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INCREASING THE STRUCTURE RESILIENCE OF STEEL TRUSSES

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This article examines approaches to improving the robustness and resilience of steel trusses under static and dynamic loads. Particular attention is paid to the advantages of statically indeterminate systems, redistribution of internal forces, and the use of plastic hinges and damping devices. The study highlights the role of material properties, especially fatigue strength and the use of high-strength and mild steels, in ensuring structural resilience. Numerical modeling based on the finite element method, experimental research, and structural health monitoring are emphasized as key tools for predicting limit states and extending service life. The findings underline the importance of integrating advanced design methods with practical measures to increase reliability, safety, and sustainability of steel structures.

Keywords: combined steel truss, rational design, principles of structural efficiency, metal content, total normal stress diagram, comparative analysis.

Introduction

Globally, sustainable development and resource awareness are among the most important topics of the era. The construction industry is developing at an unprecedented pace, driven by technological progress, environmental considerations and the ever-increasing demand for sustainable and efficient solutions. Steel structure, with its strength, versatility and adaptability, continues to play a key role in shaping the horizons of the future. With the development of materials science and construction technologies, the potential uses of trusses continue to expand. The main approach should be based on implementation of innovation in truss design as the discovery of the future of structural engineering. Innovation in truss design is driven by advances in materials (such as carbon fiber composites), computational design tools (such as generative algorithms and artificial intelligence) and intelligent technologies (such as sensors and adaptive systems), leading to the creation of more efficient, sustainable and adaptive structures. These innovations enable complex, optimized and cost-effective structures, improve structural performance, reduce environmental impact and create more resilient and durable steel trusses at the design stage. When designing steel truss structures, the key is to achieve the ideal balance between safety, functionality and cost-effectiveness, ensuring that the design meets both performance requirements and budget constraints. The most important aspect of sustainable development in manufacturing is the conservation of energy and natural resources.

The purpose of the study is to increase the structural resilience (load-bearing capacity) in accordance with the requirements of design standards, in which local structural failure should not lead to a disproportionate spread of damage.

Materials and Methods

Throughout history, engineers have sought opportunities to develop adaptive structures that were able to adapt to ever-changing requirements and conditions. The reasons for this interest are related to the growing need for such properties as flexibility, resilience and enhanced design capabilities. This requires a comprehensive review of the conceptual assessment and quantification of the structural stability of a system (the entire frame) at the micro, meso and macro levels (Strauss et al., 2025).

Scientific and technological progress in the field of construction is closely linked to the development and improvement of steel structures, including steel trusses. Steel is uniquely suited to withstand extreme conditions, from high winds to seismic activity. Due to the constant occurrence and, apparently, increasing frequency of catastrophic structural failures, recent years have been marked by an increase in data on progressive failure (e. g., impact, explosion, fire, earthquakes), which requires new theoretical, computational, and experimental studies to predict the impact of such factors on the structural resilience of buildings and individual structural element systems (Shymanovsky, 2019; Shymanovsky, 2018).

The main solution of this problem for assessing the impact of these factors is analysis of the risk of progressive failure under conditions of one and several extreme hazards: probabilistic assessment of resistance to progressive failure and the impact of aging and deterioration of structures and the most demanded in practical terms – increasing the resilience of steel structures (trusses) at the design stage based on strengthening structures using innovative technologies (Shymanovsky, 2019). The task is to create structures capable of perceiving additional effects from aggressive environment impact, explosion, fire, earthquake, and interpreting them, thus achieving self-adaptation.

Designing the building taking into account strength is the main component of the constructive solution (GSA, 2003; UFC, 2016). Structural resilience is important criterion for assessing the safety of structures to improve their resistance to gradual failure. In the context of structural engineering, strength refers to the ability of a structure to sustain damage or failure of individual components or groups of components to a certain extent without failure. Any failure or damage should remain proportional and limited compared to the overall scale of the event, ensuring that structural integrity is not disproportionately compromised (Strauss et al., 2025). At the same time, an analysis of existing design and construction experience has shown that, compared to traditional truss structures, insufficient attention is paid to improving their survivability and resilience at the design stage. This is due to a number of factors, including the lack of detailed theoretical and experimental studies, design recommendations and calculations according to modern requirements that ensure increased survivability and resilience. Also, there are no in-depth studies of such systems, depending on the design features of the system.

