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Building Constructions, Buildings and Engineering Structures
Footings and Foundations, Subsurface Structures
Construction Materials and Products
Technology and Organization of Construction
Structural Mechanics
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Современные тенденции в строительстве, градостроительстве и планировке территорий

Рецензируемый научно-практический журнал (издается с 2022 года)

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Журнал создан в целях информирования читательской аудитории о новейших достижениях, тенденциях и перспективах в области строительства, архитектуры, градостроительства и смежных научных направлений. Издание является платформой для научно-образовательного сотрудничества российских и иностранных исследователей, вовлеченных в строительную сферу.

Журнал включен в перечень рецензируемых научных изданий, в котором должны быть опубликованы основные научные результаты диссертаций на соискание ученой степени кандидата наук, на соискание уч—еной степени доктора наук (Перечень ВАК) по следующим научным специальностям:

2.1.1 – Строительные конструкции, здания и сооружения (технические науки)
2.1.2 – Основания и фундаменты, подземные сооружения (технические науки)
2.1.5 – Строительные материалы и изделия (технические науки)
2.1.7 – Технология и организация строительства (технические науки)
2.1.9 – Строительная механика (технические науки)
2.1.13 – Градостроительство, планировка сельских населенных пунктов (технические науки)
2.1.14 – Управление жизненным циклом объектов строительства (технические науки)

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Analysis of Control of Construction Timing Taking into Account the Early Warning System of Missed Deadlines

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Abstract

Introduction. The study is dedicated to evaluating the existing methods for monitoring the construction time of residential buildings and substantiating the advantages of the early warning system (EWS). Traditional tools such as schedules and monitoring are insufficiently effective due to their reactivity and inability to identify risks ahead of time. The aim is to demonstrate the transition from reactive management to proactive predicting likely problems [1]. Modernization of traditional methods by integrating digital tools, introducing predictive analytics and using hybrid management methodologies transforms time control from simple tracking into proactive projection becoming an important competitive edge, allowing the construction industry to effectively deal with challenges and achieve goals with a maximum accuracy.

Materials and Methods. The object of the study is a construction time management system that includes planning, monitoring, and response methods. The major drawbacks of the traditional approach are delayed identification of problems as these methods mainly record problems as they emerge. Assessments are biased and holistic information environment is lacking.

Research Results. As part of the study, the author is expected to design a unique system of EWS indicators adapted to the realities of the Russian construction conditions, a methodology for integrating predicative analytics into the BIM environment, as well as an economic and mathematical model for calculating the effect of EWS implementation. These solutions will reduce the number of missed deadlines by 20–30%, automatically detect risks a week or a week and a half before they emerge, and achieve up to a 95% accuracy in predicting project completion.

Discussion and Conclusion. The proposed measures have a high practical value as they contribute to reducing developers' financial and reputational costs, implementing legislative norms and increasing amount of trust among those involved in the market. Integration of modern technologies, use of predictive models and flexible management approaches transform timing control from passive monitoring into active prevention of possible disruptions. It is assumed that the implemented method will provide a reduction in the number of cases of missed deadline by 20–30%, and will allow early detection of possible threats prior to the impact of negative consequences improving the quality of project time frame assessment.

Keywords: construction timing control, project management, missed deadlines, early warning, calendar and network planning, Earned Value Management, BIM predictive analytics

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Оригинальное эмпирическое исследование

Анализ контроля сроков строительства с учетом методов раннего предупреждения срыва сроков

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Аннотация
Введение. Исследование посвящено оценке существующих методик контроля сроков возведения жилых зданий и обоснованию преимуществ подхода раннего предупреждения (EWS). Традиционные инструменты, такие как календарные планы и мониторинг, недостаточно эффективны ввиду своей реактивности и неспособности заранее выявить риски.
Целью является демонстрация перехода от реактивного управления к проактивному, предвосхищающему потенциальные проблемы [1]. Модернизация традиционных методов путем интеграции цифровых инструментов, внедрения предикативной аналитики и использования гибридных методологий управления трансформирует контроль сроков из простого отслеживания в проактивное предвидение, что становится важнейшим конкурентным преимуществом, позволяя строительной отрасли эффективно преодолевать вызовы и достигать поставленных целей с максимальной точностью.
Материалы и методы. Объект изучения — система управления сроками строительства, включающая методы планирования, мониторинга и реагирования. Основные недостатки традиционного подхода заключаются в запоздалом выявлении проблем, эти методы преимущественно фиксируют проблемы по факту их возникновения, субъективизме оценки и отсутствии целостной информационной среды.
Результаты исследования. В рамках работы ожидается создание авторской системы EWS-индикаторов, адаптированных под реалии условий российского строительства, методики интеграции предикативной аналитики в BIM-среду, а также экономико-математической модели для расчета эффекта от внедрения EWS. Данные решения позволят снизить количество срывов сроков на 20–30 %, автоматически обнаруживать риски за неделю–полторы до их наступления и достичь точности прогнозирования сроков сдачи до 95 %.
Обсуждение и заключение. Предложенные меры имеют высокую прикладную ценность: сокращают финансовые и репутационные издержки застройщиков, способствуют выполнению законодательных норм и повышают доверие участников рынка. Интеграция современных технологий, использование предиктивных моделей и гибких управленческих подходов превращают контроль сроков из пассивного наблюдения в активное предупреждение возможных нарушений. Предполагается, что внедренный метод обеспечит снижение количества случаев нарушения дедлайнов на 20–30 %, и позволит заблаговременное обнаружение возможных угроз до наступления негативных последствий, что улучшит качество оценки временных рамок исполнения проектов.

Ключевые слова*:* контроль сроков строительства, управление проектами, срыв сроков, раннее предупреждение, календарно-сетевое планирование, Earned Value Management, BIM. предиктивная аналитика

Для цитирования. Розанцева Н.В., Бабурин Н.А. Анализ контроля сроков строительства с учетом методов раннего предупреждения срыва сроков. *Современные тенденции в строительстве, градостроительстве и планировке территорий*. 2025;4(4):7–18. https://doi.org/10.23947/2949–1835-2025-4-4-7-18

Introduction. Construction delays do not merely result in additional financial costs, but they actually undermine customers' trust, affect contractors' reputation, entail legal disputes and might eventually cause a project to terminate altogether.

The aim of the study is to develop a practice-oriented algorithm for preventive control of missed deadlines in construction based on integrating the early warning system.

The development tasks are as follows:

1. Critical analysis of current timing control systems.
2. Structuring the EWS (Early Warning System) for the construction industry, identifying the key risk indicators.

Materials and Methods. The object of the study is a system aimed at monitoring construction timing of residential facilities in its current state, including:

– planning procedures (calendar schedules, CPM analysis, resource allocation);
– progress monitoring methods (reporting, data collection tools);

– deviation response mechanisms;

– interaction of project participants (customer, contractor, subcontractors).

Traditional control methods such as calendar planning, Gantt charts (Fig. 1), use of the critical path method (CPM) (Fig. 2), recording and stage-by-stage inspections have certainly been the foundation for systematic planning and tracking progress[1] and have dominated the industry over decades.

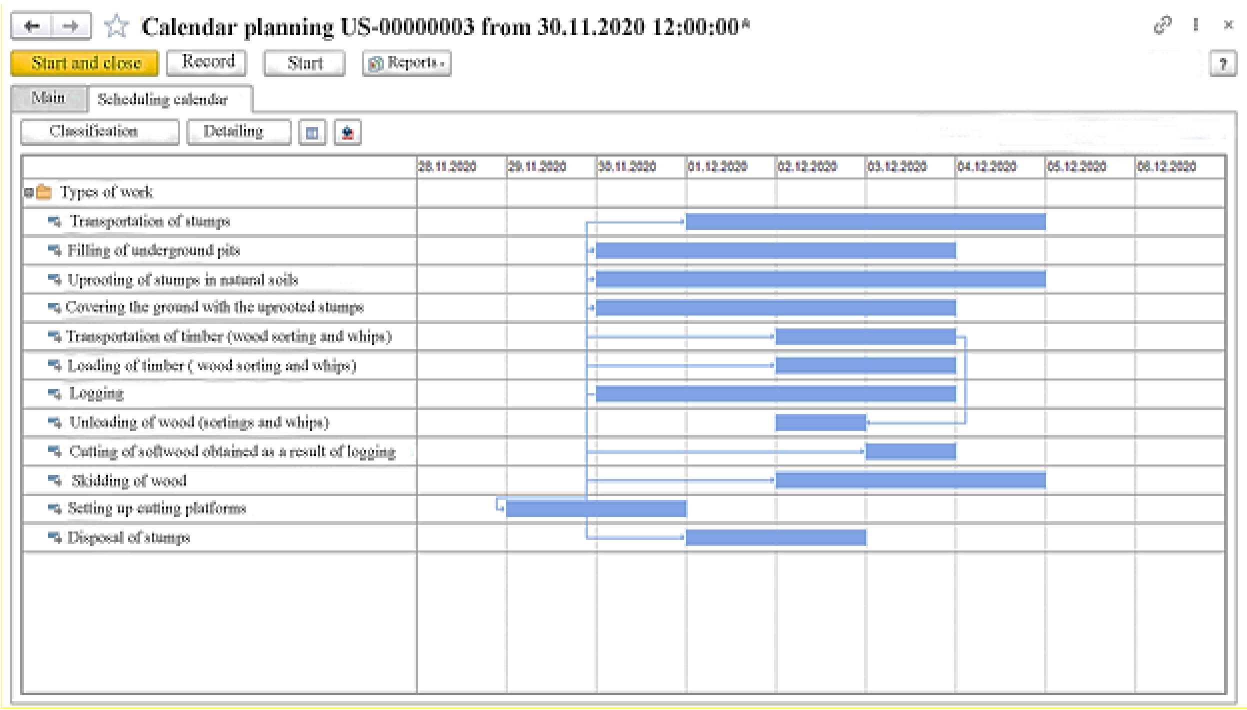

Fig. 1. Example of a Gantt chart

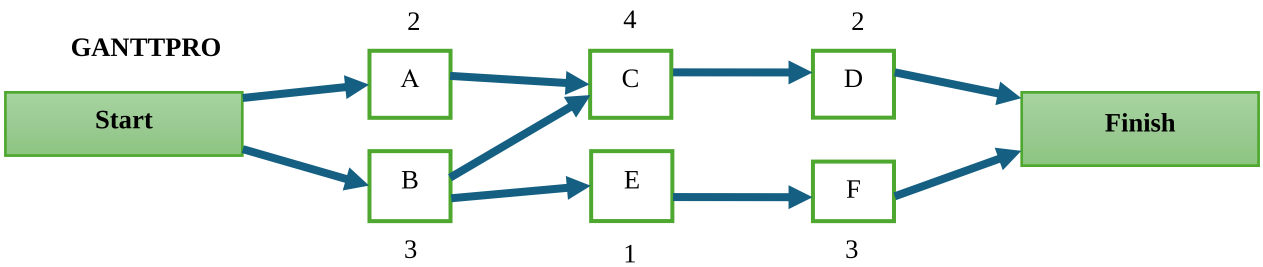

Fig. 2. Critical path method in construction management based on a network graph

Let us analyze the major traditional approaches to timing control [2]:

1. *Calendar (mostly linear) planning*:

The essence of the method, its main mechanism: development of step-by-step plans with fixed dates for the start and end of work.

Main tools: Gantt charts, network graphs (PERT).

Application methods: typical for any projects with preliminarily predictable construction stages, e.g., foundation → frame → finishing→ quality control (particularly hidden work) → commissioning.

2. Journal recording and reporting:

The main mechanism is recording of completed works in paper or electronic journals, e.g., in the "Work Production Journal".

[1] Bovteev SV *Methods and Forms of Organizing Construction Production: a Study Guide.* Saint Petersburg: Saint Petersburg State University of Architecture and Civil Engineering; 2022. 221 p.

Application methods by means of data recording: incoming daily reports from foremen on the time spent, amount of work completed over a period of time, and problems that occur in the process.

3. Stage-by-stage inspections [3]:

The essence of stage-by-stage inspections is quality control at the key construction stages in order to prevent defects and ensure that the project adheres to the standards.

Ways and forms of control (see Fig. 3):

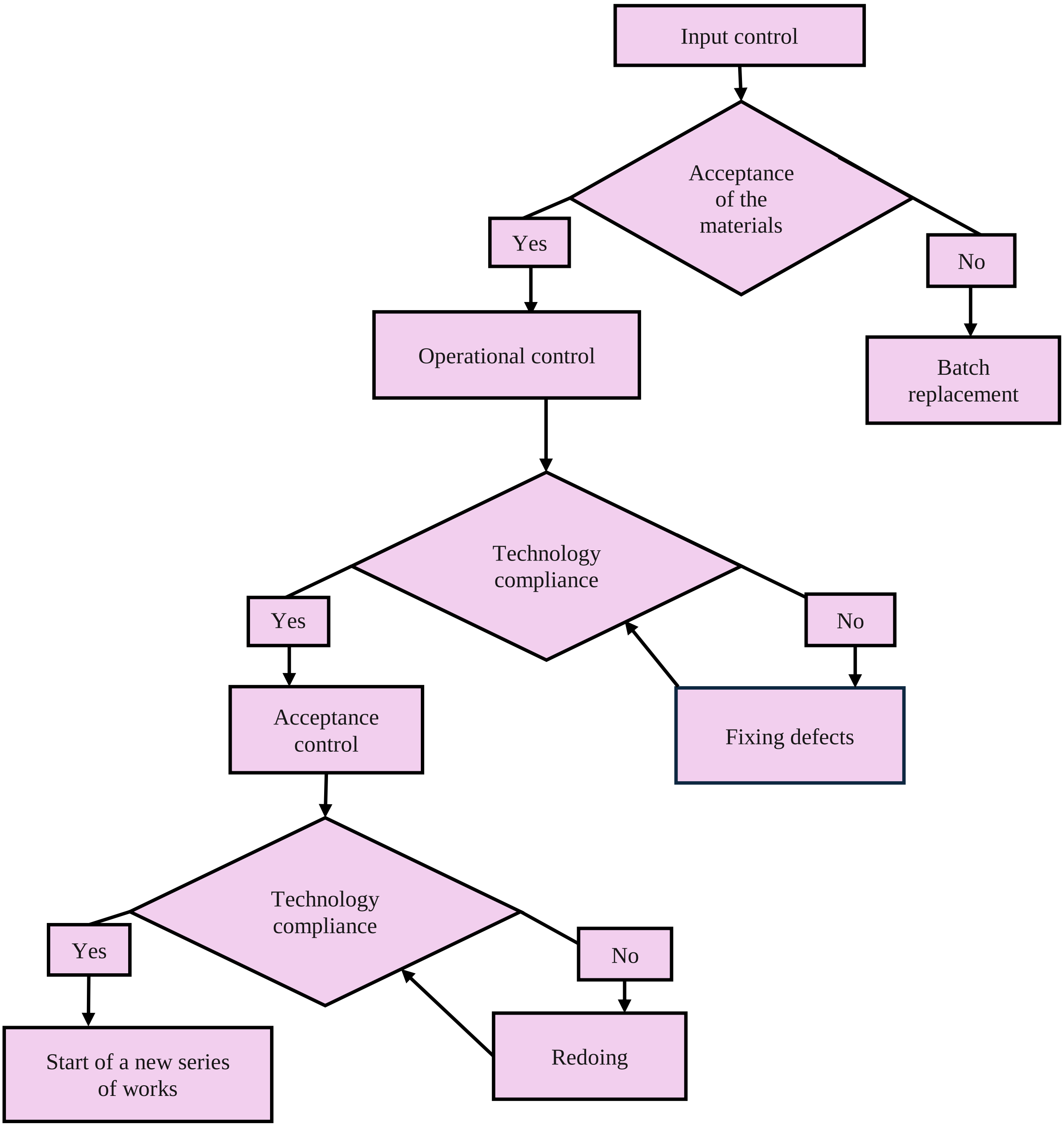

Fig. 3. Current scheme of stage-by-stage inspections

– *input control*: inspection of materials and equipment, including machinery and mechanisms, prior to the start of a work phase: certificates, passports, compliance with the GOST, possible defects ranging from packaging to more significant ones. E.g., at the construction site of the Lakhta-2 residential complex in St. Petersburg, a batch of fittings was rejected due to a diameter discrepancy of 12 mm instead of 14 mm according to the project;

– *operational control*: monitoring of technological processes through the course of work (technology, geometry, temperature during concreting) can be very highly efficient provided that modern technical tools are properly utilized. E.g., during the construction of monolithic ramps from the Bolshoy Smolensky Bridge across the Neva River, temperature sensors detected concrete overheating up to + 40 °C instead of + 25 °C, and the work was stopped for cooling to be held. The use of Concrete DNA sensors with a strength prediction for 72 hours in advance contributed to the high-quality performance with zero defects and a time reduction of 18 days;

– *acceptance control*: as the final stage prior to the start of the next series of work, checking compliance with the drawings, strength of materials, documentation, signing acts after the stage completion (e.g., "Certificate of Inspection of Hidden Works"), fairly commonly implies the need for defect elimination. E.g., in the Etalon residential complex in Yuzhny Butovo in Moscow (2021), the acceptance of the frame of the last object was delayed due to some cracks detected in the columns by means of ultrasound, which called for reinforcement of the column structures.

A critical analysis of current timing control systems enables one to identify the main strengths and weaknesses of traditional methods (Table 1).

Table 1

Comparative analysis of the methods and their flaws

Method	Strengths	Weaknesses	Example of consequences / assessment of economic losses
Calendar graphs	Visual, easy to use	Rigidity, Operational adjustments are not possible	A 3-month delay in a residential complex completion (Moscow)
Journal recording	Legal significance	Subjectivity, falsification	Budget overruns: – Residential complex "Severnaya Dolina", St. Petersburg: cracks in the walls were identified following the commissioning, i.e., demoulding with insufficient concrete strength due to lack of thermometers; – Residential complex "Etalon", Moscow, 2021: adding water to the concrete - mixer drivers diluted the mix to facilitate the unloading.
Stage-by-stage inspections	Compliance with the standards (SP 48.13330)	Narrow focus, overlooking defects	Slab collapse in Kirovsky shopping center — spot ultrasonic inspection overlooked the voids in the concrete

The key results are specified in Table 2.

