розселенню біженців від російської агресії доцільно реконструювати існуючі списані промислові будівлі у зруйнованих містах та міграційних зонах під житлові приміщення. Враховуючи специфіку об'ємно-просторових рішень виробничих будівель, необхідний значний обсяг робіт з реорганізації внутрішнього простору таких приміщень для пристосування їх до житлових. При цьому каркаси виробничих приміщень, завдяки значним відстаням між несучими конструкціями, дозволяють отримати більш відкриті та просторі приміщення з сучасним інтер'єром у стилі лофт. Одним із способів ефективного досягнення цієї мети є влаштування в промислових будівлях додаткових перекриттів з використанням металевих балок. Мала вага і висока несуча здатність таких конструкцій дозволяють створювати додаткові приміщення в межах існуючого об'єму будівлі з мінімальними додатковими навантаженнями на несучий каркас і фундамент будівлі. Такий підхід є не тільки економічно

ефективним, але й пропонує унікальний сучасний спосіб організації інтер'єру для комфортного проживання.

Метою дослідження є визначення ефективності та доцільності використання металодерев'яних двотаврових профілів у процесі перетворення промислових будівель у житлові приміщення. У дослідженні проаналізовано вітчизняний та зарубіжний досвід оновлення та реконструкції промислових будівель. Висновки вказують на те, що можливі різноманітні функціональні адаптації промислових будівель або комплексів залежно від цілей проекту, а також їх подальша інтеграція в існуючу інфраструктуру міста. Однак реалізація цієї концепції стикається з проблемою обмеження структурного навантаження, яке можна застосувати до існуючих несучих рамних конструкцій.

Проект реконструкції повинен забезпечувати стійкість (або мінімізацію) додаткових навантажень, що дозволяє скоротити необхідні обсяги робіт, терміни реалізації проекту та мінімізувати інвестиції. Враховуючи індустріальний характер оригінального інтер'єру виробничих приміщень, стиль лофт найкраще підходить для концепції переобладнання промислових будівель у житлові. Застосування стилю лофт для реконструкції промислових зон рекомендовано як економічно вигідний варіант, підтверджений світовим досвідом. Особливої уваги заслуговує формат перетворення виробничих приміщень у житлові з використанням полегшеної металево-дерев'яної покрівлі, яка може стати органічною частиною внутрішнього простору.

Наукова новизна. Реконструкція промислових будівель під житлові цілі – складний і багатогранний процес, який вимагає зважених рішень і грамотного підходу. У цій статті ми розглянемо переваги використання конструкцій з комбінованих металодерев'яних систем для створення технічних рішень, що відповідають вимогам економічності, екологічності та енергоефективності в процесі реконструкції.

Практичне значення. Застосування металодерев'яних конструкцій дозволяє швидко та ефективно відновлювати промислові будівлі, перетворювати їх на житлові будинки для вирішення проблеми дефіциту житлової площі через переміщення біженців від російської агресії. Ці конструкції мають значно меншу вагу та вартість порівняно з традиційними матеріалами, такими як бетон чи сталь, забезпечуючи при цьому високу міцність та надійність. Крім того, вони виготовлені з екологічно чистих відновлюваних матеріалів і мають привабливий зовнішній вигляд, що робить їх ідеальним вибором для реконструкції промислових будівель під житлові будинки.

Ключові слова. Реконструкція; лофт; промислові будівлі; відновлення; металодерев'яні конструкції; комбіновані конструкції.

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