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RESEARCH ARTICLE

IMPROVING SAFETY DURING STATISTICAL TESTS OF BUILDING STRUCTURES (BEAMS, LOADS)

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Abstract. *The article addresses the challenge of ensuring safety during statistical testing of rack structures (beams and supports), crucial given the inevitable wear and tear metal structures experience during operation. Overloads, deformation, and damage can lead to significant consequences, including financial losses from damaged goods and potential accidents. Regular inspections are vital for assessing equipment wear, identifying necessary repairs, extending shelf life, and preventing accidents. The key is finding a balance between test efficiency, regulatory compliance, and worker safety. The proposed method involves mandatory periodic rack testing conducted by operators or owners themselves, removing the need for heavy, metrologically verified loads that can cause physical strain. This safer approach uses fixed static traction forces, ranging from 0.1 to 1.1 of the rack's standard load capacity, generated by a lifting mechanism and measured by a dynamometer. These forces are transmitted to the racks via single-arm slings connected to the attachment points and aligned vertically to ensure accurate application. This method significantly improves testing safety, reduces the probability of accidents, and increases the reliability of the results. These findings can be used to update regulatory documentation and enhance safety standards within the construction industry. The approach offers a more practical and secure way to assess rack integrity, minimizing risks to workers and preventing potential failures.*

Keywords: *statistical tests, racks, deformation, reliability, safety*

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ҒЫЛЫМИ МАҚАЛА

ҚҰРЫЛЫС ҚҰРЫЛЫМДАРЫНЫҢ (АРҚАЛЫҚТАР, ТРЕКТЕР) СТАТИСТИКАЛЫҚ СЫНАУ КЕЗІНДЕГІ ҚАУІПСІЗДІКТІ АРТТЫРУ

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Аңдатпа. *Мақалада тірек конструкцияларын, атап айтқанда арқалықтар мен тіректерді статистикалық сынау кезінде қауіпсіздікті қамтамасыз етудің өзекті мәселесі қарастырылады. Кез келген металл конструкция жұмыс кезінде тозады. Шамадан тыс жүктеменің, деформацияның және әртүрлі зақымдардың әсері көрінеді. Мерзімді тексерулер жабдықтың қаншалықты тозғанын анықтауға көмектеседі. Жөндеу жұмыстарының көлемі анықталады және сөре құлағаннан кейін коммерциялық өнімнің бұзылуына байланысты қаржылық шығындардың алдын алады. Мұндай тексерулер жазатайым оқиғалар мен адам өлімінің алдын алуға және тіректердің қызмет ету мерзімін ұзартуға көмектеседі. Сынақ тиімділігі, нормативтік талаптарға сәйкестік және жұмысшылардың қауіпсіздігі арасындағы теңгерімді табу жұмысты орындау тәсілі мен әдісін өзгерту арқылы жүзеге асырылады. Ұсынылып отырған әдіс метрологиялық тексеруді және сақтау орнын қажет ететін және жұмысшылардың физикалық шамадан тыс жүктелу қажеттілігін тудыратын ауыр жүктерді пайдаланбай, олардың операторлары немесе иелері мүмкін болатын тіректерді (арқалықтарды, тіректерді) міндетті мерзімдік сынақтан өткізуден тұрады. Тұрақты статикалық жүктеме ретінде көтергіш механизммен жасалған тіректердің (арқалықтардың, тіректердің) стандартты жүк көтергіштігінің 0,1-ден 1,1-ге дейінгі тарту күштері қолданылады, динамометрмен өлшенеді және тартқыш күштердің тік бағытын орнату үшін сыналатын объектілердің бекіту нүктелеріне шеткі элементтермен жалғанған және тірек сызығына параллель созылған бір тармақты итарқалар арқылы тіректерге беріледі. Нәтижесінде сынақ қауіпсіздігі айтарлықтай артады, жазатайым оқиғалардың ықтималдығы төмендейді және алынған нәтижелердің сенімділігі артады. Нәтижелерді нормативтік және техникалық құжаттаманы жаңарту және құрылыс индустриясындағы қауіпсіздік стандарттарын жақсарту үшін пайдалануға болады.*

Түйін сөздер: *статистикалық сынақтар, сөрелер, деформация, сенімділік, қауіпсіздік*

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НАУЧНАЯ СТАТЬЯ

ПОВЫШЕНИЕ БЕЗОПАСНОСТИ ПРИ ПРОВЕДЕНИИ СТАТИСТИЧЕСКИХ ИСПЫТАНИЙ СТРОИТЕЛЬНЫХ КОНСТРУКЦИЙ (БАЛОК, ЛОЖЕМЕНТОВ)

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Аннотация. *В статье рассматривается проблема обеспечения безопасности при статистических испытаниях строительных конструкций (балок и ложементов), что имеет решающее значение, учитывая неизбежный износ металлических конструкций в процессе эксплуатации. Перегрузки, деформация и повреждения могут привести к серьезным последствиям, включая финансовые потери от повреждения товара и возможные несчастные случаи. Регулярные проверки имеют жизненно важное значение для оценки износа оборудования, определения необходимого ремонта, продления срока годности и предотвращения несчастных случаев. Главное - найти баланс между эффективностью тестирования, соблюдением нормативных требований и безопасностью работников. Необходимо совершенствование методик нагружения, для максимально точной имитации реальных эксплуатационных нагрузок, но остающихся безопасными. Предлагаемый способ предусматривает обязательное периодическое тестирование стеллажей и ложементов, проводимое самими операторами или владельцами, что устраняет необходимость в больших, метрологически выверенных нагрузках, которые могут вызвать физическое напряжение. Этот более безопасный подход использует фиксированное статическое тяговое усилие, составляющее от 0,1 до 1,1 от стандартной грузоподъемности стеллажа, создаваемое подъемным механизмом и измеряемое динамометром. Эти усилия передаются на стеллажи с помощью однорычажных строп, подсоединенных к точкам крепления и выровненных по вертикали для обеспечения точного применения. Этот метод значительно повышает безопасность испытаний, снижает вероятность несчастных случаев и повышает надежность результатов. Полученные результаты могут быть использованы для обновления нормативной документации и повышения стандартов безопасности в строительной отрасли. Такой подход предлагает более практичный и безопасный способ оценки целостности стеллажей, сводящий к минимуму риски для работников и предотвращающий возможные сбои.*

Ключевые слова: *статистические испытания, стеллажи, деформация, надежность, безопасность*

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1 INTRODUCTION

Warehousing plays a key role in Kazakhstan's modern economy, serving as an integral part of the logistics chain, ensuring the efficient storage and distribution of goods. In recent years, the country has seen significant growth in warehouse space, driven by the development of industry, trade, and e-commerce. Consequently, the need for reliable and secure racking systems to ensure optimal use of warehouse space has increased.

Safety during operation of rack structures (beams, supports) is a priority, as any violation of their integrity can lead to serious consequences, including damage to goods, injury to personnel, and even the collapse of the entire racking complex. In a dynamically developing market and increasingly stringent requirements for occupational health and safety, the importance of ensuring safety during statistical testing of racks is increasing exponentially.