It can thus be concluded that the efficiency of the traditional methods is constrained by some hidden disadvantages, the main one is that they are more commonly employed in order to identify missed deadlines rather than prevent them [4].

To put it in another way, most traditional approaches are inherently reactive that turn active after the timing problem has become obvious.

The need to move from reactive to proactive construction time management has become the fundamental aim of the study.

The modern approach calls for early warning methods to be introduced that are capable of identifying potential threats to deadlines long before they become critical. This enables the project management team to develop and implement corrective actions in a timely manner keeping negative impacts to a minimum [5]. The key to effective early warning is integrated use of data, technology, and well-established communication processes. The major ways of enhancing the verification stages include digitalization, monitoring sensors, blockchain, and indispensable construction control records.

Table 2

Specifying the key focus. Impact of delays [4]

Criterion	Study object/ Problem statement/Consequences	Subject matter in decision making
Essence	The timing control system is flawed – a low level of accuracy – unreliable source data Human factor: control subjectivity (visual assessment of the formwork); reporting falsification (overestimation of the volume of work by 15–20%). Technical limitations: narrow focus control allows hidden defects (plate collapses in Kirovsky shopping center in 2020, Hollywood shopping center in December 2021).	Transformation with the EWS methods
Problem focus	The problems of the current system: – *reactivity:* deviations from the schedule are detected late, oftentimes only in the weekly reporting; – *delays:* impossibility of surgical intervention causes delays to accumulate; – *financial losses:* error correction takes up to 30% of the project budget.	Proactivity, predicting risks at early stages
Tools	Weakness of the traditional system: – disparate databases (graphs, journal records, geodata is stored separately); – manual input of information slows down the process; The result: delays in approvals, loss of documents, discrepancies between plans and facts for up to 7–10 days.	Digital technologies (BIM, AI), automated KPIs, prediction algorithms. „Stroykontrol“ blockchain platform
Study aim	Diagnostics of the deficiencies in the current system	Developing an integrated EWS control model for residential buildings

Methods for predicting schedule deviation risk[2] [6] are to include:

1. Early detection and digital management of possible risk factors by analyzing a timing performance monitoring system.
2. An integrated approach with delay warning monitoring, including a delay analysis strategy.
3. Prevention of missed deadlines in construction based on analytical approaches in time parameter management.

One of the fundamental methods of early warning is the Earned Value Management (EVM) system. EVM integrates cost, schedule, and work volume data, providing valuable metrics such as cost value (CV) and scope value (SV) [7]. A negative SV value indicates running behind the schedule, and the SPI index reflects the efficiency of the project in relation to the schedule. Monitoring these metrics helps one toidentify a problem in a timely manner, predict its impact, and take action before there are some irreversible delays occurring. The analysis of SPI dynamics allows for an accurate assessment of the work progress and prediction of the completion dates. Apart from EVM, detailed risk analysis and management have a major role to play [8]. Early identification of risks and their systematic assessment at the early stages of a project (e.g., risks associated with materials supply, lack of qualified professionals, changes in weather conditions, obtaining permits), allow preventive measures to be developed. The formation of a risk register with the calculation of a likelihood and impact lays a foundation for foreseeing threats. Scenario analysis and modeling (Monte Carlo method) help to more accurately predict timelines and plan time resources.

Integration of BIM and network planning (4D BIM) provides a visual representation of construction progress, allowing for future conflict resolution and proactive problem solving (Fig. 3). The use of IT (Internet of Things) sensors on equipment and in key areas of a construction site ensures real-time data collection on work progress, equipment performance and resource location [9].

[2] Oleinik PP, Brodsky VI, Kuzmina TK, Cherednichenko ND Theory, *Methods and Forms of Organizing Construction Production: a coursebook in the study area 08.04.01 Construction. Part 1.* Moscow: National University of Science and Technology MISiS — Moscow State University of Civil Engineering; 2019. pp. 174–244.

Fig. 4. Example of using BIM technology

Artificial intelligence and machine learning analyzing huge amounts of data (Fig. 4) from past projects, current metrics, and external factors (weather, economic indicators), are capable of identifying hidden patterns and predict likely delays with a high degree of accuracy offering optimal corrective actions to be taken [10]. Project management systems (PMS) with automatic alerts and dashboards (Fig. 5) displaying the key indicators in real time also significantly improve the early warning efficiency.

Fig. 5. Example of a dashboard

In this case, all incoming user requests are arranged in sequence and are visible. Based on the priority, a request or incoming information is ranked, tasks are assigned to the relevant services and a schedule for their completion is generated, the algorithm then reduces the integrated tasks. Effective communication helps to address early warning problems. The open exchange of data on current tasks, difficulties encountered, and resources needed helps to respond to deviations in a timely manner [11]. Regular meetings of all of the project participants ensure prompt discussion of progress and emerging difficulties. It is also critical to implement clear change management procedures: clear design of changes (design, scope of work, materials) and analysis of their impact on timing and cost reduce schedule disruption risks. Uncontrolled changes are one of the major causes of missing deadlines.

Constant monitoring of the critical path [12] identified at the planning stage is vital for early warning. Dynamic path updates are regularly recalculated and analyzed to account for actual execution rates. A change in the critical path or new critical tasks signal potential timing issues. The assessment of time reserves (float) allows one to identify potentially dangerous stages, where even minor delays might affect the overall completion time.

Research Results.

Structuring the EWS methodology for the construction industry:

1. Identifying the *key risk indicators:*

– consumption rate of temporary buffers;

– labor productivity dynamics (deviation of > 15 % from the standard);

– delays in delivering the critical materials.

2. Development of a *predictive analytics algorithm* based on historical data (ML-models).

Managerial innovations:

– a system of triggers for rapid response;

– adaptation of risk management processes to a preventive model.

A trigger example: when the IT sensors detect an 18 % drop in the installation speed of ferroconcrete structures, the system automatically:

– recalculates the timing of the critical path;

– initiates the order of additional equipment;

– notifies the general contractor of a stage delay risk.

It was proposed that the technological architecture of a system is structured taking into account the optimization of the critical path [15].

Table 3

Tool integration

Technology	Functional
BIM 4D/5D	Graph visualization + automatic progress update
IT-sensors	Monitoring the pace of work (e.g., the volume of concrete laid per shift)
Cloud-platforms	Data aggregation → warning generation (SMS/e-mail)

Process model of risk management

1. Introducing a *three-level trigger system* (Fig.6):

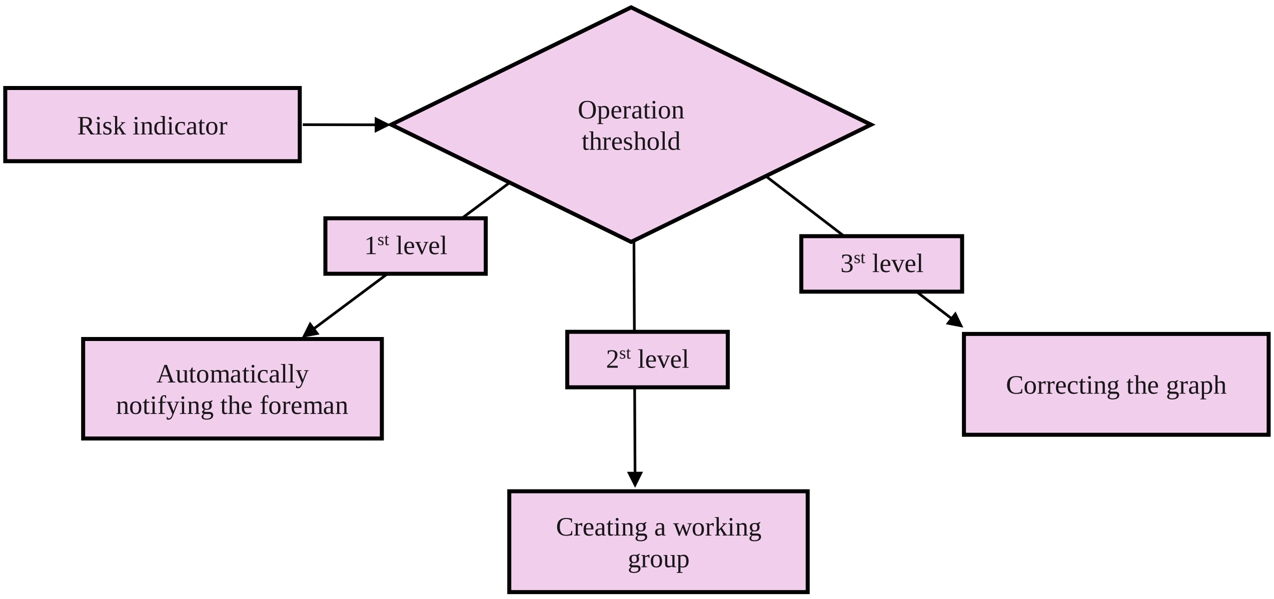

Fig. 6. Algorithm for implementing a three-level system

2. *Operational response regulations* (time period: 1–24 hours).

3. *Case study of the model testing.*

Pilot implementation of EWS at the residential complex "Lakhta-2" (2022–2024 data).

Parameters: 24 floors, 356 apartments, construction time — 28 months.

Results:

– a delay reduction of 27 %;

– 11 mln roubles saved due to downtime reduction.

4. *Designing the recommendations:*

– for developers: EWS implementation algorithm (stages, budget, ROI);

– for regulators: proposals for updating the SNiP/GOST accounting for preventive control.

The subject focuses on designing *an algorithm for proactive timing management* that:

– *Reduces the frequency of delays.* The algorithm continuously monitors the key indicators of the project. Deviations (a 15 % drop in productivity, delayed deliveries) trigger an early warning. An early reaction prevents negativity accumulation and reduces the costs of correcting the schedule.

– *Integrates EWS*-indicators into routine processes. The central element of the algorithm is the Early Warning System (EWS). The indicators reflect changes in the project and warn of impending problems. An example: the consumption rate of the critical path reserve. A rapid depletion of reserves signals impending deadlines and calls for urgent action. EWS integration provides access to up-to-date information and real-time decision support.

– *Formalizes the response.* In order to ensure a prompt and uniform response to identified risks, the algorithm provides for the formalization of the response. This means that for each potential scenario deviation or when certain threshold values of the EWS indicators have been reached, specific corrective measures are identified ahead of time. E.g., setting a trigger: "if the time reserve is reduced by 50% → initiate a review of the logistics." This approach reduces decision-making time, eliminates subjectivity, and ensures instant implementation of pre-approved response protocols.

In order to get some understanding of the algorithm mechanics, let us consider the following scenario: introduction of IT sensors designed to continuously monitor the rate of concrete hardening on monolithic structures. The collected data, including temperature, humidity, and other environmental parameters, are subjected to machine learning (ML analysis). Based on historical data and current indicators, the ML model is capable of predicting a potential delay in completing monolithic work, e.g., 10 days prior to this delay becoming obvious and causing disruption. Upon receiving such a projection, the system initiates automatic or manual adjustments to the overall construction schedule, which might include reallocating the resources, changing the sequence of related works, or activating alternative plans to compensate for the delay identified. This example is indicative of how the algorithm transitions from data collection to data analysis, prediction, and ultimately to proactive control.

Anticipated Research Novelty.

1. *The system of EWS*-indicators *we have developed* for the construction industry (adapted to the realities of the Russian Federation). The first specialized Early warning Indicator System (EWS) has been designed for the Russian construction sector. Apart from the consideration of the local factors (climate, legislation, prices, workers' qualifications), a unique methodology for measuring, prioritizing and combining indicators has been set forth.

2. *Method of integrating* of predictive analytics in the BIM environment.

The scientific novelty of the research lies in the design of an original method for algorithmizing a two-way data exchange between predicative models (machine learning, neural networks) and a BIM platform transforming it into a BIM model. The method allows one to predict deviations in terms of time, resources, and costs using historical and current project data. A two-way, automatically updated data exchange between analytical models and BIM transforms the latter from a diagnostic tool that displays the current state of a project into a tool of predicting and optimizing the construction processes.

3. *Economic and mathematical model* of calculating the impact of the EWS implementation.

The novelty of the model is in its capacity to account for both direct financial benefits (e.g., reducing penalties for failure to meet the deadlines, optimizing resource costs, minimizing the risks of budget overruns) and indirect, albeit no less significant advantages (such as increasing a developer's reputational value, reducing legal costs, and increasing the degree of shareholders and investors' trust). The model will include algorithms for calculating return on investment (ROI), net present value (NPV) and the other key performance indicators, as well as enable a scenario analysis and sensitivity assessment to a wide array of parameters providing reliable justification for management decisions.

The practical significance of the study lies in radically improving the reliability and stability of the construction process by means of introducing a proactive timing control system based on the deep integration of early warning systems (EWS). The model reduces developers' financial and reputational risks, improves compliance with the requirements of Federal Law No. 214-FZ from 31.12.2004 "On Participating in the Shared-Equity Construction of Apartment Buildings and Other Real Estate Objects and on Amendments to Certain Legislative Acts of the Russian Federation", increases shareholders and investors' confidence in construction companies – transparency, predictability and timeliness of project implementation considerably reduce the number of potential lawsuits and claims, which creates a favorable investment climate and bolsters a developer's competitive position in the residential construction market.

The model provides:

– a 20–30 % reduction of missed deadlines due to continuous monitoring of the key indicators;

– automatic identification of risks 7–14 days prior, which provides project managers with an invaluable window of opportunity to take timely corrective action, reallocate the resources, or activate alternative plans, minimizing a negative impact;

– an increase in the accuracy of timing prediction of up to 95 %.

As a result, projects are implemented on time, legal claims and administrative sanctions are reduced, and companies' investment attractiveness and competitiveness are boosted.

Prospects of modernization of traditional methods. Digital tool integration:

– *BIM (Building Information Modeling):* One of the key areas is the use of BIM for 4D planning. This technology enables one to dynamically link detailed work schedules with 3D project models, which automatically identifies potential collisions, conflicts and inaccuracies in the sequence of operations as early as at the starting stages of planning. This contributes significantly to a reduction in the risk of errors and alterations on the construction site.

– *IT-sensors:* The widespread adoption of IT sensors ensures continuous monitoring of the key construction parameters in real time. E.g., tracking the pace of concreting, vibration levels, or temperature conditions on the construction site. The successful experience of projects such as the Lakhta-2 residential complex in St. Petersburg is a clear indication of a high efficiency of such systems in increasing control and predictability of work progress.

Implementation of predictive analytics: early risk warning. The active use of predictive analytics is the second major aspect of modernization. Modern algorithms based on analysis of extensive historical data and machine learning methods are capable of predicting potential delays and risks with a high level of accuracy. E.g., when a 15% drop in productivity is detected in a segment of work, the system automatically generates an alert, allowing managers to respond swiftly and adjust plans before a problem has become critical.

Hybrid management methodology: Waterfall + Agile: Modernization of management methods also involves development of hybrid methodologies combining elements of the traditional Waterfall and Agile approaches. This involves integrating rigid planning and consistent execution of the key project milestones (typical for Waterfall) with flexible, adaptive sprints for rapid adjustments and response to changes and risks identified (typical for Agile). The advantages of this blend have been practically proved, e.g., during the construction of the bridge over the Neva River, the use of digital twins within the framework of a hybrid methodology allow a 18-day reduction in the total work time indicating the potential for synergy of a wide array of approaches in improving management efficiency of large and complex projects.

Discussion and Conclusion. Traditional methods of monitoring construction deadlines suffer from reactivity, subjectivity, and fragmented data. In order to address these flaws, an integrated approach is essential combining digitalization (BIM, AI), management flexibility (Waterfall + Agile) and a shift towards proactive management. The experience of the construction of the Lakhta-2 residential complex is a proof that digital integration provides a 20–30% delay reduction.

The new approach changes the paradigm of time management transforming passive observation into active projection. Integrated risk management, data analytics, technology and communications are called for. The implementation of such methods reduces a likelihood of disruptions, optimizes costs, enhances quality and reputation.

The suggested proactive monitoring algorithm is based on the early warning (EWS) system adapted to the Russian conditions. The system provides EWS indicators, predictive analytics, and effect assessment. The results: a 20–30% reduction in missed deadlines, automatic risk detection in 7–14 days, and prediction accuracy of up to 95%. This approach keeps financial and reputational risks to a minimum, adheres to the requirements of Federal Law No. 214 and enhances market participants' trust. Digital tools and predictive analytics transform time control into strategic projection that warrants sustainability and growth of the construction industry.

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NA Baburin: development of the idea, aims of the research, preparation of the manuscript.

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Development of a Methodology for Decision-Making in Urban Planning and Design of Coastal Areas of Small Rivers in Cities

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Abstract

Introduction. The study is aimed at solving the problem of non-systematic use of coastal areas of small rivers in Russian cities. The relevance is due to the existing fragmentary approach to their urban planning and design, while global experience has been displaying complex solutions. The aim of the study is to develop a methodology for decision-making in urban planning and design of coastal areas of small rivers in large cities based on a multi-criteria analysis.

Materials and Methods. The object of the study are coastal areas of small rivers of large cities. The authors propose making use of a systemic approach that accounts for adjacent functional zones, their mutual influence and expert assessment of significance.

Research Results. A methodology for decision-making in urban planning and design of coastal areas of small rivers has been developed, allowing for the analysis of the functional purposes of individual sections and their interaction at the pre-design stage. In addition, an algorithm for identifying synergetic effects between different development zones has been designed.

Discussion and Conclusion. The approach proposed by the authors allows one to overcome the fragmentation of urban planning solutions regarding coastal areas of small rivers. The prospects of the study include expansion of the methodology due to incorporating environmental, economic, social and functional factors, as well as the application of the approach to a larger number of types of functional zones.