Rational design of truss structures allows the system to maintain its load-bearing capacity even if some structural elements are destroyed or damaged. After damage to local structural elements, the rest of the structure can rely on neighboring elements to form a new load path so that the structure can still withstand some external load (Feng et al., 2021). That is, the main role here is played by the assessment of the importance of elements, which can change according to the load distribution.

A larger number of redundant degrees of freedom reflects how the structure has a richer force transmission path (Feng et al., 2021).

The advantages of statically indeterminate structures over statically determinate ones have long been known and consist in increased reliability and resilience, which is achieved due to the possibility of redistributing forces between individual elements. Unlike statically determinate systems, where the failure of one element can lead to the loss of the load-bearing capacity of the entire structure, in statically indeterminate trusses the design scheme provides for redundancy of connections. This reduces the risk of sudden failure and provides an additional safety margin which is shown in examples of beam (Fig. 1), frame (Fig. 2) or truss (Fig. 3). Taking into account the above, the transition to statically indeterminate systems allows to increase the reliability of the structure as a whole.

A similar approach for combined steel trusses increases their efficiency (Fig. 4). The transition from hinged structures (Fig. 4, *a*) to continuous ones (continuous upper chord, Fig. 4, *b*) allows you to change the design scheme in such a way that the bending moments are reduced. This, in turn, provides the possibility of reducing the cross-sections of individual elements, optimizes the mass of the entire structure and leads to material savings.

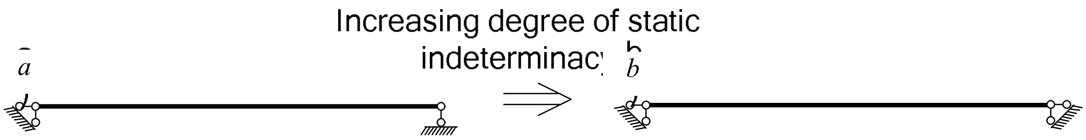

Fig. 1. Increasing degree of static indeterminacy in beams:
a – statically determined beam; b – statically indeterminate

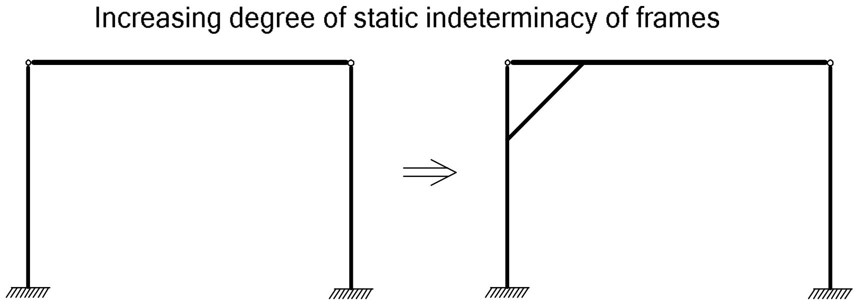

Fig. 2. Increasing degree of static indeterminacy of frames

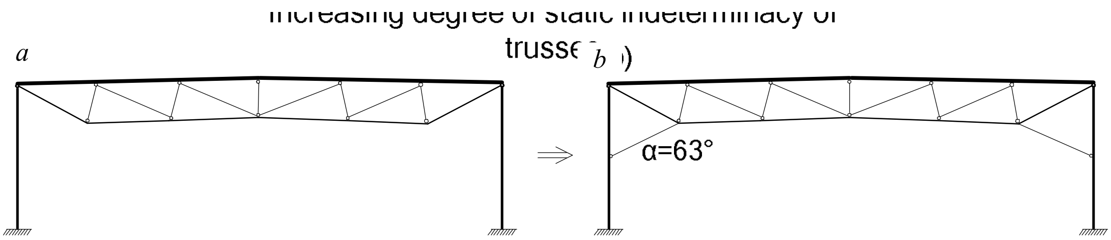

Fig. 3. Increasing degree of static indeterminacy in a truss:
a – statically determined truss; b – statically indeterminate truss