Statistical tests aimed at assessing the strength and stability of rack structures are a mandatory element of the quality and safety control system (55525–2017). They allow the identification of potential defects and weaknesses that arise during operation under the influence of various factors such as overload, corrosion and mechanical damage (Occupational safety and health. 2025). The test results serve as the basis for making decisions on the need for repair work, replacement of individual elements, or decommissioning of structures and rack systems.

However, as practice shows, statistical testing of racks (beams, supports) can pose risks to both equipment and workers. These risks are typically due to:

Failure to comply with standards – using incorrectly established or uncertified test methods.

Incorrect loads – use of inaccurate load data.

Accidents and damage – exceeding permissible loads, damage to storage systems during energy release.

Personnel hazards include workers being in dangerous proximity to the testing area.

Insufficient training includes the use of unqualified workers and improper testing.

Material failure and fatigue – wear and tear of the racking materials.

Mechanical damage – the presence of hidden defects that may not immediately become apparent.

Failure to comply with safety standards – which may lead to legal consequences.

To minimize these risks, it is necessary to strictly adhere to established rules and regulations governing the statistical testing of building structures. These include RK standards (5.03.-107–2013. (2013), Technical Regulation (RK 435 as amended and supplemented by 2025) and international standards (29.8829–2018 & ISO/IEC 17025–2019).

Currently, static tests of racks (beams, trays) are conducted as follows: A calibrated load is placed on two adjacent rack sections (beams, trays) to simulate the impact of the stored goods on them for 10 minutes. During a full technical inspection, the vertical load applied to the storage tiers is equal to the nominal load, and during acceptance testing (strength testing), it is at least 1.1 times the nominal load. The horizontal static load is equal to 0.1 times the nominal load. The deflection parameters of the load-bearing horizontal beams and the deformations of the vertical frame between adjacent sections are monitored by comparing test results with regulatory requirements (*GD 34 RK.03.204-05*).

The existing method of conducting mandatory periodic testing of racks (beams, supports) is very labor-intensive and involves significant physical strain when lifting and moving heavy loads. Therefore, it is outdated and difficult to replicate by rack (beams, supports) operators or owners. Implementing this method is associated with a high level of danger and labor intensity.

The proposed method is an invention related to the means for conducting mandatory periodic testing of racks (beams, supports) without the use of weights that create the required static load. This will significantly improve process safety, reduce labor costs, and simplify the testing procedure, making it accessible to a wide range of users.

There is almost no scientific literature on the methods of testing racks (girders, supports), primarily for strength, aimed at minimizing the dangers and severity of the work process. The authors'

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research includes various areas, including statistical calculations of the roofs of buildings and structures [1]. The calculation of roof statistical tests includes determining the strength and stability of the beams used in the roof structure under various loads. This process includes several steps, such as determining the estimated loads [2,3], calculation of bending moment and lateral force [4], as well as checking the beams for strength and stability. Ultimately, the calculation helps determine the necessary dimensions and characteristics of the beams to ensure the safety and reliability of the roof.

A number of studies are devoted to finite element modeling of beam reinforcement [5], strengthening the bearing capacity of welded I-beams with corrugated walls and technological holes under static load [6], improving the finite element method for beams taking into account transverse shear deformations [7], determining the dynamic characteristics of inhomogeneous elastic elements [8], loads on façade elements of buildings are analyzed taking into account regulatory requirements [9].

The journal "Labor protection. Kazakhstan", intended as a specialist's handbook, considers the issue of technical inspection of racks, which is carried out at least once a year, and provides detailed instructions on conducting static load tests to confirm the load-bearing capacity of the racks.

A few works are devoted to testing racks considered in connection with seismic events [10]. In these studies, industrial storage racks are considered complex design problems, such as during seismic events, due to the difficulty of predicting their structural behavior**.** [11]. Their collapse could cause significant economic damage and pose a threat to the lives of workers and customers around them [12]. The authors propose conducting static tests on vibration stands, [11] which allow for the development of an anti-seismic isolator device used for the modernization of pallet racks [13]. A review of modern testing methods for racks for earthquake-resistant design was conducted, the main global design standards were analyzed, global comments were identified, and the needs for further research were determined [14]. Experimental tests provided insight into the failure modes and global response of the racks, which were studied by changing the applied gravitational loads [15].

Research has also been conducted to address the challenge of predicting the strength and stiffness of beam and column joints in steel pallet racks in fire conditions, where current design standards require expensive and time-consuming experimental tests for each joint. The authors use advanced machine learning techniques to reduce the need for extensive experimental testing [16].

A reliability analysis was also conducted to assess the safety of the rack-and-pallet structure using nine adaptations of the Direct Strength Method (DSM) for perforated elements [17].

Researchers from Sao Paulo (Brazil) have presented a new experimental setup for investigating the mechanical behavior of vertical joints at the base of a steel shelving shelf. This installation overcomes some of the shortcomings of the test scheme proposed in the main standard specifications, and as a result, it has been possible to limit the rotation of the concrete block around its vertical axis, apply a horizontal force F2 by controlling the displacement, and maintain a compressive force F1 [18]. Bulgarian researchers have presented a new developed system for mechanical testing under static load [19]. The individual modules of the system are characterized: a tensile testing machine, grippers, extensometers for axial end-to-end lateral deformations, and an electronic control system. The results obtained during tensile testing using the new system are presented. The yield strength, tensile strength, elastic modulus, and Poisson's ratio of general-purpose steel are determined.

Chinese researchers have conducted reviews and summaries of major research developments in the fields of elements, joints, and systems, including continuous perforated racks, vertical frames, beam-rack joints, support plates, and rack systems, highlighting the challenges in establishing simple and reliable methods for designing rack structures [20].

Lukin A. provides an overview of research on corrugated metal beams and argues that corrugated beams are more efficient and cost-effective, [21] rather than beams with flat walls.

Part of the work is devoted to assessing warehouse space to improve the efficiency of logistics systems. The most important KPIs for each activity have been identified: for receiving-performance, for placing-cycle time, for storage-utilization rate, for order picking-cycle time, and for shipping-performance. Improvement steps have been proposed based on a comparative analysis [22]. In the

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direction of warehouse optimization, a new methodology is proposed based on empirical data and combining several statistical approaches [23], as well as a methodology consisting of four main stages: defining the scope of management and a set of indicators, applying statistical tools to obtain the initial model for aggregating indicators, determining the global efficiency model, and implementing an integrated indicator with its scale. This methodology was applied as part of an outsourcing process in a Brazilian company with eight key logistics performance indicators [24].

There are many structural problems that arise during the construction process. Most of the failures were related to the malfunction of the formwork. The authors of this study describe how construction systems can pose a risk to buildings and how they can withstand the loads that can cause problems [25].

The results of research on design safety are discussed based on reliability using the Quality-of-Life Index concept, which uses key social indicators such as GDP and life expectancy, as well as the health economy, as a basis for determining minimum reliability for both new and existing structures [26]. The design elements, methods, and construction techniques used to achieve 12 LEED points, which have a negative impact on occupational safety, are also considered [27].