Keywords: urban development, small rivers, improvement, urban planning, urban design, multi-criteria analysis

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Оригинальное эмпирическое исследование

Разработка методики принятия решений при градостроительном планировании и проектировании береговых территорий малых рек в городах

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Аннотация

Введение. Исследование направлено на решение проблемы несистемного использования береговых территорий малых рек в российских городах. Актуальность обусловлена существующим фрагментарным подходом к их гра-

достроительному планированию и проектированию, в то время как мировой опыт показывает комплексные решения. Цель работы — разработка методики принятия решений при градостроительном планировании и проектировании береговых территорий малых рек в крупных городах на основании многокритериального анализа.
Материалы и методы. Объектом исследования выступают береговые территории малых рек крупных городов. Авторы предлагают использовать системный подход, учитывающий прилегающие функциональные зоны, их взаимовлияние и экспертную оценку значимости.
Результаты исследования. Разработана методика принятия решений при градостроительном планировании и проектировании береговых территорий малых рек, позволяющая анализировать функциональные назначения отдельных участков и их взаимодействие на предпроектной стадии. Кроме того, создан алгоритм выявления синергетических эффектов между различными зонами освоения.
Обсуждение и заключение. Предложенный авторами подход позволяет преодолеть фрагментарность градостроительных решений относительно береговых территорий малых рек. Перспективы исследования включают расширение методики за счет включения экологических, экономических, социальных и функциональных факторов, а также применение подхода для большего количества типов функциональных зон.

Ключевые слова: градостроительство, малые реки, благоустройство, градостроительное планирование, градостроительное проектирование, многокритериальный анализ

Благодарности. Статья опубликована в рамках субсидии из федерального бюджета образовательным организациям высшего образования на реализацию мероприятий, направленных на поддержку студенческих научных сообществ.

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Introduction. Small rivers are the most common elements of the hydrographic network of the Russian Federation occupying vast territories with 30% of the country's population living in their drainage area [1]. In almost every major city there is at least one small river that passes through densely populated and promising areas. At the same time, there is still a problem of competent scientific and sensible use of their coastal areas with no urban planning mechanism in place for their planning and design. Hence creating an urban planning model for integrated planning and design of coastal areas of small rivers in large cities is becoming an essential element of the scientific and methodological foundations of urban planning and design of coastal areas of small rivers [2]. To this end, it is imperative that a decision-making methodology is developed for urban planning and design of coastal areas of small rivers with a multi-criteria analysis an indispensable part of this.

Materials and Methods. The decision-making process in urban planning and design is presently discrete, with gaps between its stages [3–4]. This is an obstacle to the integrated development of the urban environment accounting for the previously identified groups of factors. Any choice in urban planning practice should be justified and made comprehensive to various population groups, as well as account for a host of criteria and uncertainties, including temporary ones due to ongoing scientific and technological progress, as well as disaster risks (accidents at nuclear power plants, dams, earthquakes, flooding, etc.) and various interest groups.

At the same time, it is seldom that problems in the construction and urban planning spheres are one-dimensional (those with simple values). These are mostly multidimensional problems with complex values [5–8], where the consequences cannot be objectively and adequately assessed by means of one criterion (e.g., using monetary expressions). A systematic approach would cause changes to the practice.

It is to be noted that there have already been some examples of solving problems in urban planning, transport planning, and administrative and economic activities of territorial entities using multi-criteria selection described in a few papers (Table 1) making it possible to make use of this method in order to select and justify urban development scenarios for specific urban areas.

Table 1

Theory of decision-making with lots of criteria: practical examples based on the studies by R.L. Kini and H. Rife [9–11]

No.	Name of an example	Brief description	Conclusions based on the results of using multi-criteria selection tools
1	Air pollution problems	Systematization of the initial data, pollution problems with the release of individual substances, final results and control measures into a common model for assessing air pollution control programs	Using the results of the analysis and using them in forming and implementing air pollution control programs in New York
2	Activities of individual departments	Analysis of the work organization of the department using the example of a fire station, including the use of the utility function for response periods as the foundation for decision-making in operational activities	Obtaining a utility function for five criteria — response periods identifying the relative value of each minute of the response period, which generated a utility structure in the area
3	Disposal of wastewater treatment products	Four major goals (minimizing costs/water pollution/air pollution/land pollution) caused the issue of possible substitutions	Probabilistic distributions were designed in four directions and work stages on the disposal of wastewater treatment products were chosen.
4	Choosing a job or a place of work	The peculiarity is a profound personal decision, but a possiblity of a formalized procedure for assessing the "advantages" of various situations with a large number of criteria.	Reducing the proposals to alternatives with a hierarchy of goals and criteria, systematizing choices based on Miller's goals and using the Tevels gradation of goals (security, confidence, independence, etc.)
5	Choosing technical solutions for environmental protection	Generalization and formalization of data and sequence of multi-criteria selection in choosing technical solutions for environmental protection	Choosing an option (equivalent options) of technical solutions for environmental protection system that is in compliance with the requirements of not absolutely all, but the largest number of the criteria involved
6	Analysis of the airport development problem for Mexico City	Analyzing alternatives from the perspective of each group of decision makers and citizens, designing a decision-making model identifying possible implications of the alternatives and conducting design experiments, assessing for a year and introducing time dependence	Making a decision based on a multidimensional utility function and considering scenarios for possible developments showing the implications of alternatives for subsequent changes to a city's development strategy.

Coastal territories of urban (small) rivers were chosen as the object of the study for structuring the methodology interacting simultaneously with the transport planning and natural and ecological frameworks, as well as with the adjacent functional zones and the engineering support system (Fig. 1).

For the basic scheme of multi-criteria selection (Fig. 2), a special mathematical apparatus was developed in order to simplify the calculation compared to the general case of decision theory including a preliminary analysis, structural analysis, a decision tree with two types of vertices, uncertainty analysis, and then utility and value followed by optimization procedures [9].

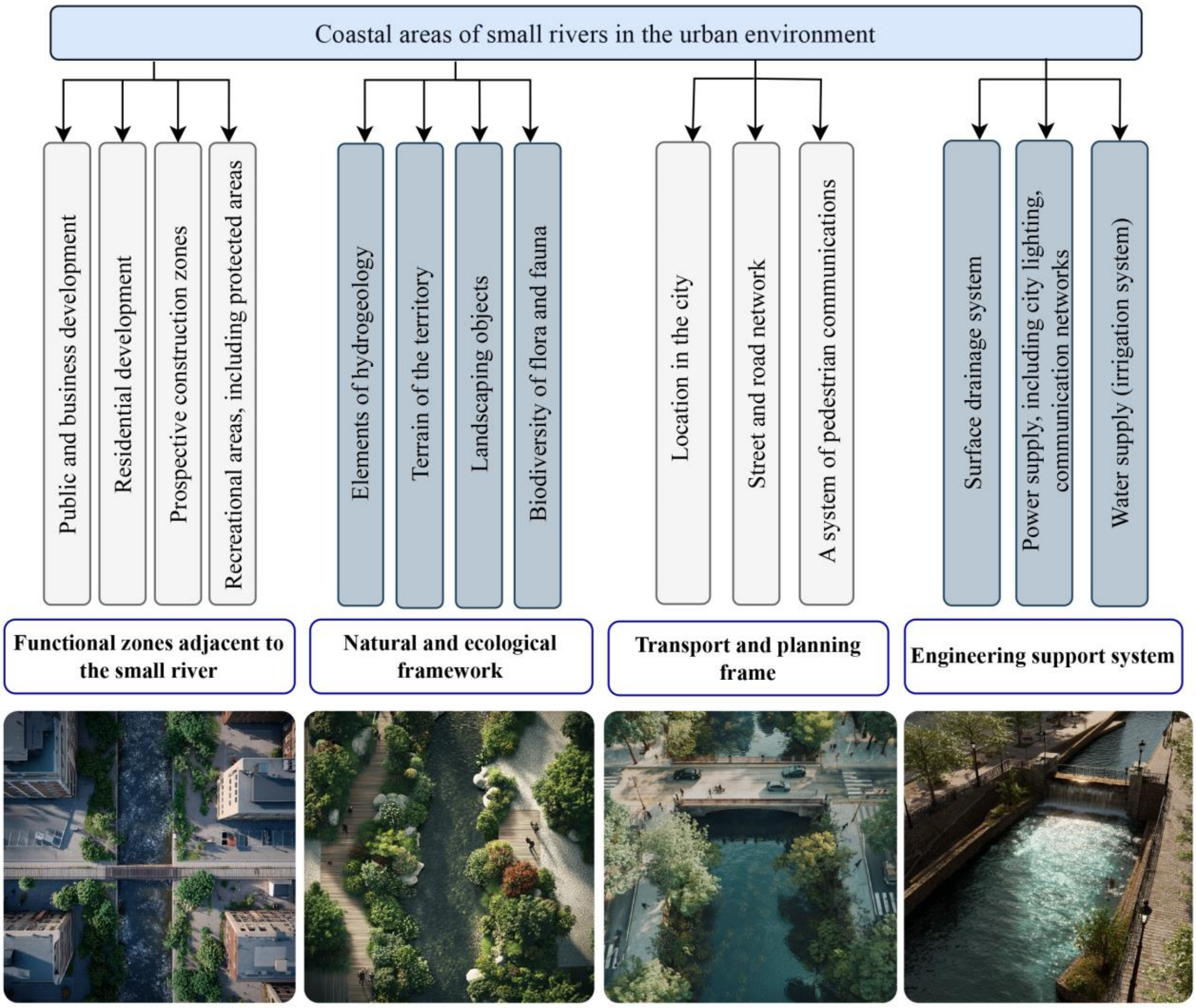

Fig. 1. Small rivers as part of an urban environment

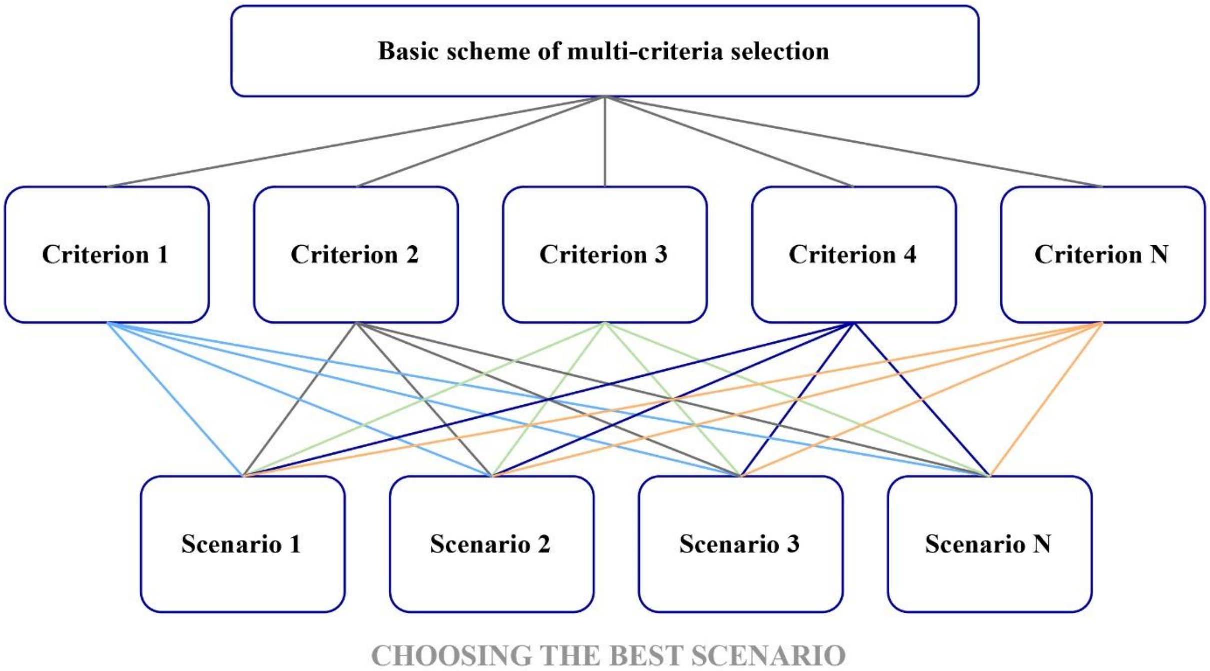

Fig. 2. Generalized structure of a multi-criteria selection scheme

Urban planning decisions include, among other things, the allocation of land in view of a range of restrictions, including environmental or cultural heritage-related ones. It is to be noted that an area in a city is valuable primarily from the perspective of making use of what is located in it. If it is assumed that this value can be formalized by means of a function that can be expressed numerically at the current level of the forecasting period and development of various interests, the task is to design an area distribution that would maximize the value of this function and thereby the value of land use. While designing such a function, it is to be noted that its variables are the criteria characterizing various factors in their measurement scales. Further formalization is associated with defining the options that cannot be improved based on at least one criterion without making it worse according to another one ("a Pareto set").

There are mathematically justified "value substitutions" of the selected criteria both in conditions of certainty and uncertainty. Within the framework of the process it is possible to assume the results of the transition of certain types of actions into implications by using multidimensional value functions [9–11]. Researching choices that require no formalization of the structure of preferences has led us to make some conclusions regarding their structuring for urban planning and the capacities of the suggested scientific approach.

Research Results. As a result of the study, it was found that in urban planning, the task of allocating areas in a particular territory depends on the replacement coefficient, i.e., which area of destination A we are willing to give away for incrementing the area of destination B by one unit. What is challenging is that the replacement coefficient is not constant, but varies depending on the ratio of areas: if the area of destination A is very small, the area of destination B is large. The replacement coefficient will thus differ from the opposite option or with equal-sized areas of assignments A and B.

It is considered possible to apply the general theory of multicriteria selection to a specific urban planning task, i.e., the distribution of coastal areas.

Two types of area distribution on the same site with a variety of distribution options were chosen, which simplifies the selection of the area from the boundary of the coastline to that of a specific functional area.

In order to form a systematic approach based on a multi-criteria analysis, let us assume that:

a) restrictions have already been taken into account while selecting options for possible area allocation;

b) specific features of a certain territory (relief, prospects for developing the neighboring areas, etc.) are not accounted for in order to design a basic model of the area.

Based on this, it is assumed that only the impact of different territorial assignments on each other is being assessed. Having accounted for the impact, the location of the selected areas is specified considering the functional features of the areas.

Hence the basic version of the system approach includes two purposes of areas: S_1 is for the placement of a recreational area, S_2 is for residential buildings (Fig. 3), and only the mutual influence of S_1 and S_2 is analyzed rather than their specific location and configuration to be considered at the next stage of the study.

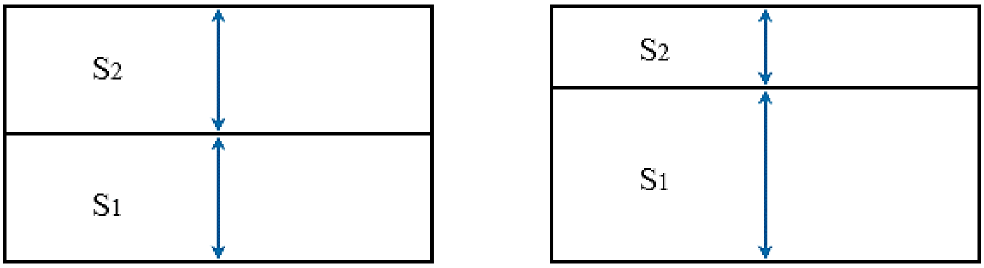

Fig. 3. Systematic approach by means of the allocation of two types of areas

Next, the substitution coefficient for various ratios needs to be used and a value function $W(V_1, V_2)$ where $V_1(S_1)$ and $V_1(S_2)$ needs to be designed. The values of S_1 and S_2 can be identified using it when W reaches its maximum value.

At the second level of the system approach, there might be a case with three types of area assignment (S_1, S_2 and S_3). In this case, the ratio becomes three-dimensional and the substitution coefficient changes between each two area values that are also affected by the area of the third destination.

The third and further levels of the system approach are working with diagrams (areas) for 4, 5 or more purposes.

One of the tasks is thus to examine the possibility of mutual compensation of criteria values relative to each other (substitution by value). This is possible with their systematic structuring and use of an appropriate coefficient that might be influenced by the environment (the already built-up area around) and other factors.

The next stage might be to interview an expert or a decision maker (within the framework of a list of proposals) on changing the value of the areas, as well as accounting for the environmental, economic, social and functional factors characterizing the area as well as their combined groups (Fig. 4).

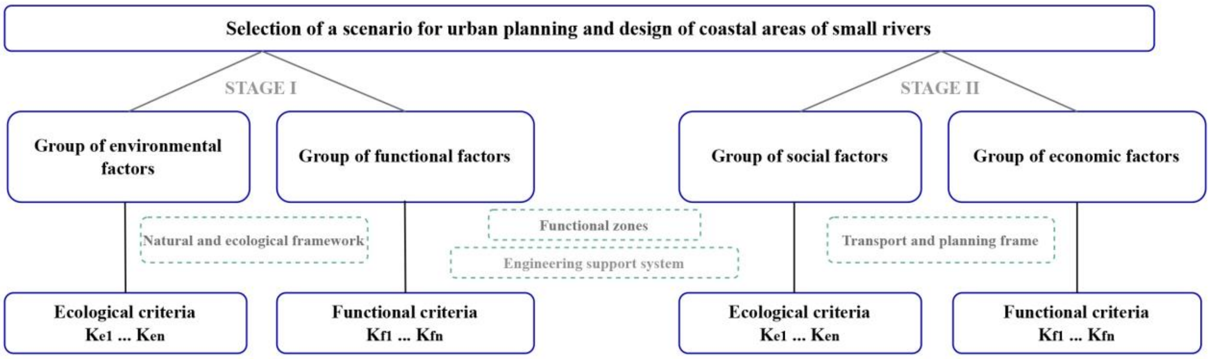

Fig. 4. Multi-criteria analysis while choosing a scenario for urban planning and design of coastal areas of small rivers

The decision-making methodology in urban planning and design of coastal areas of small rivers in large cities should also account for the interests of various population groups, including business communities and local as well as federal governments experiencing considerable changes over time. The results of the research will become part of the solution to the scientific problem of contradictions between the modern discrete approach to urban planning and design of coastal areas of small rivers and the need to move to an integrated step-by-step approach for planning and designing them accounting for socio-economic and environmental-functional factors.

Discussion and Conclusion. The study has thus confirmed the need to move from the existing discrete system of urban planning and design to a systematic approach in developing coastal areas of small rivers. The suggested method of multi-criteria analysis would help to address the fragmentation of decision-making and provide a scientifically sensible approach to the distribution of functional areas.

The major result of the work has been the development of a theoretical model based on the principles of multidimensional optimization and decision theory accounting for the mutual influence of various functional purposes of areas by means of a system of substitution coefficients allowing one to maximize the overall value of the selected area with no reference to a specific configuration at the initial stage.