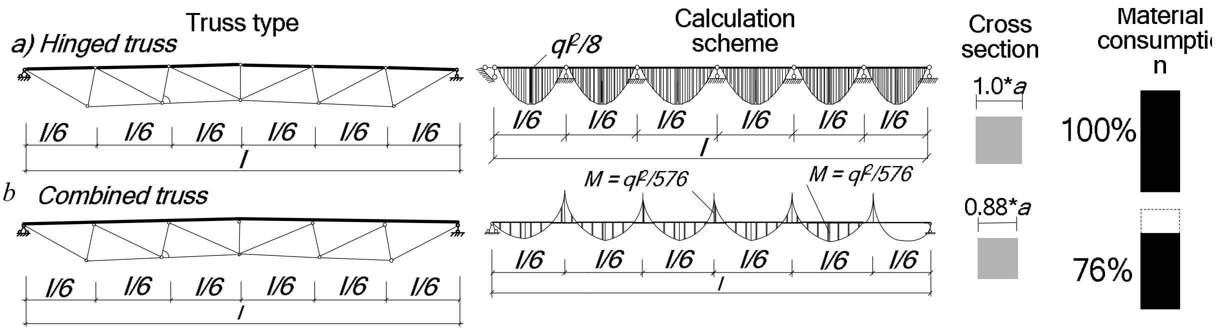

Fig. 4. Comparison of the properties of a statically determinate and statically indeterminate truss

In recent years, innovative approaches to steel truss design have emerged that have revolutionized the way efficient and sustainable buildings are constructed. They facilitate detailed structural analysis and modeling of steel truss systems. The Finite Element Method (FEM) and other numerical methods can accurately predict the behavior of a truss under various loading conditions. This helps to identify potential structural weaknesses and ensure that the truss meets the required safety and performance standards (Barabash, 2014). Modeling also allows for the evaluation of dynamic behavior, such as wind or seismic response, ensuring the stability of the truss under extreme conditions. Computer-aided design (CAD) software has revolutionized the engineering process by allowing accurate calculations and visualization of complex truss geometries before construction begins. The advent of Building Information Modeling (BIM) systems has further integrated the design process, providing a multidimensional approach to building planning and construction.

Traditionally, urban environment is static, and the building structures of this environment are designed taking into account the worst case, the greatest stress that the structure can face. This means that this or that cross-section is always larger than the required dimensions in normal situations. Thus, we waste more material. Contrary to this understanding, one of the main philosophies of the adaptability of building structures is to design structures that are as light as possible, while at the same time performing well under dynamic loads (Ellingwood et al., 2007).

To increase their survivability and resilience, efficiency, industrialization and competitiveness, it is necessary to ensure an appropriate, modern level of their design. This will allow designing and implementing competitive rational structures compared to analogues and the ability to create economic and technological solutions, which will lead to a significant economic effect.

Systemic reliability-based design (S-RBDO) optimization of structures considering progressive failure is a challenging problem, as the number of potential failure sequences increases geometrically with the degree of static uncertainty of the structure (Tanner et al., 2018). In this context, identifying the most critical failure sequences to simplify the problem is fundamental.

The design of steel trusses requires attention to a number of factors that must be taken into account at the design stage and will determine their survivability and resilience, because it is precisely on the design solutions that the reliability of structures throughout their entire life cycle depends. The basis of the research on which these or other constructive solutions will be based are structural-dynamic approaches, which allow not only to assess the operation of the structure under static loads, but also to analyze its behavior under the action of variable, impulse or random influences (Starossek et al., 2011). The use of numerical methods, primarily the finite element method, made it possible to move from simplified schemes to accurate modeling of specific systems and assessment of processes occurring in structures under the action of given influences. This made it possible to more accurately determine limit states and predict the resilience of structures under various operating conditions. In addition to the structural-dynamic approach, to take into account elastic and plastic deformations, it is advisable to combine linear and nonlinear structural analysis. Linear methods allow you to quickly determine the stress-strain state within small deformations and ensure efficiency at the early stages of design. At the same time, real operating conditions can sometimes go beyond the linear formulation of the problem, as they include plastic deformations, loss of stability, formation (or targeted laying) of plastic hinges in rod systems. Therefore, nonlinear analysis becomes an indispensable tool for assessing residual strength, determining limit loads and studying the behavior of structures in supercritical stages of operation. This allows you to reduce the risks of structural failure and predict the safety margin of the structure (Strauss et al., 2025).

When calculating steel structures, in particular trusses, one should take into account the characteristics of structural materials, since the characteristics of steel directly affect the resilience of the structure. The use of high-strength steels with an increased yield strength allows you to reduce the mass of structures, while simultaneously increasing their reliability. In modern construction, it is also important to take into account the influence of the environment, in particular aggressive atmospheric factors that accelerate corrosion processes. Additional alloying of steel or the use of protective coatings can significantly extend the service life of steel structures.