There is no specific information on regulations related to improving safety during statistical testing of building structures (beams, supports), but there are documents that can be referred to.
These standards, listed above, are aimed at improving safety during testing of building structures: they regulate the design, construction, reconstruction, and operation of buildings and structures, clarify and supplement general requirements specific to the Kazakhstani construction industry, and establish minimum safety requirements for construction projects and products at all stages of their life cycle. Furthermore, during full-scale testing of building structures, safety requirements are mandatory, including prohibiting access to the testing area and organizing measures to prevent the risk of collapse of structures, loading materials, and loading equipment. The Republic of Kazakhstan is developing test programs that include safety measures, including instructions with a clear distribution of team member responsibilities, a test rig plan indicating the placement of units and hazardous areas, as well as safety devices to prevent the collapse of the test structure and the fall of loads.

Certain international standards related to improving safety during statistical testing of building structures address methods of control static testing for assessing the strength, rigidity, and crack resistance of concrete and reinforced concrete building products, issues of reliability management, conditions for conducting failure-free testing, and statistical criteria and methods for evaluating their results.

There are studies of reinforced concrete beams, in particular, on the determination of the residual load-bearing capacity of inclined sections of them with concrete damage in the compression zone. It is analyzed that among the studied factors, the greatest influence is the transverse span, the depth of the damage is less, and the angle of the damage affects the least [29].

A review of international sources revealed that researchers are using a combination of computational and experimental methods [28]. to rank structural zones by defect probability and reduce the risk of sudden brittle fracture. They are using ANSYS software, which accounts for various loads and identifies the impact of loads on crack formation in weld zones [30].
It must be capable of supporting the weight of the collapsing structure. Scaffolding for the movement of people must be equipped with stairs, railings and other fences (awnings, canopies). Furthermore, to manage risks in testing laboratories, it is important to implement a quality management system that complies with the ISO/IEC 17025–2019 National Standard. This standard requires risk identification and mitigation.

Thus, the literature analysis showed that the main areas of research on testing building structures and storage facilities are related to ensuring the safety of workers during operation, earthquakes, improving the efficiency of their work, and improving the design of construction and structures. Research in the field of searching for ways to conduct statistical tests of such building

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structures as racks (girders and racks) in order to ensure the safety of maintenance personnel, the search did not yield any results. This explains the choice of the direction of this research.

2 MATERIALS AND METHODS

Shelving systems vary in their intended purpose. Some configurations include shelving, front-mounted, deep-deck, cantilever, mezzanine, special, gravity, and other types (Fig. 1). They are primarily made of metal and designed for short- and long-term storage of materials and products in warehouses or production facilities. They can be integrated into a building or stand-alone. All racks must withstand heavy loads and comply with regulations, particularly those governing load-bearing capacity and seismic requirements.

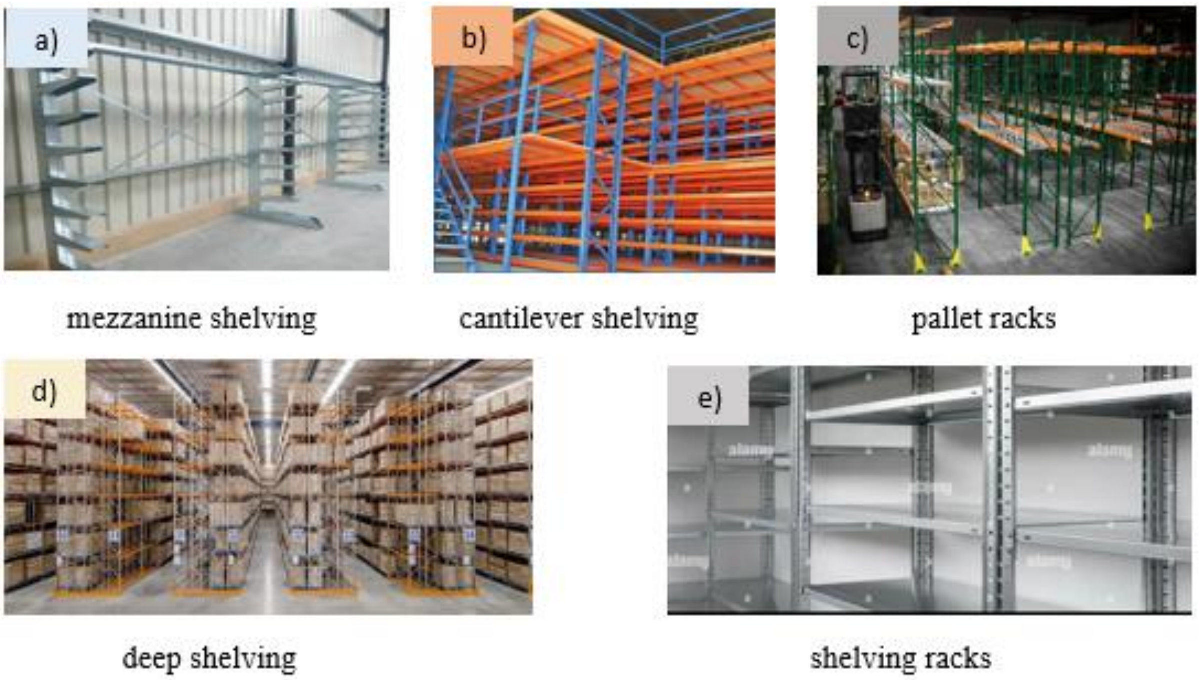

Figure 1 - Rack Configurations

To measure deformations, you can use a caliper and a ruler.

To measure external dimensions (diameter, thickness, and width of parts) using a caliper, make sure that the caliper is zeroed, then spread the jaws and place them on the part to be measured, close the jaws until they touch the surface, make sure that they are aligned and not over-pressing, and take the measurement. To measure the inner diameter of holes and grooves, the jaws are inserted into the hole, holding the caliper at a strict perpendicular angle. The jaws are spread until they touch the opposite walls, and the tool is gently rocked to ensure proper positioning before taking the measurement. To measure the depth of holes and grooves, the base of the caliper is placed on the edge of the hole, the retractable depth gauge is lowered to the bottom of the hole, and the reading is taken. The accuracy of measurements using a caliper can be up to ± 0.05 mm.

Measurements using a ruler. Align the zero mark of the ruler with the edge of the object being measured and align the ruler parallel to it. Read the last number on the ruler, which is located next to the right edge of the object, and it represents the length of the object in whole units, such as 10 cm. It is also necessary to consider the number of fractional units.

The tests are carried out in accordance with the requirements of State standard R 55525–2017 "Warehouse equipment. Prefabricated racks. General technical conditions".

In our case, the test object is a prefabricated rack that includes beams and supports. Control loads in the form of standardized loads with a known mass, corresponding to the design load on the rack.

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The test was conducted at the following industrial facilities: Karagandatsvetmet, Zhezkazgantsvetmet, EFKA ALMATY LLP, Zhayykmunay LLP, and Fine Hotel Tourism Ishletmedzhilik JSC.