The practical significance of the study is the formation of tools for comparing alternative scenarios for developing areas accounting for the relevant groups of factors, as well as increasing the validity of urban planning decisions.

The prospects for further research are to expand the number of functional purposes to be considered, to integrate the factor of the dynamics of changes in criteria over time into the model, to develop mechanisms for accounting for the interests of various stakeholders, and to test the methodology on real sections of the coastal areas of small rivers in a city.

It is our belief that the implementation of the suggested decision-making methodology in urban planning and design of coastal areas of small rivers in cities will contribute to designing a balanced and sustainable urban environment that makes an effective use of their potential considering the principles of biospheric compatibility.

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Critical Analysis of the Use of Digital Image Analysis Technology to Monitor Construction Facilities and Materials

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Abstract
Introduction. Due to the latest wide-scale adoption of advanced technologies in the construction sector and the pressure to complete projects in the shortest time and at minimal cost, the principle of achieving a high-quality level in project implementation is a daunting task for those working in construction. In this context digital image analysis technology has served as a viable solution to meet the requirements for improving project management efficiency at different stages. This literature review examines the role of digital image processing technologies in monitoring construction materials and structures throughout the project lifecycle in order to improve their quality and efficiency. The aim of the study is to evaluate the efficiency of this technology compared to traditional methods, review the latest developments in digital image processing for monitoring building structures, and identify performance indicators such as time and cost, as well as mention obstacles preventing its wide-scale adoption in engineering.
Materials and Methods. More than 30 publications (2015-2024) covering AI algorithms (CNN, YOLOv4), 3D modeling (LiDAR, Structure from Motion) and BIM integration were systematically reviewed. Their applicability, scalability, and impact on structural condition monitoring were evaluated.
Research Results. According to the results, the use of digital image analysis technology as a tool for monitoring structures and quality control of construction materials at different stages of a project lifecycle caused improved project quality, reduced time and costs, and boosted decision-making at different stages of a project cycle. The integration of image processing with artificial intelligence and building information modeling systems proved to be accurate in detecting defects in buildings and building materials with a 25% increase in the project management efficiency.
Discussion and Conclusion. Digital image processing (DIP) holds a transformational potential, but it is facing some obstacles such as environmental influences, data heterogeneity and lack of standardization. LiDAR integration, development of sustainable machine learning models for multimodal data analysis, and strengthening interdisciplinary collaboration are set forth. In order to overcome the restraints, further research is required to optimize technologies for real-world operating conditions. DIP is revolutionizing design monitoring, but mass adoption is possible only by means of sustainable innovation, industry-wide partnerships, and adaptation to external factors.

Keywords: digital image analysis, project lifecycle, quality control, monitoring

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Оригинальное эмпирическое исследование

Критический анализ использования технологии анализа цифровых изображений при мониторинге строительных конструкций и материалов

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Аннотация

Введение. В связи с недавним широким внедрением передовых технологий в строительном секторе и неотложной необходимостью завершать проекты в кратчайшие сроки и с минимальными затратами принцип достижения высокого уровня качества при реализации проектов представляет собой сложную задачу для тех, кто работает в области строительства. В этих условиях технология цифрового анализа изображений стала перспективным решением для обеспечения требований по повышению эффективности управления проектами на различных этапах их жизненного цикла. В данном обзоре литературы анализируется роль технологий цифровой обработки изображений в мониторинге строительных материалов и конструкций на протяжении всего жизненного цикла проекта с целью повышения качества и эффективности. Исследование направлено на оценку эффективности этой технологии по сравнению с традиционными методами, обзор последних разработок в области применения цифровой обработки изображений для мониторинга строительных конструкций и определение показателей эффективности, таких как время и стоимость, а также упоминание препятствий, мешающих ее широкому внедрению в инженерной практике.

Материалы и методы. Проведён системный обзор более 30 публикаций (2015–2024 гг.), охватывающих алгоритмы ИИ (CNN, YOLOv4), 3D-моделирование (LiDAR, Structure from Motion) и интеграцию BIM. Оценены их применимость, масштабируемость и влияние на мониторинг состояния конструкций.

Результаты исследования. Полученные результаты показали, что использование технологии цифрового анализа изображений как инструмента для мониторинга конструкций и контроля качества строительных материалов на разных этапах жизненного цикла проекта привело к повышению качества проектов, сокращению времени и затрат, а также улучшению процесса принятия решений на разных стадиях проектного цикла. Интеграция обработки изображений с искусственным интеллектом и системами информационного моделирования зданий обеспечила точность в обнаружении дефектов в зданиях и строительных материалах, повысив эффективность управления проектами на 25 %.

Обсуждение и заключение. ЦОИ демонстрирует трансформационный потенциал, но сталкивается с барьерами: влияние внешней среды, гетерогенность данных и отсутствие стандартизации. Предложены интеграция LiDAR, разработка устойчивых моделей машинного обучения для анализа мультимодальных данных и усиление междисциплинарного взаимодействия. Для преодоления ограничений требуются дальнейшие исследования, направленные на оптимизацию технологий под реальные условия эксплуатации. ЦОИ революционизирует мониторинг конструкций, однако массовое внедрение возможно лишь через устойчивые инновации, партнёрство между отраслями и адаптацию к внешним факторам.

Ключевые слова: анализ цифрового изображения, жизненный цикл проекта, контроль качества, мониторинг

Для цитирования. Сабитов Л.С., Али Л. Критический анализ использования технологии анализа цифровых изображений при мониторинге строительных конструкций и материалов. *Современные тенденции в строительстве, градостроительстве и планировке территорий.* 2025;4(4):27–36. https://doi.org/10.23947/2949-1835-2025-4-4-27-36

Introduction. Due to the rapid development of the construction design sector, quality control of materials and infrastructure is a major task for engineers and designers. For decades, the industry has relied on traditional methods such as manual visual inspection or manual measurements that have proved to be up to 30–40% susceptible to human error, in particular in high-risk areas or in hard-to-reach locations. These methods typically fail to detect early signs of degradation in a timely manner, such as fading or peeling of the protective coating, which might signal the inception of corrosion or moisture penetration into a structure. In combination with microcracks, such defects might eventually result in a decrease in the bearing capacity of the elements and thus jeopardize the safety of an object [1].

In contrast, digital image processing methods have served as a viable solution for improving observation accuracy and reducing costs. In [2] the combination of the Otsu algorithm and the YOLOv4 network enabled classification of cracks in concrete with an accuracy of 99.75%, while there was a 40% drop in interference due to surface inclusions. The use of unmanned aerial vehicles (UAVs) with thermal imaging systems has shown the possibility of examining reinforced structures in record time reducing the survey period by 30% compared to traditional methods [3].

However, these methods are being faced with environmental and operational conditions. According to [4], in low light or random vibrations, detection accuracy decreases to 75% highlighting the need for noise-resistant algorithms. On the other hand, [5] emphasizes the complexity of analyzing asphalt mixes using two-dimensional images, which caused the authors to develop the IPAP index using a color segmentation algorithm in order to improve the accuracy of evaluating the distribution of aggregates. Moreover, the integration of computer vision and BIM methods is a major factor in improving efficiency. In [6] the integration of LiDAR data with BIM models provided a comparison of a geometric design with an actual structure with a spatial clarity of ± 2 mm improving proactive maintenance. Digital image correlation (DIC) has proven to be efficient in measuring dynamic deformations of bridges under load, where the measurement sensitivity reaches 0.1 mm outperforming manual methods with no more than 0.5 mm [7].

Despite these achievements, the results of [8] indicate that the efficiency of monitoring systems mostly depends on the quality of input data, in particular while using spectral imaging and electromagnetic detection in order to identify corrosion risks of reinforcing steel and concrete coating properties allowing a 90% accuracy in combination with laboratory data. In [9, 10] there are discussions of the need to develop machine learning models capable of processing heterogeneous data, e.g., combining LiDAR images with thermal imaging, in order to increase the reliability of outdoor projects.

The aim of this study is to review the latest advances in digital image processing for structural monitoring, with an emphasis on the following:

1. Innovative technological approaches.
2. Integration between systems, e.g.: integration of UAVs with BIM to improve inspection efficiency.
3. Practical problems, e.g.: the effect of poor lighting or vibrations on the accuracy of the results.

Having analyzed more than 30 studies published between 2015 and 2024, we are going to provide a comprehensive view of the role of these technologies in achieving sustainability and reducing costs to improve project management efficiency. Some solutions have also been set forth to eliminate the limitations hindering the use of these technologies in future projects.

Materials and Methods. The research examines digital image processing technologies in the field of monitoring buildings and construction materials.

Digital image processing technology in building monitoring:

Digital image processing methods are becoming the foundation for developing monitoring systems for structures, with accurate and safe solutions for early damage detection. In [11], an integrated system was developed based on combining the developed Otsu algorithm with morphological filters (Fig. 1), such as a median filter and a Gaussian filter, for detecting cracks in reinforced concrete, where the detection accuracy was as high as 98.75% while classifying damage types (surface, capillary, longitudinal/transverse cracks) [12] with a 40% reduction in the impact of interference caused by contamination. In [2] the YOLOv4 network based on artificial intelligence was also employed to increase the classification speed, allowing 120 image sections per second to be examined. To compare manual examination takes a few minutes for each site.

During field observations, unmanned aerial vehicles have proven to be useful for evaluating dangerous or hard-to-reach areas. In [1] UAVs equipped with high-resolution cameras used an image processing mechanism (heuristic processing) based on a combination of a few types of algorithms (hat transformation, HSV threshold processing, grayscale threshold processing) in order to inspect reinforced concrete structures and detect cracks and surface destruction in a university campus project, and proved to contribute to qualitative performance improvement compared with traditional methods. At the same time, minimizing errors (such as the confusion between the cracks and the other edges) and improving the clarity of detection results were given prominence, the algorithm presented was found to yield 35% more accurate results than traditional algorithms, while [3] showcases a more advanced mechanism for identifying the state of an object based on algorithms Canny & Prewitt Edge Detectors (for crack identification, algorithm Color Thresholding (for detecting any living organisms on the concrete surface and the reinforcement condition (Fig. 1).

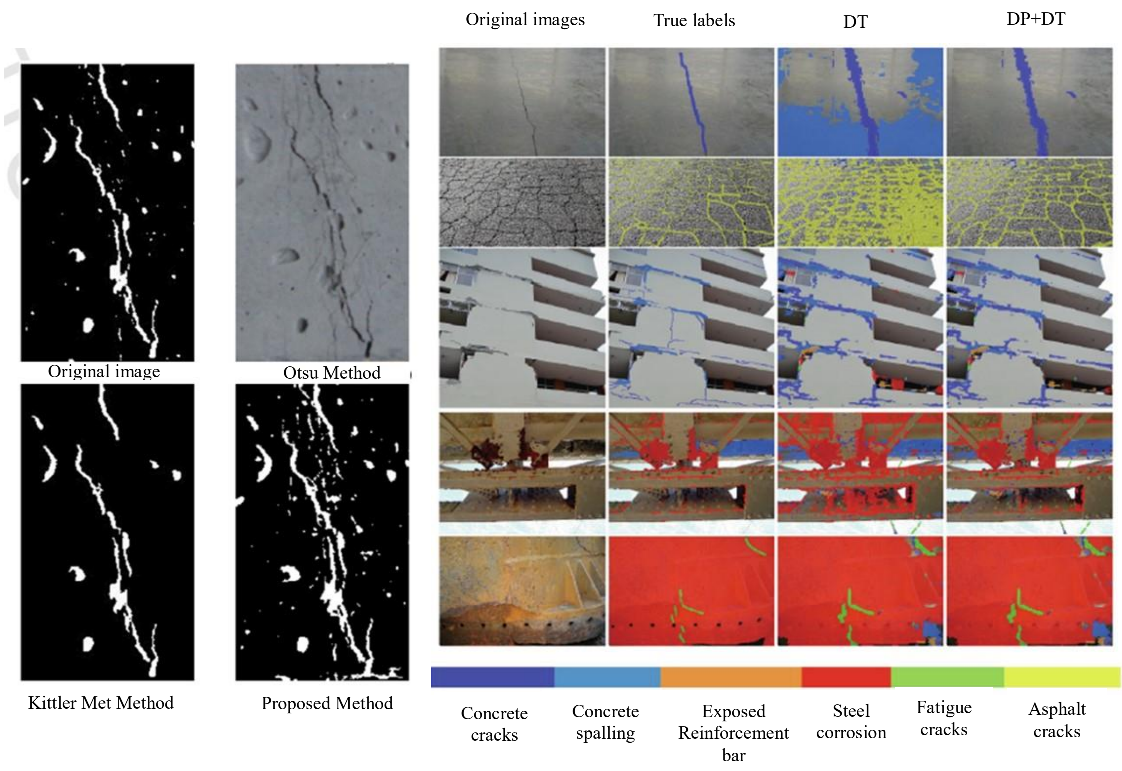

Fig. 1. Digital image analysis for monitoring cracks in concrete elements [2, 7]

The methodology was applied to a 177-meter-high concrete telecommunication tower in Portugal. According to the study, the system was able to detect corrosion and cracks in concrete with a 92% accuracy, as well as bio-leaks and corrosion of reinforcement with a 90% accuracy, while reducing the inspection time by 30% compared to traditional methods using scaffolding and manual tools [3]. The results of using digital image processing technology captured by drones and their processing by means of algorithms (Rich Feature Hierarchies) and (Fast R-CNN) in order to detect surface damage to culverts and bridges (cracks and corrosion), as well as the use of methods (t-SNE) to reduce the size and visualization of complex data, yielded a 95% accuracy of detecting surface cracks, while reducing the inspection time by 70% compared to traditional manual methods. This resulted in an increase in the inspection accuracy and efficiency as well as monitoring of facilities while reducing the number of risks individuals are exposed to [7].

Methods and algorithms based on the use of fractal analysis to digital images have also been employed in order to identify changes in concrete bridge defects (cracks) by calculating the fractal dimension by means of the box counting algorithm [13]. All of these methods rely on those for detecting defects and monitoring structures with images. On top of that, the digital image correlation (DIC) method in [13, 7] displayed an excellent capacity to measure bridge deformations under dynamic loads by detecting a 0.1 mm sensitivity on a bridge subjected to repeated vibrations. The data (DIC) were combined with the results of finite element modeling (FEM), which confirmed a 95% agreement of the results, indicating that they can be used in order to evaluate the integrity of a structure in real time (Fig. 2).

In the context of combining technologies, the integration of 3D LiDAR scanning and digital image processing with BIM (Building Information Modeling) has contributed to an increase in the accuracy and flexibility of monitoring facilities throughout their whole lifecycle. At the design stage, a study was conducted [14] that showed the efficiency of laser scanning in designing precise 3D models of historical structures, such as the Santa Marina Church in Spain, where data was collected using a digital single-lens reflex camera to obtain multispectral images of the church structure, and combined with 3D laser scanning data to design a precise digital model of the church structure. The images were then transformed in two stages: firstly, segmentation by color and texture characteristics, and secondly, classification using an objective classification methodology to identify the material (biocarentine limestone) and types of destruction (cracks, biocorrosion, salting). The data was analyzed, the model was then combined with the preprocessed images, and using a laser scanner, metric maps were designed to identify the locations of damage on the stone with a higher accuracy than by means of traditional methods. The crack detection accuracy was 100%, and the salinity detection accuracy was 80%, with detailed measurements of surface tolerances of ± 3 mm. Integration (LiDAR and BIM) has improved quality evaluation of the material and restoration planning, as well as reduced the costs by 20% by means of integration (ReCap Pro and AutoCAD) in order to convert 3D models into detailed restoration drawings (Fig. 3).

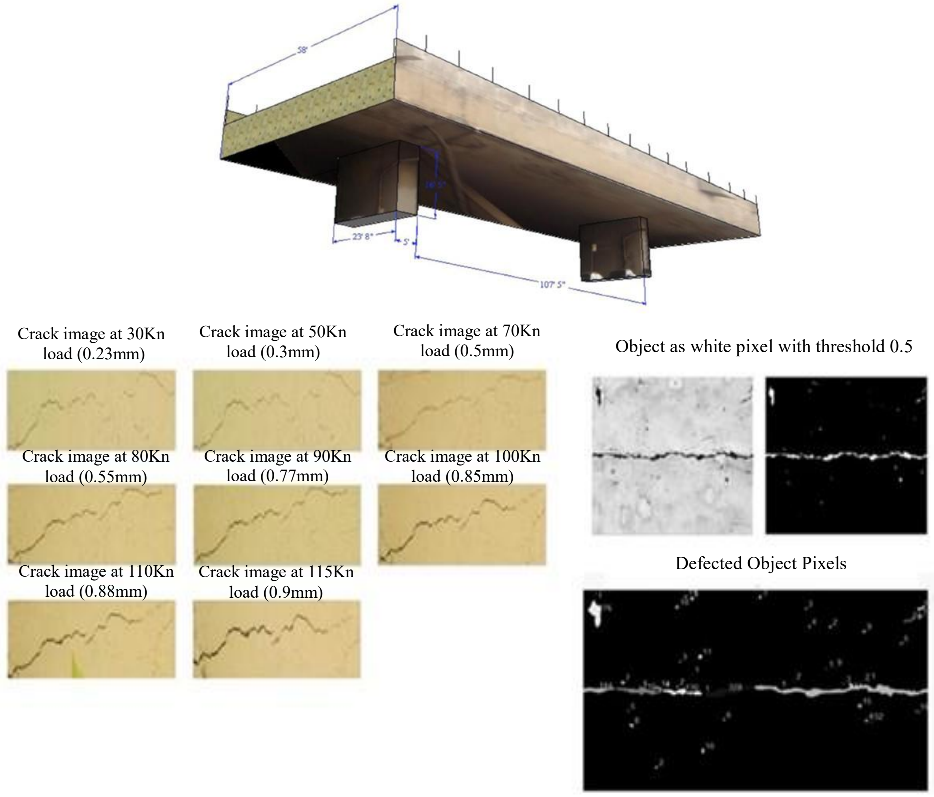

Fig. 2. Digital image analysis for monitoring the condition of an object [7]

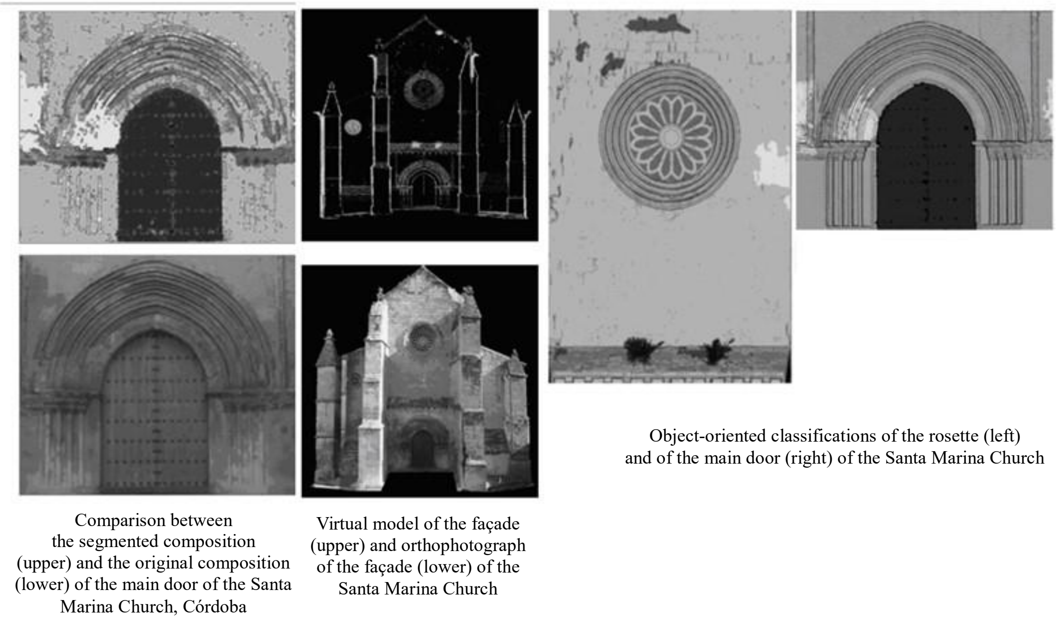

Fig. 3. Integration of digital image analysis with laser scanning and BIM [14]

In [12] the role of digital image technology at the construction stage to monitor work progress is also described, where the indicators obtained using the suggested model were integrated with BIM models in order to update information about the schedule and predict structural risks, which reduced the dependence on manual visual control (Fig. 4).