In design practice, an important direction for increasing the reliability and resilience of structures is the use of mild steels, which are capable of significant plastic deformations without loss of bearing capacity. Due to this, the structure has a certain strength reserve, because local overloads do not lead to instant destruction, but cause a gradual redistribution of forces. The use of such steels is especially advisable in nodes and elements where increased dynamic or seismic loads may occur, since they provide increased energy intensity and contribute to the formation of a more reliable and stable system under conditions of operation under dynamic influences.

The issue of durability of materials is closely related to their operation under dynamic loads. During operation, steel structures undergo metal fatigue, when even relatively small cyclic stresses lead to the accumulation of microdamage and the development of deformations. Therefore, when designing steel trusses, it is necessary to take into account fatigue strength and residual deformations, which makes it possible to predict the service life of elements and provide for timely strengthening measures. Particular attention is paid to welded and bolted joints, which are the most vulnerable areas to the formation of defects.

Increasing the reliability and resilience of steel structures is largely determined by their ability to perceive dynamic effects and vibration loads. One of the design solutions is the formation of special zones in the form of plastic hinges, which take on excess deformations and prevent sudden failure. An additional effective means of reducing vibrations is the use of damper inserts, which provide energy dissipation and stabilize the operation of the entire system (Fig. 5)

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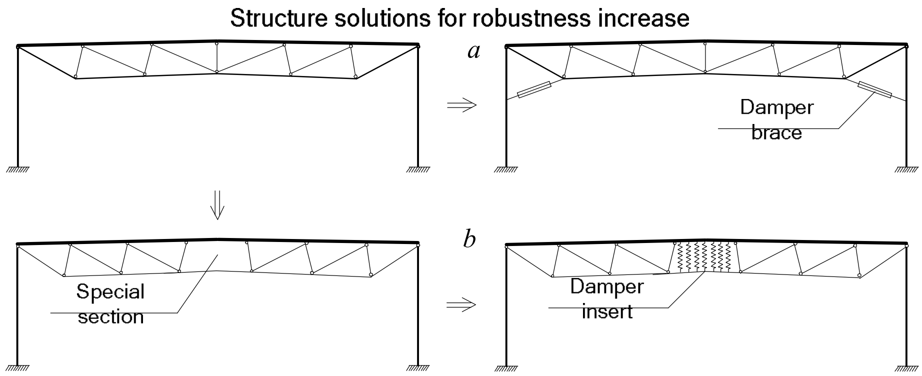

Fig. 5. Structural solutions of trusses to increase resilience:
a – dampers in the design of struts; b – dampers in the design of the insert

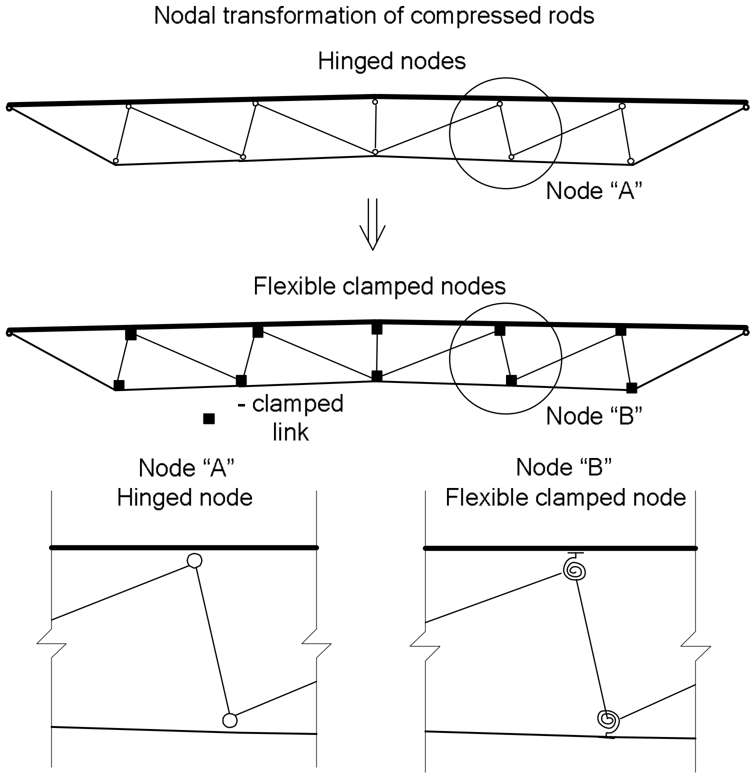

Fig. 6. Arrangement of elastically clamped nodes instead
of hinged nodes in compressed rods