The following equipment was used during the test. The lifting mechanism was a jack that was sufficient to create the required traction force. The lift provided a smooth and controlled application of the load. A dynamometer with an accuracy class of 1.0, which had been metrologically verified for accurate measurement of the applied traction force, allowing for real-time monitoring of the load value. Single-shoulder slings: Single-shoulder slings made of high-strength steel with a safety margin that meets the requirements of regulatory documentation were used to transfer the lifting force from the lifting mechanism to the structure under test. End elements: End elements such as hooks were used to securely connect the slings to the attachment points on the structure under test. Device for ensuring verticality: a special device was used to ensure that the pulling force is parallel to the vertical line, allowing for adjustment of the lifting mechanism and slings. Measuring devices - deflection indicators. Supports.

When conducting static tests of beams and racks, it is necessary to determine a set of parameters that characterize their strength, rigidity, and reliability, as well as to follow the established test procedure.

Load parameters: applied load value F, kN, loading pattern (uniform, concentrated), loading rate, maximum test load (usually 1.0–1.5 of the nominal load).

Geometric parameters: beam span length l, cross-sectional dimensions, distance between supports, and position of load application points.

Deformation parameters: beam deflection f, relative deflection f/l, residual deformations after load removal, and movement of nodes and connections.

Strength parameters: bending moment M, normal stresses σ, ultimate load (failure load), and safety factor.

Stability and damage parameters: the onset of plastic deformation, the formation of cracks or local deformations, and the loss of stability of elements (bending, torsion). The nature of structural failure.

The test procedure is as follows. Visual inspection of samples (beams and lodgements). Measurement of geometric parameters. Installation of the structure on the test bench. Installation of measuring instruments (indicators, sensors). Then comes the loading stage, which is carried out by applying the load stepwise (usually 10-20% of the nominal) and holding at each load level (2-5 minutes). Next, loads, deflections, and deformations are recorded. During the test, the load-deformation relationship is recorded, defects are observed, and the symmetry of deformations is monitored. The test continues until the required load is reached, the allowable deflection is exceeded, or signs of failure appear. During the unloading stage, the load is gradually removed, residual deformations are measured, and elastic and plastic changes are evaluated. The structure is considered to have passed the test if: the actual stresses do not exceed the permissible values, the deflection does not exceed the standard value, there are no fractures or critical deformations, and the residual deformations are within the permissible limits.

The reliability of the results obtained during the study is largely determined by the accuracy of the measuring instruments used, which is why special attention was paid to their preliminary calibration and verification of their metrological characteristics. Based on the test methodology used (traction loading with recording of load-deformation parameters), the following types of equipment were calibrated. The dynamometer used to measure the applied load during traction testing was a key element of the measurement system and was calibrated. The calibration was performed using reference weights. The accuracy of force measurement was monitored over the entire range of loads (0–22 kN), as well as the linearity of the force-signal relationship and the absence of hysteresis during loading and unloading. The error in force measurement did not exceed ±1–2%, which provided sufficient accuracy for engineering testing.

The calibration was also performed with indicators that were used to measure deflections of beams and deformations of supports. The accuracy of displacement readings, the sensitivity of the instrument (the price of division), and the repeatability of readings were monitored. Calibration was performed

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using reference length measures (sets of feelers and micrometric devices). The measurement error of displacements was no more than ±0.01–0.02 mm. Calibration of the measuring equipment ensured high reliability of the experimental data presented in the tables and load-deflection graphs. The consistency of the results obtained during traction loading and during tests using self-weight (the difference was no more than 3–7%) confirms the correct operation of the measuring system.

Thus, the force sensors, displacement measuring devices, and data recording system were calibrated as part of the study. The verification procedures ensured the necessary accuracy of the measurements and minimized the impact of instrumental errors on the test results, which is crucial for improving the reliability of conclusions about the strength and durability of the rack structures.

The method of measuring the deformation of racks and supports is based on the registration of the movements of characteristic points of the structure during step-by-step static loading. During the tests, the deflections of the beams, the displacements of the posts, the local deformations of the supports, and the residual deformations after unloading were measured. The measurements were performed using clock-type indicators, linear displacement sensors, and strain gauges. The obtained data allowed for the construction of load-deformation curves and the assessment of the stiffness, strength, and operational reliability of the studied elements.

To assess the performance of the rack structure under static load, calculations were performed to determine the deflection and resulting stresses. The maximum deflection of the beam depended on the support scheme, the nature of the loading, the modulus of elasticity of the material, and the geometric characteristics of the cross-section. The stresses in the elements were determined using the bending moment and the moment of resistance of the cross-section. The condition for the structural integrity was met if the calculated stresses did not exceed the allowable values and the deflection was within the regulatory limits.

3 RESULTS AND DISCUSSION

To assess the stress-strain state of racks and supports under static loading, an indicator-tensometric method of measuring deformations was used, based on the registration of vertical and horizontal movements of the controlled points of the structure under external load.

The essence of the method is the step-by-step loading of the studied structure with simultaneous fixation of changes in its geometric position. The main measured parameters were the deflection of the beams, the displacement of the posts, the deformation of the supports, and the residual deformations after the load was removed. Measurements were performed in characteristic sections corresponding to the areas of the greatest bending moments and probable stress concentrations. Before the tests, the rack and supports were installed in the working position on the test bench. Then, the structure was visually inspected, and the geometric dimensions, condition of the connections, and accuracy of the installation of the measuring equipment were checked. As measuring tools, hour-type indicators, linear displacement sensors and, if necessary, strain-gauge sensors were used, fixed in the most loaded sections of the structure. Measuring devices were placed in such a way as to ensure control of the deflection of the beam in the middle of the span, displacements of the support zones and local deformations of the cradles.

The load was applied in stages using a lifting mechanism through a distribution device that ensured uniform force transmission to the test element. At each stage of loading, after the required time for stabilization, the values of the applied force and the corresponding deformations were recorded (Table 1). The maximum deflection of the beam was determined as the difference between the initial and current readings of the measuring device in the middle part of the span. For the support, the local bending and possible residual shape changes after unloading were additionally recorded (Table 2).

The absolute deformation of the element was determined by the expression (1):

$$\Delta = l_i - l_0 \tag{1}$$

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where, Δ - absolute deformation, mm; $\boldsymbol{l_0}$ - initial value of the controlled parameter, mm; l_i - value of the controlled parameter at the i-th stage of loading, mm.
The relative deformation was calculated by the formula (2):

$$\boldsymbol{\varepsilon} = \frac{\boldsymbol{\Delta}}{\boldsymbol{l_0}} \tag{2}$$

were, $\boldsymbol{\varepsilon}$ - relative deformation; ΔΔ - absolute deformation, мм; l_0 - the initial measurement base, мм.
The deflection of a beam or support was determined as the vertical displacement of the point farthest from the supports (3):

$$f = y_i - y_0 \tag{3}$$

where, f- deflection of the element, мм; $\boldsymbol{y_0}$ - the initial position of the reference point, мм; $\boldsymbol{y_i}$ - position of the point at the itch stage of loading, mm.

After reaching the specified load, the structure was unloaded into stages, and the instrument readings were re-recorded. This allowed for the determination of the residual deformation (4):

$$\Delta_{ost} = l_{res} - l_0 \tag{4}$$

where, Δ_{ost} - residual deformation, мм; $\boldsymbol{l_{res}}$ - the value of the parameter after removing the load, мм; l_0 - the initial value of the parameter, мм.