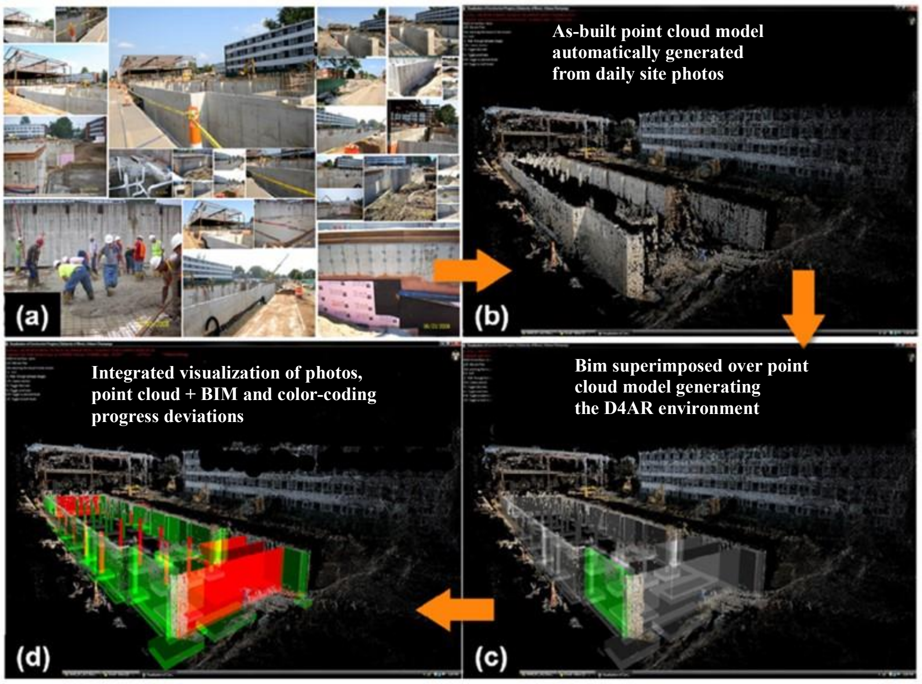

Fig. 4. Digital image analysis for quality control during the construction phase [12]

At the stages of operation and repair, neural networks (CNNs) trained on LiDAR survey data enabled concrete surface defects to be identified with a 95% accuracy, as in [9] where DenseNet-12 showed the top performance in automatic classification and sizing of damage (cracks and efflorescences) using smartphone cameras. Fractal analysis by means of the box counting algorithm also facilitated the measurement of changes in structural defects with no need for accurate image registration, as the fractal dimension rose from 1.13 (main crack) to 1.28 (extended crack) in simulated images, while the rate of change was 13.26% compared with exaggerated changes (up to 184%) in traditional methods such as image subtraction. The Poisson surface reconstruction algorithm transformed the point cloud into a closed and smooth grid model that supports digital reconstruction of complex structures (Fig. 5).

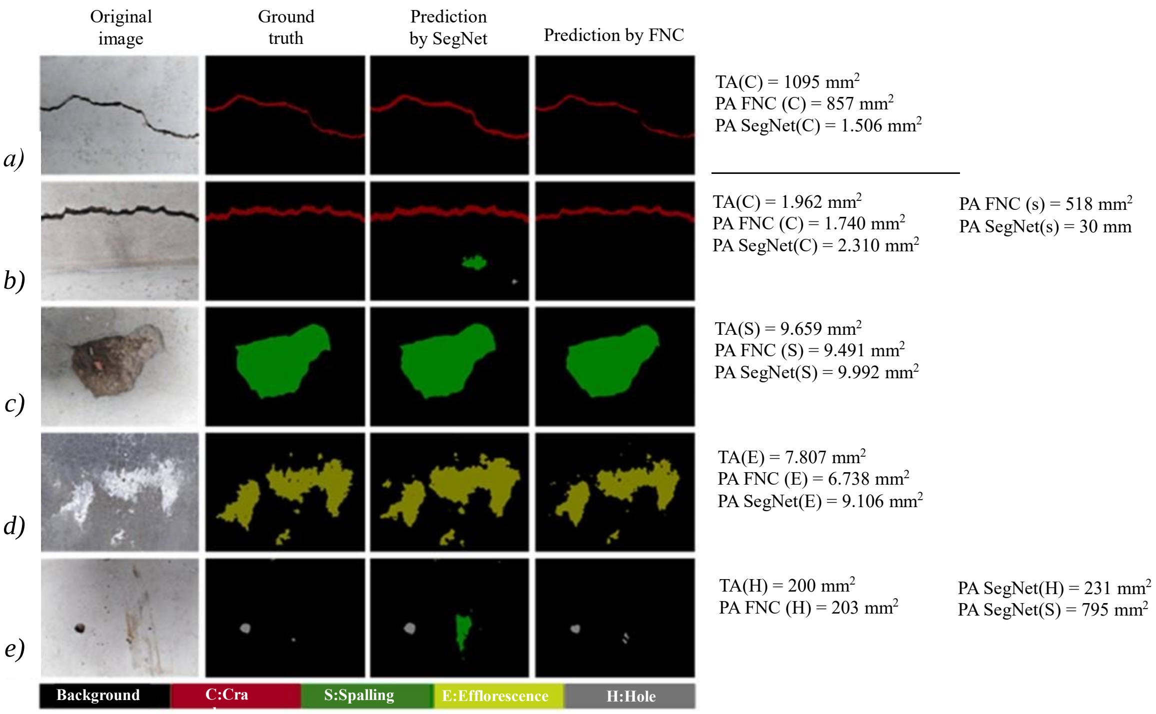

Fig. 5. Image analysis method for predicting multiple structural defects [7]

The concept of integrating digital imaging technology into object monitoring and information modeling was not restricted to the 3D field, but developed to integration with 4D CAD models, making it possible to visualize the actual progress of projects and identify the problems related to design and planning, as well as reduce the time, human effort and costs to collect and update project data. The digital image processing technique was applied during the construction of a suspension bridge in Korea, where cameras on the construction site were used to capture images and link them to a precise temporal context, and after processing these images using the filters (Hue-, Saturation- and Median) — to remove noise and identify unnecessary equipment. The processing results were combined with the project schedule using Jet Stream software, which helped to update the 4D model, and they showed a rate of 92% for the accuracy factor and correct installation of elements, and 38% of errors were corrected during the design phase, reducing the costs by 44% and construction time by 25% [15].

However, the accuracy of the results was found to be strongly influenced by environmental conditions, such as poor lighting and vibrations, as while using digital image processing technology in an underground tunnel, the detection accuracy dropped to 75% due to the high humidity and fog. On top of that, the integration of 3D images with the data (LiDAR) has increased the complexity of the required processing technology by 15%.

2. Digital image processing technology in the field of construction material monitoring:

In the field of evaluation of construction material quality, image processing methods have displayed an excellent ability to analyze the subtle characteristics of construction mixes. In [16], the algorithm (Color Segmentation) was used to identify the size distribution of aggregates in asphalt mixes, where the Image Processing Aggregate Proportion (IPAP) indicator was calculated, and using this parameter, the proportion of aggregate in the mix was identified with an accuracy of 85% helping to increase the strength of the road by 15% by changing the aggregate density. Multispectral Imaging in [5] confirmed its efficiency in detecting metal corrosion in structures with an accuracy of 90% by analyzing spectral changes caused by oxidation and comparing the results with the laboratory data for measuring the thickness of the corrosion layer. At the same time, in [17] 2D DIP image analysis was used to identify the coefficient of stone-to-stone contact in permeable friction mixes. Algorithms such as morphological analysis were applied to convert images into quantitative data indicating a close correlation between the gravel contact density and surface layer stiffness helping to fine-tune the mix design quality. On the other hand, [17] was devoted to developing quality control techniques for industrial materials (e.g., concrete and steel) using statistical image analysis to detect subtle defects that might affect industrial safety. E.g., texture analysis algorithms were applied to concrete images to detect crumbling or microcracks, and the wavelet transform was used to improve the accuracy of images obtained in poor lighting conditions (Fig. 6). This method has reduced the verification time by 30% compared to traditional methods.

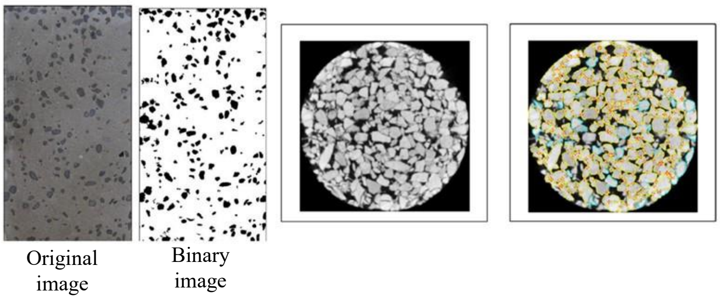

Fig. 6. Digital image analysis during quality control of the asphalt mix (identifying the aggregate-mortar ratio, the contact surface between the aggregates) [16]

The study [13] assessed the resistance to static segregation in self-sealing concrete. Methods such as grayscale conversion and Otsu threshold analysis were used to identify segregation zones, and the results were correlated with compressive strength tests to develop more accurate quality control criteria. In the field of lightweight concretes, [18] contributed to the optimization of concrete mixes using the S8 gradation index obtained by analyzing digital images of porous aggregates. Owing to the use of algorithms such as Semantic Segmentation, the aggregate distribution was measured with an accuracy of 0.1 mm, which reduced the porosity and increased the resistance of the material to moisture and salts. On top of that, [16] contributed to the analysis of the size distribution of aggregates in asphalt concrete mixes using image processing methods. The results showed that image analysis using the algorithms such as Particle Counting enables one to evaluate the properties of a mix (e.g., compression resistance) with no the need for complex laboratory tests with a 25% cost reduction.

In the field of practical application, while working on [19], a methodology was developed for evaluating the segregation of the aggregates in finished concrete by analyzing static images by means of variation analysis algorithms. This method enabled an improvement in the quality control during large-scale construction by defining segregation zones with an accuracy of 0.5 mm helping one to minimize costly post-construction adjustments. While elaborating on the problems encountered in [18], it was noted that the analysis of asphalt mixes with heterogeneous aggregates calls for the development of advanced algorithms such as PointNet for point cloud classification, where the accuracy of the model was as high as 88% while identifying the gradient of the aggregate size compared to 65% for traditional methods. [7] also looks at the complexity of monitoring materials in extreme environmental conditions (such as fog or strong winds) eventually proposing the integration of thermal imaging with computer vision in order to improve the reliability of outdoor infrastructure projects. As part of addressing the obstacles associated with lighting conditions, [5] sets forth a methodology for combining image processing technology with generative neural networks making it possible to identify and predict the degree of corrosion of reinforcing steel, while the accuracy of predicting the thickness of the corrosion layer is as high as 95%.

Research Results. The results of structural condition monitoring are the following:

1) It has been proved that digital image processing methods are capable of providing exceptional accuracy in detecting structural damage, but their efficiency varies depending on the operating conditions. While using the Otsu algorithm with a median filter and a Gaussian filter, the accuracy of identifying cracks in concrete was as high as 99.75%, while interference caused by surface defects was reduced by 40%. The use of the YOLOv4 network also facilitated a swift classification of crack types (surface, capillary, longitudinal/transverse ones), as 120 images were processed per second compared to manual inspection taking a few minutes per image.

2) Unmanned aerial vehicles (UAVs) have proved to be efficient in evaluating dangerous areas such as bridge overpasses. The use of 4K cameras with heuristic processing algorithms enabled the detection of corrosion and cracks in a concrete structure with an accuracy of 92%, while the inspection time was reduced by 30%, increasing the efficiency of proactive maintenance.

3) Despite these achievements, the accuracy of the results is strongly influenced by environmental conditions such as poor lighting or vibrations. During the experiment in an underground tunnel, the detection accuracy dropped to 75% due to the high humidity and fog indicating the need for developing noise-resistant algorithms.

4) The integration of 3D images (Structure from Motion — SfM) with the LiDAR data increased processing complexity by 15%, but contributed to the design of detailed digital models of the historical structures making it easier for progressive degradation to be tracked over time.

The results of construction material monitoring are the following:

1) In the construction material sector, image processing techniques have displayed the capacity to analyze the subtle characteristics of mixes. Using the IPAP (Image Processing Aggregate Proportion) index, the granulometric composition of asphalt mixes was calculated with an accuracy of 85%, increasing the durability of roads by 15% by optimizing the proportions of the aggregates.

2) Generative neural networks (GANs) have displayed the capacity to simulate the influence of environmental factors (humidity, salinity) on steel corrosion, where the accuracy of predicting the thickness of the corrosion layer is as high as 95%.

Discussion and Conclusion. Despite the significant progress made, the research has revealed serious problems curbing the large-scale use of these technologies. The paramount ones are poor lighting conditions or accidental vibrations that have a major impact on the accuracy of the results. The quality of the equipment used to obtain images of objects is crucial as well: the lower the resolution, the more time it takes to for data to be processed, which has a negative impact on the timing of large-scale projects. The following directions are set forth to address these obstacles:

– improving environmental resilience by developing algorithms for low light or fog conditions;

– integration with BIM systems: direct connection of image data with design models, improvement of calibration accuracy;

– expansion of the application scope: inclusion of other materials.

Digital image processing transforms monitoring of structures and materials ensuring a high accuracy and efficiency. However, in order for it to be broadly introduced, technical and environmental constraints should be eliminated via sustainable innovation and interdisciplinary collaboration. More research should be dedicated to optimizing algorithms for real-world operating conditions, integrating with BIM systems, and expanding applications of new materials to maximize the potential of these technologies in engineering practice.

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LIFE CYCLE MANAGEMENT OF CONSTRUCTION FACILITIES

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Original Empirical Research

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Improving the Efficiency of the Design Stage of the Life Cycle of the Heat Supply System of a Construction Facility

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Abstract

Introduction. The heat supply system is one of the most important infrastructural components of the engineering support of the construction site. However, the process of modeling its life cycle, particularly in terms of information support, has not been sufficiently researched in the academia.

One of the main stages of the life cycle of any engineering system is design. The need to increase energy efficiency, reduce the cost of designing and, thereby, building central heating systems, and improve the environmental situation highlights the special urgency of introducing innovative technologies, in particular, artificial intelligence that can become an effective tool for solving the existing problems. The aim of the study is to increase the efficiency of the design stage of district heating systems based on the use of artificial intelligence and to assess the prospects for such an approach.

Materials and Methods. The research methodology includes comparative analysis, modeling, statistical data processing and expert assessment. The research results can be used in the development of new approaches to the design of heat supply systems using modern digital technologies.

Research Results. The proposed concept of life cycle management of heat supply systems, which includes the sequential implementation of five key stages (from pre-design preparation to disposal) allows for an integrated approach to optimizing all of the processes. At the same time, the design stage, which determines the basic parameters of energy efficiency, efficiency and reliability of heat supply, is of critical importance. In the context of digitalization of thermal power engineering, the integration of intelligent automated systems implementing multifactorial algorithmic modeling and optimization calculations is becoming particularly relevant. Modern artificial intelligence-based solutions provide comprehensive automation of design and engineering work, including creating detailed information models of facilities, high-precision forecasting of heat consumption, hydraulic control and optimization of the energy balance of the system. The introduction of such technologies not only compensates for the lack of qualified specialists and improves the quality of project documentation, but also contributes to significant optimization of operational performance: reducing fuel costs and minimizing the carbon footprint through rational allocation of energy resources and reduction in greenhouse gas emissions.

Discussion and Conclusion. The article discusses modern approaches to automated design of district heating systems using artificial intelligence technologies. A technique based on the use of machine learning, neural networks, and optimization algorithms is proposed to improve design efficiency, minimize energy loss, and reduce operating costs.