The shapeless connection of bent-welded rectangular truss profiles does not always ensure the equal strength of its elements. One of the common approaches to increasing the strength of the nodes is the introduction of additional elements, such as stiffeners, linings or reinforced connecting plates. In order to increase the stability and load-bearing capacity of compressed elements in trusses, it is advisable to use elastically clamped nodes instead of traditional hinged connections (Fig. 6). The transition to elastic clamping increases the overall rigidity of the system without significantly complicating the design solution.

The practical implementation of such an elastic clamping device at the nodes in three variants is shown in Fig. 7.

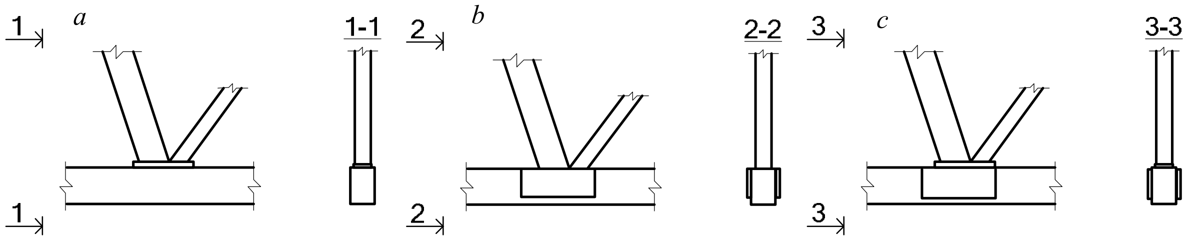

Fig. 7. Schemes of implementation of the device of partially clamped nodes in compressed rods:
a – additional horizontal plate; b – two vertical plates; c – horizontal and vertical plates

Changing the stiffness of the support nodes increases the bearing capacity of the compressed rods. Strengthening the nodes allows you to increase the bearing capacity of the truss with the assumption of ultimate plastic deformation by 1.45 times without changing the structure and geometric parameters (Portnov et al., 2025).

Results and discussion

Systematic monitoring is important for confirming calculation models and monitoring the technical condition of structures. In modern construction practice, sensor systems are used that can track changes in stresses and strains in real time. The use of non-destructive testing technologies, in particular ultrasonic and magnetic methods, allows detecting internal defects at an early stage of development. Early detection of defects allows timely measures to be taken to eliminate them and prevents the occurrence of emergency situations and structural failures (Strauss et al., 2025).

Obtaining reliable data on the operation of structures is impossible without experimental studies. Laboratory tests of steel structure samples, in particular trusses, and field experiments on truss fragments allow us to confirm theoretical results and make adjustments to numerical models. The combination of experimental and computational methods creates a synergistic effect that provides increased accuracy in predicting the operation of structures. In this case, numerical modeling is the main tool that allows us to analyze a wide range of possible scenarios and identify the most dangerous operating conditions of structures. Fig. 8 shows the technological sequence of stages for assessing the reliability of a structure.

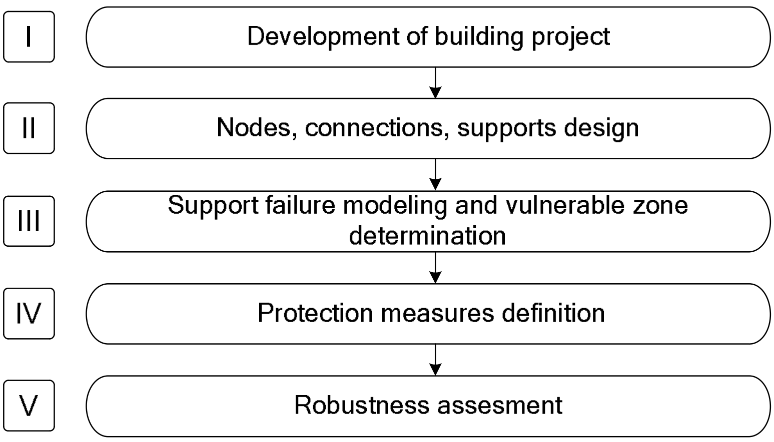

Fig. 8. Generalized algorithm for robustness ensuring and assessing

In the context of the operation of a material under the influence of dynamic loads, the analysis of vibrations and dynamic characteristics, the development of solutions to counteract vibrations are particularly relevant, since it is precisely the vibration processes that can significantly affect the survivability of the structure. The study of natural frequencies and forms of vibrations makes it possible to prevent resonance phenomena that can significantly reduce the resource of the bearing capacity of structures. This is especially important for bridge structures and large industrial buildings, where transport and technological loads create complex vibration spectra (Ellingwood et al., 2005).