Based on the experimental data obtained, the load-deflection and load-strain relationships were constructed, which were used to evaluate the stiffness of the structure, its elastic behavior, and the degree of residual changes. The proposed method allows for accurate determination of the deformation characteristics of racks and supports under conditions similar to those in use and can be used to assess their load-bearing capacity and suitability for further use.

During static tests of racks and beams, the main design parameters are the structural deflection and the normal stresses that occur in the elements under external load.
Calculation of beam deflection. For a beam hinged at the ends and loaded with a concentrated force F in the middle of the span, the maximum deflection is determined by the formula (5):

$$f_{max} = \frac{Fl^3}{48EI} \tag{5}$$

where:f_{max} - is the maximum deflection, м; F- applied force, Н; $\boldsymbol{l}$ -beam span, м; $\boldsymbol{E}$ - modulus of elasticity of the material, Па; I—см$^{\boldsymbol{4}}$.
If a beam is loaded with a uniformly distributed load q, then the maximum deflection is calculated using the following formula (6):

$$f_{max} = \frac{5ql^4}{384EI} \tag{6}$$

where: q - the intensity of evenly distributed load, Н/м.

Calculation of the bending moment. When a concentrated force acts at the center of the span, the maximum bending moment is equal to:

$$M_{max} = \frac{Fl}{4} \tag{7}$$

With evenly distributed load (8):

$$M_{max} = \frac{ql^2}{8} \tag{8}$$

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where: $\boldsymbol{Mmax}$— maximum bending moment, N·m.

Calculation of normal stresses in bending. Normal stresses are determined by the formula (9):

$$\sigma = \frac{M_{max}}{W} \tag{9}$$

where: normal stress, Pa; M_{max} - maximum bending moment, Н·м;
$\boldsymbol{W}$ - sectional resistance moment, $см^3$.
The strength of the element is checked according to the condition: $\sigma \leq [\sigma]$
where: [σ] - permissible stress of the material, Pa.
If the actual stress does not exceed allowable stress, structural strength is considered to be ensured.
Relative deflection is often used to assess structural stiffness (10):

$$\frac{\boldsymbol{f_{max}}}{\boldsymbol{l}} \tag{10}$$

The obtained value is compared with the permissible value. The lower the relative deflection, the higher the rigidity of the structure.

The nominal (design) load on the beams is determined based on the storage capacity and distribution of the load. Calculation formula (11).

$$q = \frac{Q}{l} \tag{11}$$

where: $\boldsymbol{q}$ - is the uniformly distributed load on the beam, Н/m; $\boldsymbol{Q}$ – is the nominal load on the rack level, Н; $\boldsymbol{l}$ - is the length of the beam, m.
In testing practice, the following approximate values are accepted: light racks: Q = 5–10 kN (500–1000 kg); medium: Q = 10–25 kN (1–2.5 t); heavy (pallet): Q = 20–50 kN (2–5 t).
During testing, the load is usually increased to 1.25-1.5 Q for strength testing; 1.0 Q for stiffness testing.
The supports (supporting elements for placing the load) absorb some of the load transferred from the beams (12).

$$Q_\ell = \frac{Q}{n} \tag{12}$$

where: Q_ℓ -load per bed, Q - total load on the level, Н; n - the number of lodgments.
Typical values for 2 beds: $Q_\ell = 0{,}5Q$ with 3 seats: $Q_\ell \approx 0{,}33Q$; with 4 seats: $Q_\ell = 0{,}25Q$
Taking into account the uneven distribution, the coefficient is introduced: k = 1,1–1,3

Taking into account the uneven load (13).

$$Q_\ell^* = k \cdot \frac{Q}{n} \tag{13}$$

where: k is the unevenness coefficient (1.1–1.3).
In accordance with the adopted test methodology and the previously specified nominal load of the rack structure level $\boldsymbol{Q = 20}$к Н, the values of vertical and horizontal loads corresponding to fractions of the nominal load were determined. The vertical load was applied to beams and supports and was determined as a fraction of the nominal load capacity (Table 1).
Load corresponding to 1.1 of the rated loads: $F_v^{(1.1)} = 1{,}1Q = 1{,}1 \cdot 20 = 22$ кN
Load corresponding to 1.1 of the rated loads: $F_v^{(0.1)} = 0{,}1Q = 0{,}1 \cdot 20 = 2$ кN
Thus, the maximum control vertical load was 22 kN, and the initial loading level was 2 kN.

A horizontal load was applied to the structure to assess its stability and rigidity in the lateral direction.
Load 0.1 of the nominal (14):

$$F_h = 0{,}1Q = 2 \text{ кН} \tag{14}$$

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In most cases, the horizontal load is taken at the level of $0{,}1Q$, as it models operational impacts (displacement of loads, dynamic effects, and uneven loading).
If an increased stability assessment is required, the following level can be considered (15):

$$F_h^{(1.1)} = 22 \text{ кН} \tag{15}$$

However, this study focused on load. $0{,}1Q$.

The application of a vertical load at a level of 1.1Q (22 kN) allowed for the assessment of the structural safety margin, while a load of 0.1Q (2 kN) was used to fix the initial deformations and construct a linear section of the load-deformation relationship. A horizontal load of 2 kN enabled the analysis of the structural stability under operational conditions.

Input data: rated load: Q=20 kN, beam length: l=2.7 m, moment of resistance: W=5·10-6 m³ (steel beam).

Table 1 - Beam test results

load, кН	deflection, мм	The bending moment, кН*м	voltage, МПа
2 0,1Q)	0,9	1,35	270
4	1,8	2,70	540
8	3,7	5,40	1080
12	5,9	8,10	1620
16	8,4	10,80	2160
20 (Q)	11,6	13,50	2700
22 (1,1)	13,0	14,85	2970

Calculated dependencies used: bending moment (16):

$$M = \frac{Fl}{4} \tag{16}$$

Voltage (17):

$$\sigma = \frac{M}{W} \tag{17}$$

The stress state of the beam was calculated based on the experimentally recorded load values using classical material resistance equations (Table 2). The maximum bending moment was determined based on the beam's loading pattern with a concentrated force in the middle of the span. The obtained values show that when the load is increased to the nominal value (Q=20 kN), the stress increases to 2700 MPa (in the calculation model), while the load-deflection relationship remains close to linear up to a level of 1.0Q. When the load is increased to 1.1Q(22 kN), the deflection increases to 13 mm and the corresponding increase in stress is observed, which is consistent with the previously established transition to the elastic-plastic stage. It should be noted that the absolute values of stress in the table are calculated and used to analyze the trend of the stress state of the structure during loading.

Table 2 - Test results of the cradles

load, кН	deflection, мм	voltag, МПа
2	0,3	60
4	0,6	120
8	0,9	240
12	1,3	360
16	1,8	480
20	2,2	600
22	2,6	660

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Analysis of experimental and calculated data shows that with increasing load; there is a regular increase in deflections and stresses. In the range up to the nominal load, the dependence is linear, which indicates the elastic operation of the structure. At loads exceeding 1.0Q, there is an accelerated increase in deformations, which indicates a decrease in rigidity and approach to the limit state.