Keywords: life cycle, life cycle management, heat supply system, district heating, construction site, artificial intelligence, computer-aided design, machine learning, optimization, energy saving

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Оригинальное эмпирическое исследование

Повышение эффективности этапа проектирования жизненного цикла системы теплоснабжения строительного объекта

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Аннотация
Введение. Система теплоснабжения является одним из важнейших инфраструктурных компонентов инженерного обеспечения строительного объекта. Однако процесс моделирования ее жизненного цикла, особенно в части информационного обеспечения, остается недостаточно исследованным в академической среде.
Одним из основных этапов жизненного цикла любой инженерной системы является проектирование. Необходимость повышения энергоэффективности, снижения затрат на проектирование и в последующем строительство систем центрального теплоснабжения, улучшения экологической ситуации подчеркивает особую актуальность внедрения инновационных технологий, в частности, искусственного интеллекта, который может стать эффективным инструментом решения существующих проблем. Цель исследования — повышение эффективности этапа проектирования систем централизованного отопления на основе применения искусственного интеллекта и оценка перспектив такого подхода.
Материалы и методы. Методология исследования включает сравнительный анализ, моделирование, статистическую обработку данных и экспертную оценку. Результаты исследования могут быть использованы при разработке новых подходов к проектированию систем теплоснабжения с применением современных цифровых технологий.
Результаты исследования. Предложенная авторами концепция управления жизненным циклом теплоснабжающих систем, включающая последовательную реализацию пяти ключевых этапов (от предпроектной подготовки до утилизации), позволяет обеспечить комплексный подход к оптимизации всех процессов. При этом критическое значение приобретает стадия проектирования, определяющая базовые параметры энергоэффективности, экономичности и надежности теплоснабжения. В контексте цифровизации теплоэнергетического проектирования особую актуальность приобретает интеграция интеллектуальных автоматизированных систем, реализующих многофакторное алгоритмическое моделирование и оптимизационные расчеты. Современные решения на базе искусственного интеллекта обеспечивают комплексную автоматизацию проектно-конструкторских работ, включая создание детализированных информационных моделей объектов, высокоточное прогнозирование теплопотребления, управление гидравлическими режимами и оптимизацию энергобаланса системы. Внедрение таких технологий не только компенсирует дефицит квалифицированных специалистов и повышает качество проектной документации, но и способствует существенной оптимизации эксплуатационных показателей: снижению топливных затрат и минимизации углеродного следа за счет рационального распределения энергетических ресурсов и сокращения выбросов парниковых газов.
Обсуждение и заключение. Рассмотрены современные подходы к автоматизированному проектированию систем централизованного теплоснабжения с использованием технологий искусственного интеллекта. Предложена методика, основанная на применении машинного обучения, нейронных сетей и оптимизационных алгоритмов для повышения эффективности проектирования, минимизации энергопотерь и снижения эксплуатационных затрат.

Ключевые слова: жизненный цикл, управление жизненным циклом, система теплоснабжения, централизованное теплоснабжение, строительный объект, искусственный интеллект, автоматизированное проектирование, машинное обучение, оптимизация, энергосбережение

Для цитирования. Тихомиров А.Л., Лысова Е.П. Повышение эффективности этапа проектирования жизненного цикла системы теплоснабжения строительного объекта. *Современные тенденции в строительстве, градостроительстве и планировке территорий*. 2025;4(4):37–43. https://doi.org/10.23947/2949-1835-2025-4-4-37-43

Introduction. The concept of integrated lifecycle management is a solid component of the modern management toolkit, acting as a major factor in optimizing functioning of diverse facilities, from individual products to large-scale projects and complex systems [1, 2]. This concept has a particularly important role to play in the construction industry, where it serves as a foundation for organizing effective operation and management of real estate, first and foremost, capital structures for a broad range of purposes [3, 4].

The introduction of a comprehensive approach to lifecycle management allows for the design of an integrated system of regulation and control at all stages of a facility life cycle, starting from the design and ending with the decommissioning stage. This approach ensures not only the rational use of resources at each stage, but also helps one to strike an optimal balance between the operational characteristics, economic efficiency and technological parameters of a facility [1–3].

In the context of the construction industry, this concept is gaining momentum as it allows accounting for the specific features of capital facilities, their long-term use and need for constant technical condition monitoring. At the same time, a comprehensive approach serves a solid foundation for innovative technologies, cost optimization and quality improvement of construction products at all of their life cycle stages [4].

In the construction industry, engineering systems are a vital component of infrastructural support of buildings and structures creating optimal or acceptable microclimate parameters and ensuring comfort. In spite of the high relevance of these systems for efficient operation of construction facilities, the field of modeling their life cycle, including information, has not been sufficiently studied in the academic environment and is currently fragmentary in research literature [5–7]. This results in a major gap in developing the theoretical foundations of engineering systems management throughout all of their operation stages.

Modern district heating systems must account for a host of factors, such as increasing urbanization, growing demand for comfort, and the ability to customize the microclimate. Traditional methods of designing and managing heat supply systems often fail to address these challenges resulting in design errors, unjustified material costs during construction, energy overruns, increased heat loss and reduced operational reliability.

Organizations designing heat supply systems are facing a few difficulties, including the need to increase energy efficiency, reduce the cost of designing and building systems, and tackle the environmental issues. Lately a major problem has been the lack of design professionals in the field of developing full-volume information models of heat supply systems. One of the key tools for addressing the above problems is the use of artificial intelligence (AI).

In the article the authors are exploring the possibility of improving the efficiency of the design stage of district heating systems based on the use of artificial intelligence, as well as the advantages and prospects of this approach.

Materials and Methods. As part of the study, a comprehensive analysis of the life cycle of the heat supply system of buildings and structures was conducted by means of the method of analogies, comparative and systemic synthesis. A detailed study of the stages of the life cycle, including design, installation, operation and modernization, is a testimant of the possibility of developing an adaptive control mechanism for the system at all its stages.

The subject of the study was the district heating supply system, and the main aim is to examine the use of artificial intelligence for complete design automation, a major life cycle stage, which provides energy effectiveness, efficiency, reliability and environmental friendliness of future heat supply systems.

The use of artificial intelligence technologies will enable one not only to systematize the accumulated scientific and practical data, but also to identify patterns of functioning of a heat supply system, which will open up new prospects for optimizing its life cycle and increasing energy effectiveness.

Research Results. In modern conditions of urban infrastructure development, district heating systems are characterized by a variety of constructive and technical solutions. The constantly expanding range of main and auxiliary equipment causes some difficulties while choosing a district heating system. This calls for a meticulous consideration of the numerous parameters and characteristics of each element of the complex engineering structure of a district heating system. The task of developing a methodology for selecting the optimal district heating system capable of providing the required level of efficiency, safety and economic feasibility at minimal operating costs is highly relevant. An integrated approach to addressing this problem calls for a comprehensive analysisis of all the aspects of functioning of a system throughout its life cycle.

It makes perfect methodological sense to investigate the life cycle of a district heating system through implementing five consecutive stages: pre-design preparation, design, direct operation, modernization and disposal (Fig. 1).

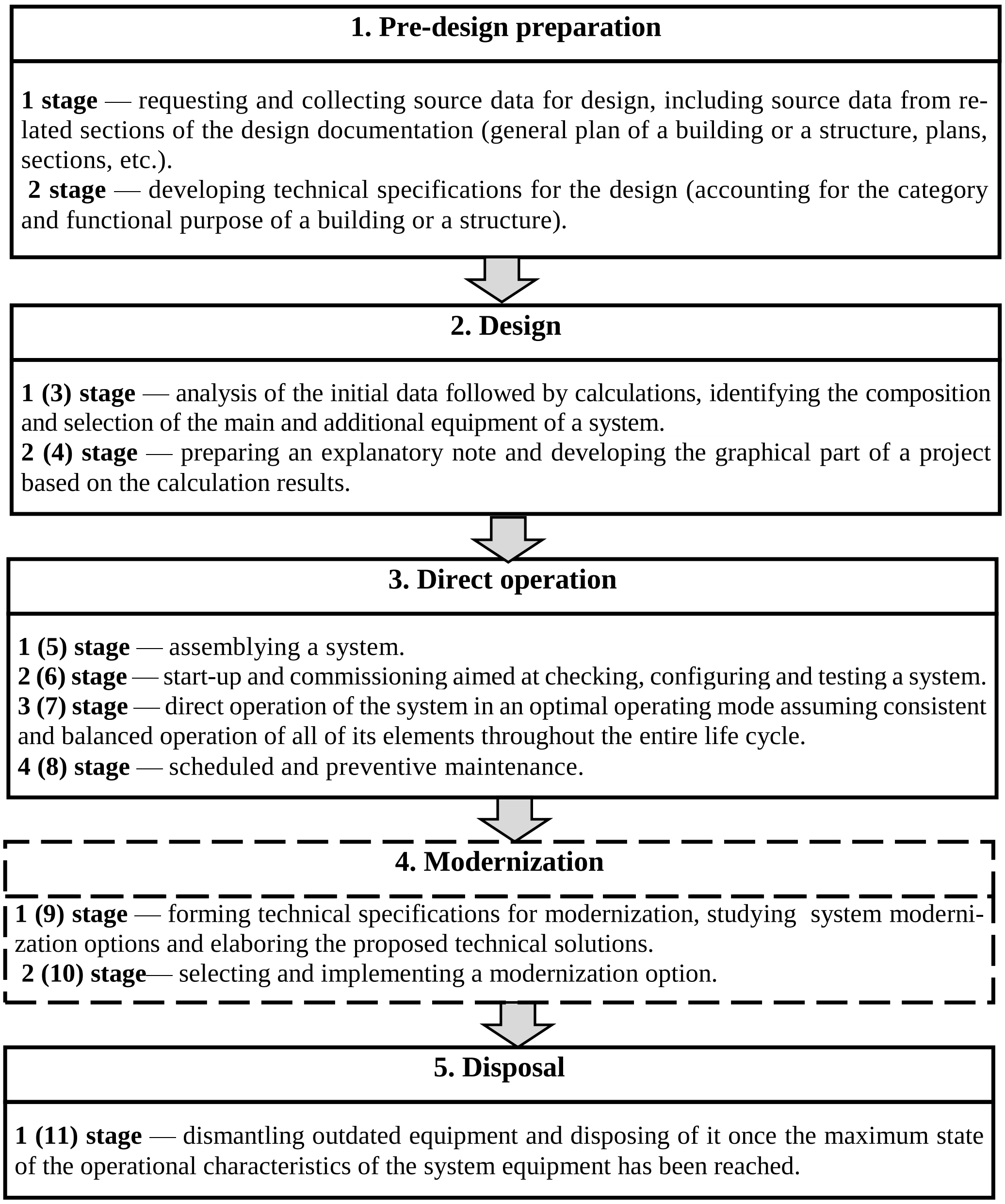

Fig. 1. Structure of the life cycle of the central heating system of a construction facility

Each of these stages is characterized by the implementation stages where the current state of a system, required set of works and the expected outcomes are identified. The analysis of the stages allows us to form a holistic view of functioning of the district heating system and to develop recommendations for optimizing its operation in the long run.

The design stage of district heating systems is particularly relevant, as this stage that is central for energy effectiveness and reliability of future heat supply facilities. However, the acute lack of qualified design specialists, particularly in the field of developing comprehensive information models of heat supply systems, might significantly undermine the quality of design documentation and the efficiency of future heating systems. As a result, the design time, number of design errors and as well as construction cost are on the rise due to some adjustments to be made [8].

Digital transformation of design serves as a strategic tool for improving the quality of design documentation and ensuring the reliability of thermal power facilities [9–11]. Automated design systems are a set of software and hardware tools that implement algorithmic modeling and optimization of design solutions. Their implementation makes it possible to mitigate the risks associated with a lack of highly qualified specialists and ensure a required level of quality of project documentation. The major task of computer-aided design is to create a system capable of analyzing input data (geographical, climatic, technical) and to generate optimal design solutions with minimal human involvement [12–14].

Artificial intelligence provides unique opportunities for complete design automation (information model development) of a heat supply system at all of its stages [15–17]. Artificial intelligence allows heat consumption to be accurately predicted, hydraulic modes to be stabilized and energy losses to be minimized. This enables one not only to reduce fuel costs, but also to address the environmental issues by cutting CO_2 emissions.

Automation of the design stage in the lifecycle of a district heating system allows the stages to be included implementing the following:

– developing an engineering digital model of an area (engineering surveys);

– placing heat consumers on the topplane;

– applying main and intra-block heating networks based on a geodetic substructure;

– developing a longitudinal profile of the heating networks;

– collecting and analyzing data (collecting data on the heat consumption, temperature fluctuations, etc.);

– conducting hydraulic calculations and developing thermal and hydraulic modes of a system;

– developing a mathematical model (based on the collected data, a mathematical model is created for predicting thermal and hydraulic conditions with a high degree of accuracy).

The use of artificial intelligence in the design phase of district heating systems adds a new element — machine learning – for predicting heat loads.

Artificial intelligence is trained mostly on regulatory documents in order to identify the technological limitations and best examples of design solutions for developing optimal "thinking" of artificial intelligence.

The following are applicable for accurate prediction of thermal loads:

1) regression analysis methods and neural networks (e.g., LSTM networks) capable of accounting for time series of data such as ambient temperature, historical heat consumption, and socio-economic factors;

2) genetic algorithms for optimizing network configuration (in order to identify the optimal topology of a heating network, minimize a pipeline length, pressure loss and construction cost; each solution is encoded as a chromosome, and optimization includes crossing, mutation and selection of the most effective options);

3) neural network models for hydraulic calculations (artificial neural networks are used to simulate hydraulic modes in complex branched networks; network training is based on the data obtained from numerical simulations of the behavior of complex systems or processes for quick evaluation of the system parameters — pressure, coolant flow — while operating conditions change);

4) integration with GIS systems (to account for some geographical factors (relief, location of buildings, infrastructure), it is suggested that the design system is integrated with geographic information systems (GIS); this enables automatic generation of heating network maps and spatial data analysis);

5) testing and optimization (the developed system is tested on real data and then optimized for a maximum efficiency);

6) validation and verification of the digital information model of the heat supply system;

7) transfer of a digital information model of a heat supply system using XML schemas to the next stage of the lifecycle of a system.

Discussion and Conclusion. Introduction of automated design systems is not merely a technological trend, but rather an objective necessity owing to the current requirements for energy effectiveness and reliability of district heating systems. Digital transformation of design is setting the stage for new quality of design solutions ultimately resulting in optimization of capital investments and operating costs at all of the stages of the life cycle of thermal power facilities.

The use of artificial intelligence in the design of heat supply systems provides a few major advantages:

– addresing the lack of qualified design engineers;

– a sharp reduction in the design time while improving the quality of projects;

– a possibility of employing the resulting digital information model of a heat supply system at subsequent stages of the life cycle of a system.

Designing a heat supply system by means of artificial intelligence is a promising area that is capable of greatly improving the efficiency of heat and power management processes. Introduction of such systems facilitates energy-saving, addresses the environmental issues and creates a comfortable living environment. Such technologies are expected to be further developed and improved, making them even more sought-after in the field of thermal energy.

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EP Lysova: aims of the study, analysis of the research results, correction of the conclusions.

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Predicting the Load-Bearing Capacity of Square-Section Pipe-Concrete Columns Using Machine Learning Methods

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Abstract
Introduction. In this paper, we consider the problem of predicting the strength of square-section centrally compressed short concrete-filled tubular columns using machine learning methods. Traditional methods, such as the finite element method and the theoretical-experimental approach involving selection of empirical formulas require significant computational resources and time. At the same time, these methods are not always capable of accounting for complex nonlinear dependencies between the parameters. The key objective is to develop a high-precision model capable of predicting the load-bearing capacity of columns using the major parameters.
Materials and Methods. For the current study, a database was generated containing the results of numerical experiments on calculating the load-bearing capacity of square-section concrete-filled tubular columns in a physically nonlinear formulation. As part of the study, models based on machine learning methods were designed and implemented using the Jupyter Notebook interactive computing platform. The main method is the CatBoost mechanism (Gradient Boosting Regressor). The resulting models were trained by means of nonlinear optimization methods.
Results. The article evaluates the degree of impact of each of the input parameters on the final predictions of the model. The results on the degree of impact for the CatBoost and Random Forrest Regressor (RFR) models are obtained. The quality of the resulting models evaluated using the R^2 value was 98% for CatBoost and 94% for RFR.
Discussion and Conclusions. The resulting approach has proved to be highly efficient in predicting the load-bearing capacity of concrete-filled tubular columns, providing a balance between the accuracy of the results and computational complexity.

Keywords: concrete-filled tubular columns, machine learning methods, prediction, load-bearing capacity, artificial intelligence, artificial neural networks

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Оригинальное эмпирическое исследование

Прогнозирование несущей способности трубобетонных колонн квадратного сечения при помощи методов машинного обучения

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Аннотация
Введение. В данной работе рассматривается задача прогнозирования прочности центрально сжатых коротких трубобетонных колонн квадратного сечения с использованием методов машинного обучения. Традиционные методы,

такие как метод конечных элементов и теоретико-экспериментальный подход с подбором эмпирических формул, требуют значительных вычислительных ресурсов и времени. В то же время эти методы не всегда способны учитывать сложные нелинейные зависимости между параметрами. Основная цель — разработка высокоточной модели, способной предсказывать несущую способность колонн на основе ключевых параметров.

Материалы и методы. Для исследования была сгенерирована база данных, состоящая из результатов численных экспериментов по расчету несущей способности трубобетонных колонн квадратного поперечного сечения в физически нелинейной постановке. В рамках проведенного исследования построены модели на основе методов машинного обучения, реализованные с использованием интерактивной вычислительной платформы Jupyter Notebook. Основным методом является механизм CatBoost (Gradient Boosting Regressor). Обучение построенных моделей произведено с использованием методов нелинейной оптимизации.

Результаты исследования. В статье проведена оценка степени влияния каждого входного параметра на итоговые предсказания модели. Получены результаты по величине степени влияния для моделей CatBoost и Random Forrest Regressor (RFR). Оценка качества построенных моделей по величине R^2 составила 98 % для CatBoost и 94 % — для RFR.

Обсуждение и заключение. Разработанный подход демонстрирует высокую эффективность в задаче прогнозирования несущей способности трубобетонных колонн, обеспечивая баланс между точностью результатов и вычислительной сложностью.

Ключевые слова: трубобетонные колонны, методы машинного обучения, прогнозирование, несущая способность, искусственный интеллект, искусственные нейронные сети.

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Introduction. Evaluating technical condition of monolithic reinforced concrete structures is remaining an urgent and common task, particularly considering there is a need to ensure they are durable and safe. This can be addressed not only by means of analytical and computational methods [1–3], but also using the more up-to-date reputable methods of artificial intelligence (AI) and machine learning (ML) [4–6].