An important task of modern engineering practice is the assessment and modernization of existing civil structures and infrastructure. Many steel structures are operated beyond the standard term, and therefore there is a need for repeated calculations, strengthening of elements. The use of the latest materials and strengthening technologies allows to extend the service life of structures without their complete dismantling.

Numerical modeling of structures under dynamic influences should also take into account the assessment of structural characteristics under natural disasters. Emergency situations can create additional loads that often exceed the design values. Therefore, one of the design tasks is the modeling of emergency conditions and the development of structural solutions that will minimize the destructive consequences of such influences. In this context, the analysis of risks and measures to reduce them is of key importance, which includes both increasing the strength of elements and applying additional solutions to ensure the safety of structures (Beck et al., 2023).

Thus, increasing the resilience of steel trusses at the design stage is based on a general approach that combines structural-dynamic analysis, materials research, condition monitoring and the use of numerical methods. Only a comprehensive consideration of all these aspects allows creating reliable and durable engineering structures that can operate effectively under external influences.

Conclusions

To increase the structure resilience of steel trusses at the design stage, it is necessary to provide additional measures to prevent partial or systemic destruction of the structure after damage.

Such measures include: structural-dynamic analysis, materials research, condition monitoring and the use of numerical methods and recommended strengthening methods to increase the bearing capacity of both the truss and the structural system as a whole.

Strengthening of nodes allows to increase the bearing capacity assuming ultimate plastic deformation up to 1.45 times without changing the structure and geometric parameters of the trusses.

In order to design equally strong elements in the structural system, it is necessary to strengthen the nodes, adopt a truss design combined with a rigid upper belt, use dampers in the frame structure, and also increase the static uncertainty of the system.

Carrying out such necessary actions will ensure trouble-free operation, significantly extend the service life of steel structures, which is the most important aspect of sustainable development.

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ПІДВИЩЕННЯ СТРУКТУРНОЇ СТІЙКОСТІ СТАЛЕВИХ ФЕРМ

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У статті комплексно розглянуто сучасні підходи щодо підвищення живучості, надійності та довговічності сталевих ферм за дії статичних, динамічних і випадкових навантажень. Показано, що інтегрований структурно-динамічний підхід, поєднаний із гнучким застосуванням лінійного та нелінійного аналізу, дає змогу виявляти резерви міцності, прогнозувати післякритичну поведінку системи та оцінювати вплив раптових відмов окремих елементів на загальну стійкість. Розглянуто конструктивні рішення, що зменшують концентрацію напружень і підвищують енергоємність елементів: закладання пластичних шарнірів, застосування демпферних вставок, упровадження частково защемлених вузлів, а також перехід від статично визначених конструкцій до статично невизначених, зокрема від традиційних ферм до комбінованих. Розкрито вплив матеріальних властивостей на довговічність: втомну міцність, корозійну стійкість, доцільність застосування високоміцних і м'яких сталей в окремих вузлах для підвищення енергоємності й запобігання локальним руйнуванням. Описано роль числового моделювання методом скінченних елементів для багатоваріантного аналізу, оптимізації топології та оцінювання граничних станів, а також значення експериментальних випробувань і методів неруйнівного контролю (ультразвукових, магнітних та інших) для підтвердження розрахункових схем і своєчасного виявлення дефектів. Проаналізовано підходи до оцінювання ризиків і запобігання прогресуванню руйнування та можливості модернізації наявних споруд із посиленням елементів і упровадженням систем моніторингу стану. Показано, що поєднання сучасних аналітичних інструментів, раціонального конструкторського вирішення та систем контролю створює основу для безпечної, надійної експлуатації сталевих ферм протягом усього життєвого циклу.

Ключові слова: комбінована сталева ферма, раціональне проєктування, раціональна конструкція, металомісткість та трудомісткість виготовлення, конструктивна ефективність, числові дослідження.