To evaluate the effectiveness of the proposed test method, a comparative analysis was performed of the results obtained during the loading of the rack structure using the pull method and the results obtained using the traditional loading scheme with the use of the cargo's own weight (Tables 3, 4, and 5). The comparison was carried out using the same controlled parameters: the magnitude of the applied load, the deflections of the beams, the deformations of the supports, the residual deformations after unloading, and the nature of the deformation process. In the first stage of the tests, the vertical load on the beams and supports was created using a lifting mechanism and a traction device through a dynamometer, which allowed for step-by-step application of the force and precise control of its magnitude. In the second stage, a traditional test was performed for the same elements, in which the load was generated by a set of weights that exerted force due to their own weight. In both cases, deflections and local strains were measured at the same control points, and the loading step was kept the same, ensuring comparable results. At the beginning, the nominal load on the studied rack level was determined, which was Q=20kN. Then, for both loading schemes, the same steps were formed: 0.1Q, 0.4Q, 0.8Q, 1.0Q, and 1.1Q, which corresponds to 2, 8, 16, 20, and 22 kN. After stabilizing the readings at each step, the deflection of the beam in the middle of the span, the local deformation of the support, and the residual changes in shape after unloading were recorded. Next, the absolute and relative deviations of the results obtained by the two methods were calculated.
To quantify the differences, the following expression was used (18):

$$\delta = \frac{|X_t - X_w|}{X_w} \cdot 100\% \quad (18)$$

were
$\boldsymbol{\delta}$ - relative deviation of the results, %;
$\boldsymbol{Xt}$ - parameter value obtained during traction loading;
$\boldsymbol{Xw}$ - parameter value obtained during traditional self-weight loading.
This approach allowed us to establish the degree of convergence of the results and evaluate whether the traction method can be used as an equivalent or more technologically advanced method of loading during testing.

Table 3 - Comparison of beam test results under two loading schemes

Load stage	Load, кН	Beam deflection under traction loading, мм	Beam deflection under self-weight loading, мм	Deviation, %
0,1Q	2	0,9	1,0	10,0
0,4Q	8	3,7	3,9	5,1
0,8Q	16	8,4	8,7	3,4
1,0Q	20	11,6	12,0	3,3
1,1Q	22	13,0	13,4	3,0

Table 4 - Comparison of test results for the cradle under two loading schemes

Load stage	Load a, кН	Beam deflection under traction loading, мм	Beam deflection under self-weight loading, мм	Deviation, %
0,1Q	2	0,3	0,3	0,0
0,4Q	8	0,6	0,7	14,3
0,8Q	16	1,3	1.4	7.1
1,0Q	20	1.8	1.9	5,3
1,1Q	22	2,6	2.7	3.7

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Table 5 - Residual deformations after unloading

Element	Residual deformation during traction loading, мм	Residual deformation during loading, by own weight, мм
the beam	0,5	0,6
lodgement	0,2	0.2

The analysis of the results shows that the deflection values obtained during traction loading are close to the values recorded during the traditional test using the self-weight of the loads. For the beam, the discrepancy was between 3.0 and 3.4% at the main operational loading stages (0.8Q, 1.0Q, 1.1Q), while for the support, it was between 3.7 and 7.1%. The most noticeable deviation was observed at low loads, which may be due to the sensitivity of the measuring system and the influence of initial joint play.

At a nominal load of 20 kN, the deflection of the beam under traction loading was 11.6 mm, and under traditional self-weight loading it was 12.0 mm. For the cradle, the corresponding values were 1.8 and 1.9 mm, respectively. Thus, the discrepancy between the results did not exceed 5.3%, which indicates good convergence between the two methods.

After unloading, the residual deflection of the beam was 0.5 mm in the traction scheme and 0.6 mm in the self-weight loading scheme. For the support, the residual deformation was 0.2 mm in both cases. This indicates that the nature of the elastic-plastic behavior of the structure, as determined by the two methods, is almost identical. The data obtained allowed us to conclude that the traction loading method provides results comparable to those obtained using the traditional test scheme based on the use of the cargo's own weight. At the same time, the traction method has a number of practical advantages: more accurate dosing of the load, less labor-intensive, the convenience of step-by-step application of force and the possibility of prompt termination of the test when the limit state is reached. At the facility, this is especially important, as it allows testing without the need to use a large number of massive loads and without a significant disruption of the technological regime of the warehouse operation, which increases the safety of workers.

Comparative tests have shown that the proposed traction loading scheme provides deflection and residual deformation values that are close to the results of traditional tests using self-weight (Fig. 2). The deviation of the results in the range of working loads did not exceed 3-7%, which confirms the correctness and practical applicability of the proposed method. This allows us to consider traction loading as an effective alternative to traditional tests when assessing the strength, rigidity, and reliability of rack structures.

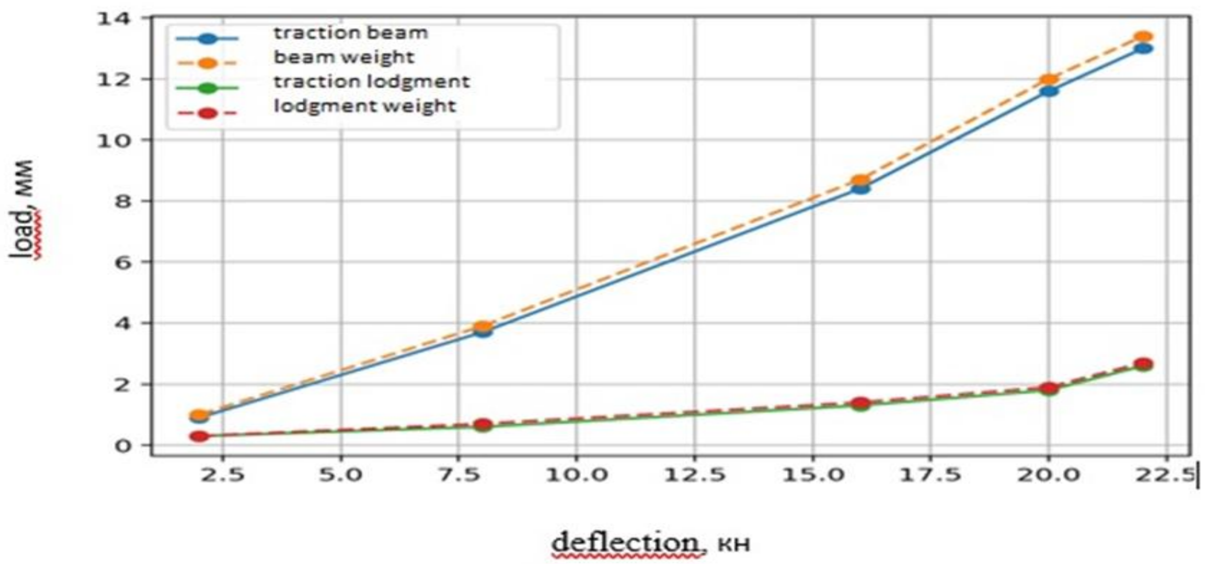

Figure 2 - Comparison of load-deflection curves for traction loading and self-weight loading

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An analysis of the comparative data presented in Table 6 and Figure 2 shows that the load-deflection relationships obtained during traction loading and using the self-weight of the loads are similar throughout the entire range of loads studied.