The commonly used finite element method (FEM) enables complex physical processes such as the nonlinear behavior of materials, interaction of steel and concrete [7], as well as the influence of a range of loads to be accounted for [8]. However, the major drawback of the FEM is its high computational complexity and the need for a large number of parameters in order to calibrate the model.

ML methods are a modern data analysis tool allowing one to identify complex nonlinear dependencies between input and output parameters [9–11]. Unlike empirical formulas, machine learning enables patterns to be automatically identified in large amounts of data making it a more versatile and efficient prediction method.

In [12], the authors examine the formation of defects in reinforced concrete structures by means of artificial intelligence algorithms such as random forest (RF), support vector machine (SVM), classification and regression tree (CART), and gradient boosting.

In modern practice, convolutional neural networks (CNN) are being increasingly used in order to predict the strength of reinforced concrete structures [13–15]. E.g., in [13], the authors developed a CNN that is capable of two-dimensional full-scale prediction of crack formation at early stages and description of the entire fracture process. A model capable of predicting both crack initiation and propagation was set forth in [14]. In order to monitor the condition of reinforced concrete structures at complex construction sites, the authors of [15] made use of a fully convolutional neural network (FCN) to segment images and localize cracks on concrete surfaces, accounting for the heterogeneity of concrete properties. The resulting FCN model minimizes false positive and false negative results and is also of high quality, which enables small and complex cracks to be segmented.

In [16], an automated classifier was developed that also functions as a tool for automatic detection and classification of cracks in reinforced concrete columns of different levels of complexity by means of deep CNN (DCNN) methods. The suggested DCNN model analyzes complex textures as well as noises and displays high crack detection accuracy of 96% due to the depth of the model layers and expansion of each layer in a parallel manner.

In order to predict cracks in time, the authors of [17] made a step forward in their research and designed a hybrid model combining DCNN and recurrent neural networks (RNN).

Hence there is no doubt that ML algorithms have a few advantages, such as identifying patterns in large amounts of data, detecting hidden patterns and dependencies accounting for the multidimensional nature of data, automatic analysis of evaluating the condition of reinforced concrete structures using the major parameters, optimization of ML algorithms and parallel computing.

However, these ML algorithms have some drawbacks, such as inaccuracy or weakness, limited generalization ability, and low-speed operation [18, 19]. One of the key ones is the dependence of machine learning models on the quality of training data and its volume.

While training most artificial intelligence models, data from field experiments is used in order to predict the strength of concrete-filled tubular columns [20–22]. Such experiments are typically conducted on samples with relatively small cross-sectional dimensions compared to actual structures. Considering the poor ability of machine learning methods to extrapolate data, serious errors are likely while predicting the load-bearing capacity of actual structures. A solution would be to make use of a combined approach, where training data is generated by means of a finite element calculation of structures with actual dimensions using a method validated based on experimental data.

The objective of the study is to develop machine-learning models for predicting the strength of centrally compressed square-section concrete-filled tubular columns using the data obtained as described above.

Materials and Methods. A database was generated for this study representing the results of numerical experiments in order to calculate the load-bearing capacity of short square-section concrete-filled tubular columns according to the methodology described in [23]. That data was used in order to develop and analyze models combining the traditional methods of structural mechanics and machine learning algorithms.

The input parameters describing the basic geometric as well as physical and mechanical characteristics of the columns were generated in uniform increments in the ranges typical of actual structures, which enabled a wide range of possible combinations to be covered.

The key parameters are as follows: a is the external size of the column cross section, mm; t is the wall thickness of a steel square tube, mm; R_y is the yield strength of steel, MPa; R_b is the compressive strength of concrete, MPa.

The output parameter is the load-bearing capacity of the concrete-filled tubular columns N_{ult}, kN. This indicator was obtained as a result of numerical experiments performed according to the methodology described in [24]. The calculations accounted for the complex interaction of the steel tube and the concrete core, including the joint operation of the materials and their deformation behavior.

The analyzed data array is partially shown in Table 1. The training sample included the total of 22,308 items.

Table 1

Table of the generated data

No.	a, mm	t, mm	R_y, MPa	R_b, MPa	N_{ult}, kN
1	100	3.00	220	10	349.71
2	100	3.45	220	10	385.27
3	100	3.91	220	10	420.72
4	100	4.36	220	10	455.76
5	100	4.82	220	10	490.38
6	100	5.27	220	10	524.59
7	100	5.27	220	10	524.59
8	100	5.73	220	10	558.38
9	100	6.18	220	10	591.76
10	100	6.64	220	10	625.31
11	100	7.09	220	10	657.89
…	…	…	…	…	…
22.299	500	10.55	840	120	44248.28
22.300	500	11.82	840	120	45887.56
22.301	500	13.09	840	120	47511.10
22.302	500	14.36	840	120	49118.97
22.303	500	15.64	840	120	50759.78
22.304	500	16.91	840	120	52338.05
22.305	500	18.18	840	120	53900.79
22.306	500	19.45	840	120	55501.41
22.307	500	20.73	840	120	57089.77
22.308	500	22.00	840	120	58609.37

In order to improve the quality of the models, data preprocessing was performed: normalization, data separation, and cross-validation. The values of each parameter were scaled in the range (0–1) in order to prevent the features with large values from dominating. The generated data was divided into the training (80%) and test (20%) arrays for the model training and evaluation.

The following machine learning algorithms were used to analyze the data and design models for predicting the strength of centrally compressed square-section concrete-filled tubular columns: Linear Regression, Decision Tree, Gradient Boosting, Random Forest Regressor, RFR.

The regularization method was used to normalize the parameters, the Optuna method for optimization, and GridSearchCV and RandomizedSearchCV for hyperparameter selection. The range of parameter values for the CatBoost model was: iterations — 1000–1500; depth — 4–8; learning_rate — 0.1–0.6; l2 reg_lambda — 1.9–4.9. For RFR: n_estimators — 100–250; max_depth — 10–20; min_samples_leaf — 1–4. As the RFR model has no iteration tracking option, model training is possible with a different number of trees and root mean square error (MSE) analysis. With a small number of trees, the RFR model is undertrained and displays a low quality score. As the number of trees increases, the MSE score gets stabilized and the quality score of the model becomes satisfactory.

For the trained models, the significance of the features was also analyzed by evaluating the degree of impact of each input parameter on the final predictions of the model. This approach allowed us to identify an extent to which the prediction results change when do the values of a certain feature.

Research Results. The statistical characteristics of the initial data set are shown in a table (Table 2). The main indicators are as follows: sample size, sample mean, variation dispersion, extremes of the variable values. All of these indicators help to statistically analyze the variables, identify their range in relation to their centre, show the asymmetry of the distribution, and deduce the distribution laws of these variation rows.

Table 2

Table of the statistical characteristics

Parameter	a, mm	t, mm	R_y, MPa	R_b, MPa	N_{ult}, kN
Number	22308	22308	22308	22308	22308
Mean	253.85	9.92	530.00	65.0	10564.50
Standard deviation	128.40	5.06	196.07	34.3	10419.09
min	100.00	3.00	220.00	10.0	349.71
max	500.00	22.00	840.00	120.0	58609.37

Fig. 1 shows the correlation between the model parameters. There is a strong correlation ($0.6 \le |\rho| \le 0.9$) between the parameters: the external size of the column cross-section and the wall thickness of the steel square tube ($\rho_{a/t} = 0.7$); the external size of the column cross-section and the load-bearing capacity of the concrete-filled tubular columns ($\rho_{a/N_{ult}} = 0.88$); the wall thickness of the steel square tube and the load-bearing capacity of concrete-filled tubular columns ($\rho_{t/N_{ult}} = 0.73$).

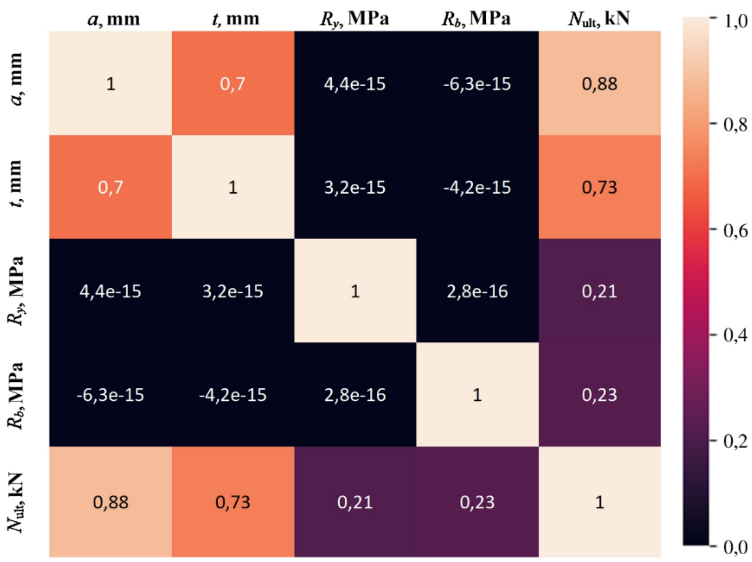

Fig. 1. Correlation matrix

The study focused on the CatBoost gradient boosting algorithm that showed the best results among the tested algorithms (R^2 = 0.98).

The most significant parameter of the CatBoost model is the external cross-sectional dimension of the column, its significance is 96%, the impact of the compressive strength of concrete was 33%, the yield strength of steel was 28%, and the wall thickness of the square steel tube was 20%. The most significant parameters of the RFR model and their degree of importance were distributed as follows: the external cross-sectional dimension of the column was 92%, the compressive strength of concrete was 21%, the yield strength of steel was 17%, and the wall thickness of the square steel tube was 14%. The significance of the influencing factors for both models coincides, and the quantitative assessment of the contribution of each feature is clearly shown in Fig. 2 and 3, respectively.

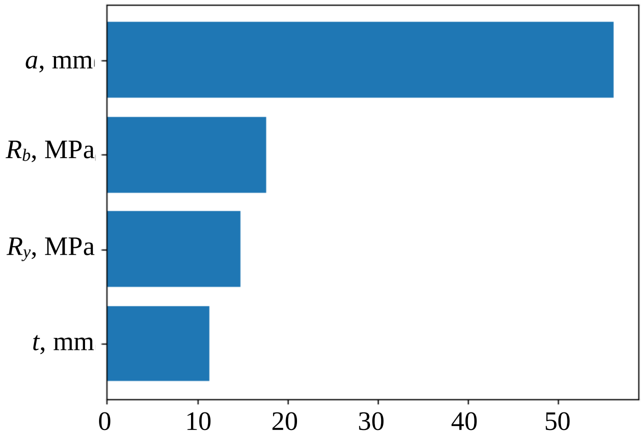

Fig. 2. Evaluation of the signifance of the features for CatBoost

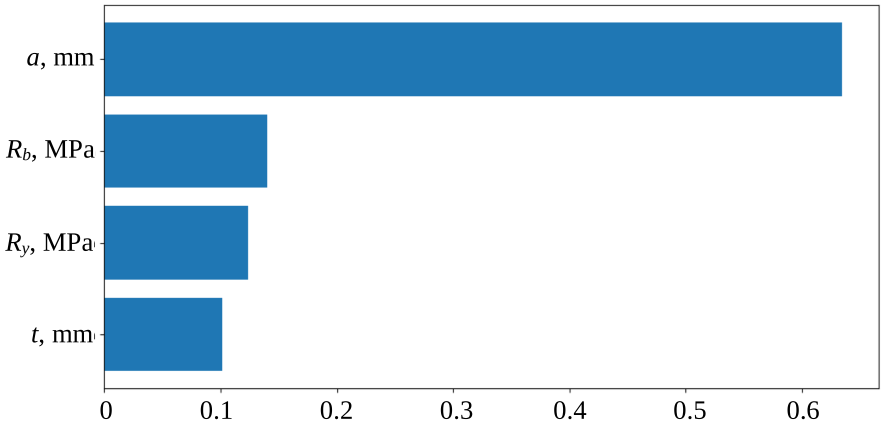

Fig. 3. Evaluation of the signifance of the features for RFR

The optimal parameter values obtained during the model training are shown in Table 3.

Table 3

Optimal values of the model parameters

Model	Parameter	Value
CatBoost	Iterations	1500
	Depth	5
	Learning rate	0.4
	l2 leaf reg	2.8
RFR	N estimators	180
	Max depth	6
	Min samples leaf	1

The evaluation of the quality of the models is shown in Table 4.

Table 4

Model quality metrics

Metrics/Model	CatBoost	RFR
MAE	3.1	7.8
MSE	5.4	4.5
MAPE, %	0.015	0.007
R^2	0.98	0.94

Fig. 4 and 5 show the error histograms: the actual values along the ordinate axis and the predicted ones along the abscissa axis.

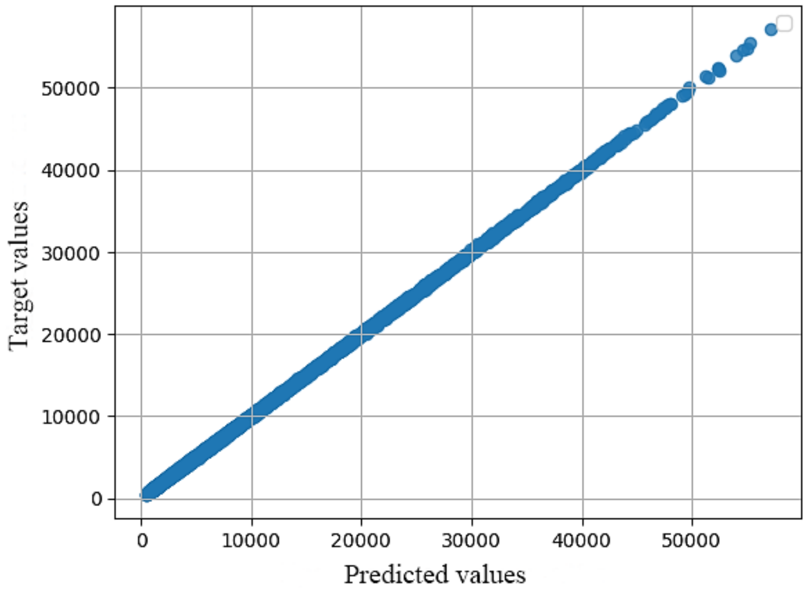

Fig. 4. Error histogram for CatBoost

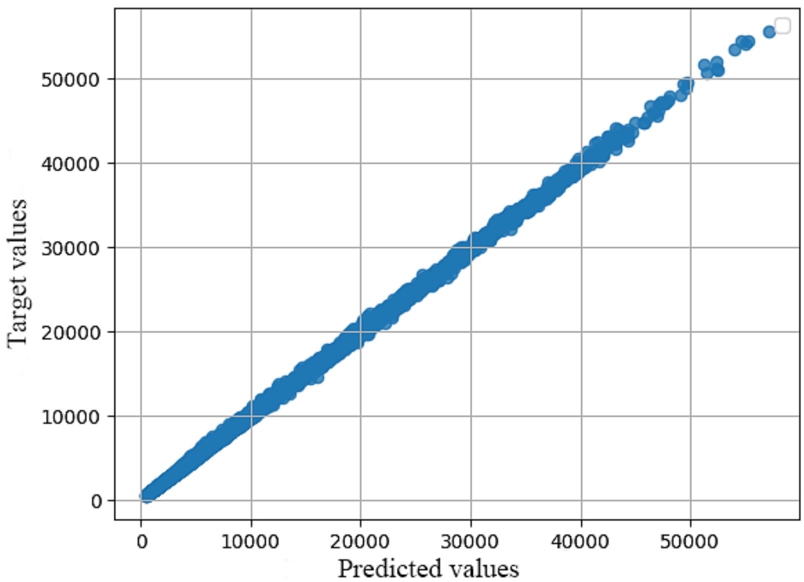

Fig. 5. Error histogram for RFR

Discussion and Conclusion. This study has provided a comprehensive overview of the existing methods for predicting the strength of concrete-filled tubular columns and outlines the advantages of using machine learning in this field.

The use of machine learning methods, particularly CatBoost, has enabled us to identify the precise dependencies between the parameters outperforming the traditional empirical methods. The prediction reliability using the R^2 value for the model based on the CatBoost algorithm was 0.98. The model based on the Random Forest Regressor method displayed a lower accuracy (R^2 = 0.94).

According to the analysis of the significance of the features, the external cross-sectional dimension of a concrete-filled tubular column is the major parameter that has the greatest impact on its load-bearing capacity.

In further studies, the range of model parameters based on the current results is going to be expanded considering some additional factors. The additional parameters can include the eccentricity of a longitudinal force, the flexibility of an element, the proportion of prolonged loads in the total loading, etc.

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Neural Network Modeling of the Strength of Normal Sections of Prefabricated Reinforced Concrete Ribbed Slabs

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Abstract

Introduction. Precast reinforced concrete ribbed slabs are broadly used as floors and coverings for industrial, residential and public buildings. Their use in this capacity is due to the high technological efficiency of manufacturing, efficient use of concrete and the possibility of automating factory production. One of the critical tasks in designing such structures is to calculate the bearing capacity of normal cross sections. Traditional calculation methods are reliable, but they are outdated. Machine learning methods are increasingly being employed in engineering, where researchers are opting for artificial neural networks (ANNs). The use of traditional methods in processing structured data such as tables and databases has its limitations. Neural networks are capable of analyzing unstructured data such as text, images, and videos, which opens up new prospects for analyzing and comprehending information. The article sets forth an approach to neural network modeling of the bearing capacity of normal sections of prefabricated reinforced concrete ribbed slabs.

Materials and Methods. A structured and processed data array (dataset) includes 20 samples for which a computational model based on a multilayer perceptron has been developed and verified. The input parameters are the geometric as well as physical and mechanical characteristics of the slabs and the applied load, the output parameter is the limiting bending moment calculated using the limit state method.

Research Results. Training on a limited sample did not lead to retraining of the model due to the correct division of data into test, training and control batches and the use of the quasi-Newton optimization method. The model has displayed a high level accuracy and reliability. Artificial neural networks are capable of identifying nonlinear dependencies between the parameters with no a priori assumptions.