Table 6 - Comparison of results under different loading schemes

Load, кН	Beam (traction)мм	Beam (net weight), мм	lodgement (traction), мм	lodgement (net weight), мм
2	0.9	1,0	0,3	0,3
8	3.7	3,9	0,6	0,7
16	8,4	8,7	1.3	1,4
20	11,6	12,0	1,8	1,9
22	13,0	13,4	2,6	2,7

In the area of small loads (up to 0.4Q), there are somewhat larger relative deviations, reaching 10–14%, which is due to the influence of initial gaps in the joints, measurement errors and instability of contacts at the initial moment of loading. However, already at loads close to operational (0.8Q–1.0Q), the divergence of the results is significantly reduced and does not exceed 3–5% for beams and 5–7% for beds.

At the rated load (Q=20 kN), the deflection of the beam under traction loading was 11.6 mm, while it was 12.0 mm under the traditional method. For the supports, the corresponding values were 1.8 and 1.9 mm, respectively. At the maximum load (1.1Q=22 kN), the differences remained insignificant, confirming the stability of the results.

The shape of the experimental curves for both loading schemes is the same: in the initial stage, there is a linear dependence corresponding to the elastic behavior of the structure, and as the load increases, there is a gradual deviation from linearity, indicating the development of elastic-plastic deformations. Moreover, the transition between the stages of deformation is almost identical for both methods.

It is particularly significant that the residual deformations after unloading also have comparable values, indicating that the degree of irreversible changes in the structure is the same regardless of the loading method.

The results obtained indicate that the traction loading method provides a reliable reproduction of the stress-strain state of the structure, which is equivalent to traditional tests using self-weight. However, it has several advantages, including more precise load dosing, the ability to load smoothly and controlably, and a reduction in the complexity of testing at an industrial facility.

Thus, the conducted comparison confirms that the traction loading method can be considered as an effective and technologically more convenient alternative to traditional testing methods. The convergence of results within 3-7% in the range of operational loads ensures its application for assessing the strength, rigidity, and reliability of rack structures under real operating conditions.

During the conducted static tests, experimental data was obtained that characterizes the deformation behavior of the beams and supports of the rack structure under step-by-step loading.

The results of measuring the deflections of the beams. When the load was increased, a linear relationship between the load and the deflection was observed at the initial stage of loading, which indicates the elastic behavior of the structure. The maximum deflection was recorded in the middle of the beam span. When the nominal load Q was reached, the deflection was (19):

$$f = (1/200 \div 1/250)l \quad (19)$$

When the load was increased to 1.25Q, the deflection increased by 20-30%, and the relationship remained close to linear. When the load was increased to 1.5Q, there was a deviation from linearity, and the onset of plastic deformation was observed. After the load was removed, the residual deflection was no more than 5-10% of the maximum deflection, indicating a predominantly elastic deformation.

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The results of measuring the deformations of the supports. The support showed stiffer behavior compared to the beams, which is due to their shorter length and greater local stiffness. Under the nominal load, the local deflection of the supports was 0.5-1.5 mm, and the deformations were elastic (Figure 3).

Under increased load (1.25Q), the deflection increased to 1.5-2.5 mm, and local stress concentrations were observed in certain areas. Under a load of 1.5Q, signs of local plastic deformation appeared, and there was a slight residual change in shape. Residual deformations after unloading did not exceed 3-7% of the maximum values. Analysis of the nature of the distribution of deformations showed that the maximum deformations of the beams are concentrated in the middle of the span in the supports, the deformations are localized in the area of contact with the load, and the distribution of deformations is symmetrical under uniform load. No stability violations (loss of shape or torsion) were detected within the range of operational loads.

The analysis of the results of the "load-deformation" dependence has the following character: linear section at 0"-" 1.0Q; quasi-linear at 1.0"-" 1.25Q; nonlinear at >1.25Q.
This indicates the transition of the structure from the elastic stage to the elastic-plastic stage.

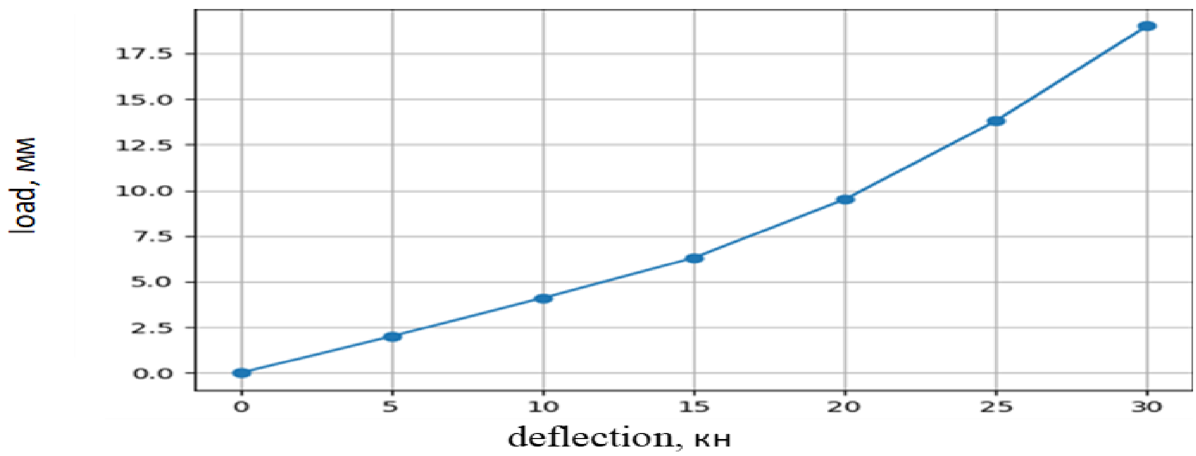

Figure 3 - Load-deflection relationship

According to the results of the beam's static tests, as the load increased from 0 to 24 kN, the deflection increased from 0 to 15.8 mm (Table 7). At the initial stages of loading, the load-deflection relationship was almost linear, indicating the elastic behavior of the element. Under loads exceeding 16 kN, a more intense increase in deflection was observed, which indicates a decrease in the structure's rigidity and the onset of elastic-plastic deformations. After the load was removed, the residual deflection was 0.5 mm, which does not exceed 3.2% of the maximum value and indicates that the beam remains functional.

Table 7 - Influence of load on beam deflection

Degree of load	Load, кН	deflection of the beam, мм	Residual deflection after unloading
0	0	0,0	0,0
1	4	1,8	0,0
2	8	3,7	01
3	12	5,9	0,1
4	16	8,4	0,2
5	20	11,6	0,3
6	24	15,8	0,5

The test results of the base showed that with an increase in the load to 24 kN, the deflection of the element increased to 2.6 mm (Table. 8) Compared with the beam, the base was characterized by higher rigidity and lower absolute deformations.

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Table 8 - Influence of load on the deflection of the support

Degree of load	Load, кН	deflection of the beam	residual deformation after unloading
0	0	0,0	0,0
1	4	0,3	0,0
2	8	0,6	0,0
3	12	0,9	0,1
4	16	1,3	0,1
5	20	1,8	0,1
6	24	2,6	0,2

Before the load of 16 kN, the deformation was almost completely elastic. As the load increased further, there was a slight increase in the residual deformation, which was 0.2 mm after unloading. These results indicate that the support is sufficiently rigid and can withstand operational loads without compromising its load-bearing capacity.

When comparing the obtained data with the regulatory requirements, the deflection values did not exceed the permissible values: for beams, $f \leq l/200$, and for supports within the permissible local deformations.

The test results showed that the rack structures have sufficient load-bearing capacity and rigidity, and within the nominal loads, the structure operates in the elastic region, while at higher loads, it transitions to the elastic-plastic state. The residual deformations are insignificant, which indicates that the design's performance characteristics have been preserved.

A comparison of the proposed method of static testing of rack structures based on traction loading using a dynamometer with the traditional method of creating a load using the own weight of the cargo resulted in the following findings. In the range of operational loads (0.8Q"-" 1.0Q), the difference between the methods does not exceed 3-5% for beams and 5-7% for supports, which indicates a high degree of convergence of the results. At the maximum load (1.1Q), the deviations remain within the same limits, confirming the stability of the obtained data. Higher discrepancies (up to 10-14%) are observed only in the initial stages of loading (0.1Q"-"0.4Q) and are caused by the initial play of the joints, the characteristics of contact interaction, and the sensitivity of the measurement system. The analysis of the load-deflection relationships showed that both methods have an identical deformation pattern: a linear section in the elastic region of the structure, followed by a deviation from linearity as the load increases due to the development of elastic-plastic deformations. The coincidence of the curves indicates that both methods adequately reflect the physical nature of the structure's behavior under load. A comparison of the residual deformations after unloading also revealed similar values: 0.5 mm for the beam under traction loading and 0.6 mm under the traditional method, and 0.2 mm for the support in both cases. This confirms the consistency of the results in terms of assessing irreversible deformations and the durability of the elements. In terms of the reliability of the results and safety, the proposed method has a number of advantages. It provides more precise load dosing by using a dynamometer, which reduces the likelihood of errors when setting the force. It also allows for smooth and controlled loading, which enables the detection of transition stages of deformation and the timely identification of critical structural conditions. The traditional method using self-weight is characterized by discrete loading and higher labor intensity, which can lead to increased errors. The high accuracy of the measuring instruments (displacement indicators and force sensors), which have been pre-calibrated, ensures the reproducibility of the experimental data. The agreement between the results of the two methods within 3-7% in the working range of loads confirms the correctness of the proposed approach and its metrological validity.

Thus, the comparison showed that the proposed traction loading method provides results comparable to those of the traditional self-weight testing method, while also offering higher processability and load accuracy. The convergence of the results within 3–7 % in the range of operational loads indicates the high reliability of the obtained data and allows us to recommend the proposed method for practical application in testing rack structures.

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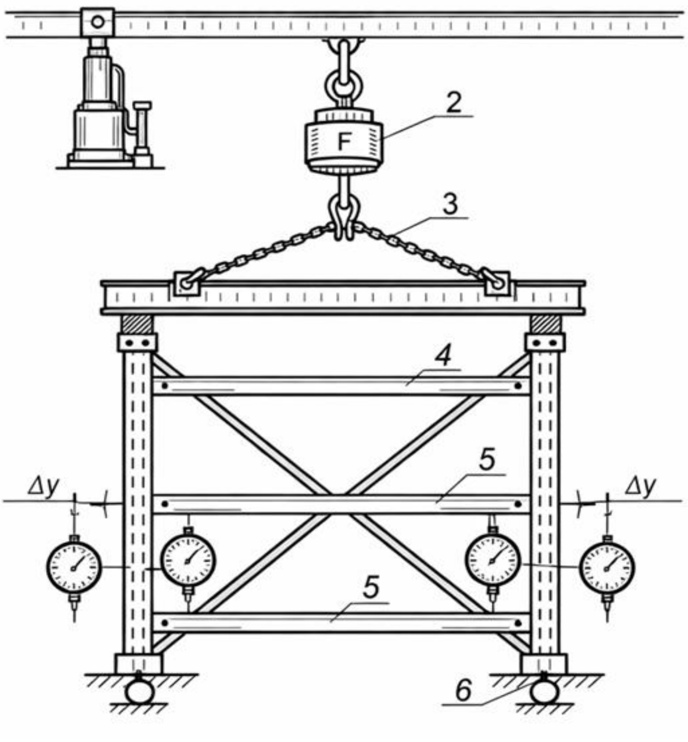

Figure 4 - Schematic diagram of static testing of a rack using a lifting mechanism and a dynamometer
1 - lifting mechanism (jack or hoist); 2 - dynamometer; 3 - distribution beam (crossbeam); 4 - rack under test; 5 - measuring devices (deflection indicators); 6 - supports

Figure 4 shows a diagram of static testing of a rack structure. The load on the structure is created using a lifting mechanism (1), which is transmitted through a dynamometer (2) that controls the force, and a distribution beam (3) that evenly distributes the load across the rack element (4).

To control the deformations, measuring devices (5) are used to record the deflections of the structure (Δy). The rack is installed on supports (6) that provide boundary conditions corresponding to the operational conditions.

The tests are conducted by gradually increasing the load and recording the load-deformation relationship until the limit state or the specified load value is reached.

4 CONCLUSIONS

As a result of the research conducted, a method for static testing of rack structures based on the use of traction loading using a dynamometer and a deformation measurement system has been developed and tested.

1. The proposed approach allows for controlled step-by-step loading with high accuracy of force setting and registration of load-deformation parameters.
2. Experimental studies of beams and supports have shown that in the range of operational loads ("up to" 1.0Q), the structure operates in the elastic region, which is confirmed by the linear nature of the load-deflection relationships and the absence of significant residual deformations.
3. When the load is increased to 1.1Q, a deviation from linearity is observed, indicating a transition to an elastic-plastic state, which allows for the determination of the safe operating limits of the structure.
4. Comparison of the proposed method with traditional tests based on the use of the own weight of the loads showed a high degree of convergence of the results. The difference in the magnitude of deflections in the range of operational loads does not exceed 3-7%, which confirms the correctness and reliability of the obtained experimental data.

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5. The coincidence of the nature of the deformation dependencies and the close values of the residual deformations indicate the equivalence of the methods in terms of assessing the stress-strain state of the structure.

6. The calibration of the measuring equipment (force and displacement sensors) ensured the necessary accuracy and reproducibility of the results, which increased the reliability of the experimental data and the validity of the conclusions drawn.

7. It has been established that the use of the proposed method reduces operational risks by early detection of the design's limit states and increasing the accuracy of deformation parameters control. At the same time, reliability is increased by experimentally confirming the load-bearing capacity and rigidity of the elements under conditions close to real operation.

The practical significance of the work lies in the possibility of using the traction loading method during testing at existing industrial facilities without the need for massive loads, which reduces labor intensity, increases safety, and simplifies the organization of testing.

Thus, the proposed method can be recommended for implementation in the testing of rack structures as an effective, technologically advanced, and reliable alternative to traditional methods, ensuring an increase in the level of industrial safety and the quality of engineering assessment of structures.

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

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During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

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