Discussion and Conclusion. The suggested model is not a substitute for the existing calculations, but it serves as an efficient digital tool for quick verification of design solutions, optimization of reinforcement and improvement of structural reliability. Its implementation into BIM systems and digital construction platforms is in compliance with the requirements of Industry 4.0 and creates new opportunities for designing prefabricated reinforced concrete structures.

Keywords: ribbed reinforced concrete floor slab, bendable elements, artificial neural networks, machine learning

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Оригинальное эмпирическое исследование

Нейросетевое моделирование прочности нормальных сечений сборных железобетонных ребристых плит

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Аннотация

Введение. Сборные железобетонные ребристые плиты получили широкое применение в качестве перекрытий и покрытий зданий промышленного, жилого и общественного назначения. Их использование в данном качестве обусловлено высокой технологичностью изготовления, эффективным использованием бетона и возможностью автоматизации производства на заводах. Одной из важных задач при проектировании таких конструкций является расчет несущей способности нормальных сечений. Традиционные методы расчёта являются надежными, но морально устарели. Сейчас в инженерной практике всё чаще применяются методы машинного обучения, где исследователи делают выбор в пользу искусственных нейронных сетей (ИНС). Использование традиционных методов при обработке структурированных данных, таких как таблицы и базы данных, имеет свои ограничения. Нейросети способны анализировать неструктурированные данные, такие как текст, изображения и видео, что открывает новые возможности для анализа и понимания информации. В статье предложен подход к нейросетевому моделированию несущей способности нормальных сечений сборных железобетонных ребристых плит.

Материалы и методы. Структурированный и обработанный массив данных (датасет) включает 20 образцов, для которых разработана и верифицирована расчётная модель на основе многослойного персептрона. Входными параметрами служат геометрические и физико-механические характеристики плит и величины приложенных нагрузок, выходной параметр — предельный изгибающий момент, вычисленный по методу предельных состояний.

Результаты исследования. Обучение на ограниченной выборке не привело к переобучению модели благодаря корректному разделению данных на тестовую, обучающую и контрольную партии и использованию квазиньютоновского метода оптимизации. Модель продемонстрировала высокую точность и надёжность. Искусственные нейронные сети успешно выявляют нелинейные зависимости между параметрами без априорных допущений.

Обсуждение и заключение. Предложенная модель не заменяет существующие расчёты, но служит эффективным цифровым инструментом для быстрой проверки проектных решений, оптимизации армирования и повышения надёжности конструкций. Её внедрение в системы BIM и цифровые платформы строительства соответствует требованиям Индустрии 4.0 и создает новые возможности для проектирования сборных железобетонных конструкций.

Ключевые слова: ребристая железобетонная плита перекрытия, изгибаемые элементы, искусственные нейронные сети, машинное обучение

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Introduction. In modern industrial and civil engineering, prefabricated reinforced concrete ribbed slabs are still one of the most sought-after solutions for building floors and coverings due to a combination of cost-effectiveness, reliability and adaptability they offer. Their use is justified by a high degree of factory readiness, ease of mass serial production, and the optimal cross-sectional shape that minimizes concrete consumption while providing the necessary bearing capacity and deformability.

The calculation of the strength of normal sections of ribbed slabs is an essential part of the calculations for the 1st group of limit states. Traditional calculation methods provided in SP (СП) 63.13330.2018 "Concrete and Reinforced Concrete Structures. Main Provisions" are reliable and reputable, but over the past two decades, machine learning methods have been increasingly used in engineering. Researchers most often opt for artificial neural networks (ANNs). The advantage of ANNs is their capacity to identify hidden non-linear relationships between a set of input parameters and a target variable. Unlike analytical models, ANNs do not call for a priori specification of functional dependencies making them of a particular value, especially for identifying the bearing capacity of building structures. The issues of information modeling in calculating building structures and using artificial intelligence in this field have been elaborated in Russian [1–8] and overseas [9–16] technical literature.

The aim of the study is to develop and verify a neural network model for predicting the bearing capacity of normal sections of prefabricated reinforced concrete ribbed slabs.

Materials and Methods. The objects of the study were 20 ribbed slabs with a cross-section width from 1460 to 1150 mm, a working height from 370 to 240 mm and a span from 4550 to 8100 mm. For more information about the dataset, see Table 1.

Table 1

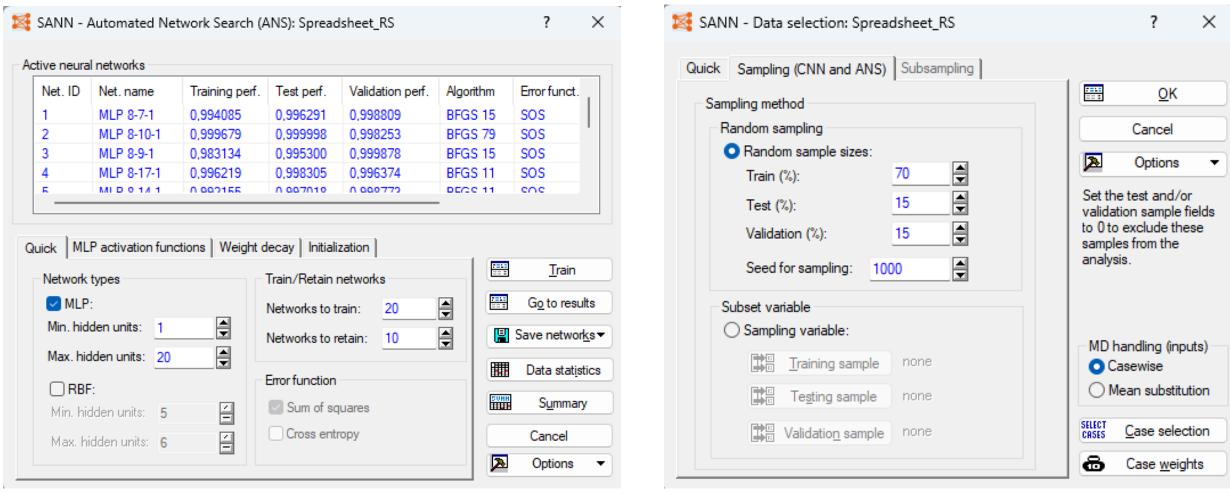
Characteristics of ribbed reinforced concrete slabs

No.	$b_f^{'}$, mm	h_0, mm	b, mm	l_0, mm	q, kN/m	R_b, MPa	R_s, MPa	A_{sp}, cm^2	M_{ult}, kNm
1	1460	370	150	6250	16.95	17	695	4.40	124.15
2	1160	370	185	7080	19.60	17	870	6.08	147.39
3	1160	344	185	7900	11.93	22	1215	2.49	111.70
4	1150	270	150	5675	18.15	17	520	5.88	87.70
5	1360	344	185	8100	18.66	22	1300	4.51	214.25
6	1360	344	185	8100	17.40	17	1300	2.27	94.54
7	1450	240	150	5400	16.90	17	1250	2.88	92.40
8	1450	270	150	7050	16.89	17	1390	3.23	157.42
9	1450	270	150	4700	11.31	17	1390	1.15	46.84
10	1360	260	185	4690	17.54	22	1130	2.12	67.52
11	1460	370	150	6200	17.05	17	690	4.50	128.20
12	1160	370	185	7050	19.30	17	880	5.98	145.10
13	1160	344	185	7850	11.53	22	1190	2.53	115.10
14	1150	270	150	5700	18.25	17	530	6.05	90.30
15	1360	344	185	8000	18.82	22	1300	4.61	220.10
16	1360	350	185	8050	17.00	17	1250	2.05	93.38
17	1450	240	150	5350	16.50	17	1250	2.72	90.50
18	1450	270	150	7000	16.68	17	1390	3.18	156.10
19	1450	270	150	4750	11.33	17	1390	1.19	49.92
20	1360	260	185	4550	17.24	22	1130	1.95	65.23

The following parameters are provided for each plate: the reduced shelf width $b_f^{'}$ (x_1), working height h_0 (x_2), reduced rib width b (x_3), estimated span l_0 (x_4), applied evenly distributed load q (x_5), prismatic concrete strength R_b (x_6), yield strength of steel reinforcement R_s (x_7), cross-sectional area of the prestressed reinforcement A_{sp} (x_8) and the limit bending moment M_{ult} (y). The latter will be the result of the prediction of the neural network model in the future. The limit bending moments are calculated using the limiting state method.

In order to design the neural network model, the STATISTICA 14.0 software package was used with the Neural Networks module providing the implementation of the architecture as a multi-layer perceptron with reverse error propagation. Designing the neural network as a multi-layer perceptron is due to the special features of the task at hand. The artificial neural network includes three layers. The input layer consisted of the above 8 independent variables. The number of neurons in the hidden layer ranged from 1 to 20. After passing through the hidden layer, the signal, transformed at each stage with the corresponding activation functions, entered the output layer containing a single dependent variable, M_{ult} (y). Each of the neurons of the hidden and output layers is connected to all of the neurons in the previous layer.

The dataset size allowed us to obtain the optimal ratio of the training, test, and control samples in percentage rates of 70, 15, and 15, respectively. The number of epochs (training cycles) is 1000 (Fig. 1). All the activation functions were tested at each stage to process the incoming signals (Fig. 2).



a) *b)*

Fig. 1. Characteristics of the neural network model: a — for a random selection; b — for the hidden layer and the ANN training

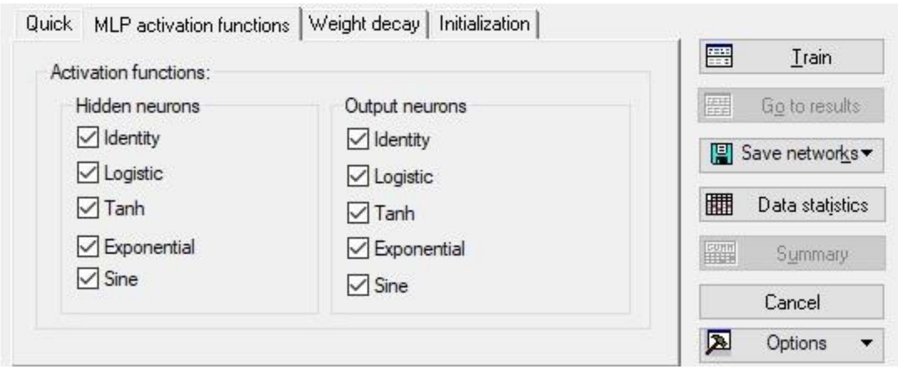


Fig. 2. Selected activation functions of the hidden and output layer of the neurons

The Broyden-Fletcher-Goldfarb-Shanno algorithm (BFGS) is one of the most efficient quasi-Newton optimization methods for training artificial neural networks. The loss function with weights is iteratively minimized. As part of the ongoing study, this algorithm was used in order to adaptively update network parameters based on the approximation of the inverse Hesse matrix allowing us to account for the second derivatives of the error function without explicitly calculating them. The Sum of squares (SOS) given by formula (1) was used as the objective function:

$$E\left(w_{ij}\right) = \sum_{i=1}^{m}(y_i - y_i')^2, \tag{1}$$

where y_i is the output value of the i-th neuron of the output layer; y_i' is the required value of the i-th neuron of the output layer.

The training was carried out iteratively, i.e., at each stage (epoch), all the observations were the sequential input, and the resulting values were compared with the target ones and the corresponding error was calculated. In the STATISTICA software package, the calculation results are presented in a table. The accuracy of the neural network forecasting results was estimated by comparing the results of the designed model with the experimental values and was calculated using the formula (2):

$$\delta = \frac{y_{i\text{инс}} - y_i}{y_i} \cdot 100\%, \tag{2}$$

where $y_{i\text{ANN}}$ is the value of the destructive bending moment obtained during prediction using ANN in the first test; y_i is the actual value of the breaking bending moment in the ith test.

10 MLP architectures with the number of hidden layers from 2 to 19 were tested (Fig. 3 and 4). The best results were shown by a neural network with the MLP 8-9-1 architecture highlighted in a green frame.

Net. name	Training perf.	Test perf.	Validation perf.	Training error	Test error	Validation error	Training algorithm	Error function	Hidden activation	Output activation
MLP 8-7-1	0,994085	0,996291	0,998809	10,62153	16,48046	9,93623	BFGS 15	SOS	Logistic	Identity
MLP 8-10-1	0,999679	0,999998	0,998253	0,69092	0,07326	15,30478	BFGS 79	SOS	Tanh	Tanh
MLP 8-9-1	0,983134	0,995300	0,999878	31,72447	12,67781	58,40971	BFGS 15	SOS	Identity	Tanh
MLP 8-17-1	0,996219	0,998305	0,996374	6,83131	18,37588	20,66575	BFGS 11	SOS	Tanh	Identity
MLP 8-14-1	0,992155	0,997018	0,998773	13,76911	21,46851	20,28928	BFGS 11	SOS	Identity	Identity
MLP 8-13-1	0,984357	0,998660	0,999682	28,98711	6,83088	53,70908	BFGS 21	SOS	Tanh	Tanh
MLP 8-11-1	0,992339	0,997115	0,999887	13,50086	16,44569	11,82677	BFGS 11	SOS	Tanh	Identity
MLP 8-19-1	0,995462	0,996490	0,998304	8,10334	15,24956	9,80945	BFGS 11	SOS	Logistic	Identity
MLP 8-9-1	0,998522	0,997551	0,998666	2,71952	7,02600	9,66670	BFGS 34	SOS	Tanh	Exponentia
MLP 8-2-1	0,999066	0,998745	0,998871	1,76863	4,50505	4,40192	BFGS 58	SOS	Logistic	Exponentia

Fig. 3. Characteristics of the resulting ANNs

Net. name	Training perf.	Test perf.	Validation perf.	Training error	Test error	Validation error	Training algorithm	Error function	Hidden activation	Output activation
MLP 8-9-1	0,983134	0,995300	0,999878	31,72447	12,67781	58,40971	BFGS 15	SOS	Identity	Tanh

Fig. 4. Characteristics of the best ANN

The values of the limiting bending moment according to the calculation and forecast of the selected ANN are shown in Table 2. It can also be seen whether each case belongs to the training or test series.

Table 2

Prediction results for the selected ANN

Case name	M_{ult} Target	Mult - Output 3. MLP 8-9-1
1	124,1500	127,8000
2	147,3900	149,7304
3	111,7000	118,3796
4	87,7000	81,9504
6	94,5400	100,3477
7	92,4000	101,5405
9	46,8400	41,1607
10	67,5200	71,4283
12	145,1000	147,2489
13	115,1000	114,5124
14	90,3000	90,6634
15	220,1000	196,9605
16	93,3800	84,6343
20	65,2300	62,0702

The average relative error of MLP 8-10-1 calculated using formula (2) is 5.6%. According to the graph (Fig. 6), the obtained model is highly accurate and is good at the task at hand. It is plain to see that there is only one case that is slightly removed from the diagonal, which is the ideal location of the prediction points. The other values predicted using the model only slightly deviate from the diagonal.

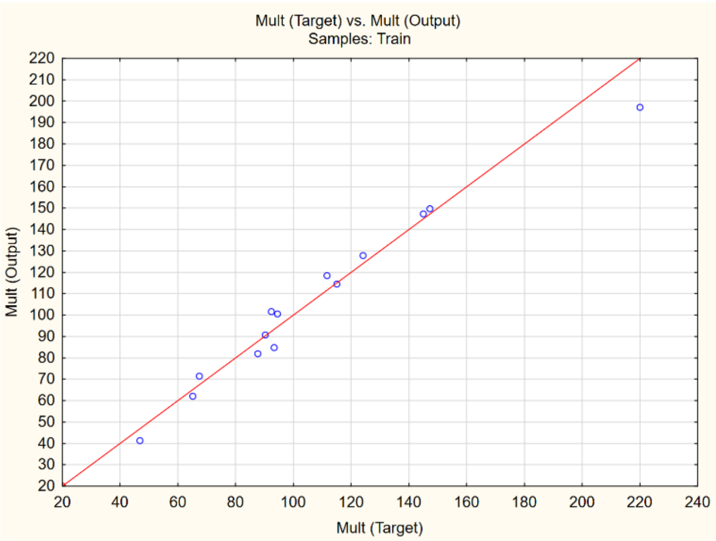


Fig. 6. The actual and prediction values M_{ult} ratio

The selected ANN has been "trained" to account for the existing implicit dependencies between all the parameters. It does not just "memorize" the data, but discovers physically justified patterns. The neural network model does not make use of any assumptions (regarding the shape of the stress plot, etc.), it is only trained on actual data. At the same time, as the size of the dataset increases, a significant rise in the accuracy of the suggested model is to be expected.

It is to be noted separately that it is not only the accuracy of the model that is an advantage, but also the calculation time using all the known methods, including numerical modeling, is inferior to neural networks. This is yet another argument in favor of further implementing ANNs in the design.

Research Results. The results serve to prove that artificial neural networks are a new viable approach to identifying the bearing capacity of bent elements and are an efficient method of the problem solution. The average ratios of actual and calculated destructive bending moments and their variation coefficients turned out to be 0.993 and 0.069, respectively. In spite of its high accuracy, to date ANN has not been able to substitute the other methods of calculating structures, but can be recommended as an additional digital tool for testing design solutions, optimizing reinforced concrete elements and improving structural reliability.

Discussion and Conclusion. The developed model can be integrated into BIM systems, which corresponds to the strategy of Industry 4.0. The successful application of ANNs in construction is a natural stage in the engineering science evolution. A further step might be developing an open API for accessing the model within a digital platform.

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Original Empirical Research

EDN: UBYKLB

Adhesive Strength of Wood Glue Joints with a Reinforcement Made from Used Band Saw Blades

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Abstract

Introduction. Due to the high volumes of lumber production in the Russian Federation, there is an issue of recycling used band saw blades (UBSB) with a service life of 20–500 hours. A way to tackle the problem at hand is to make use of UBSB as a reinforcement material for wood elements. This solution also contributes to a reduction in the cost of such structures by making a reinforcement material more affordable to purchase. This study focuses on investigating the adhesive strength of a UBSB-wood bond.

Materials and Methods. Studies of the adhesive strength of a “wood-reinforcement” adhesive joint have been a comparative analysis of the test results of samples with the inclusion of UBSB, as well as rods of a steel and composite reinforcement. Reinforcement elements were glued into pine wood blanks with an adhesive composition based on epoxy resin ED-20 (a hardener is polyethylene polyamine, a filler is quartz sand, a plasticizer is dibutyl phthalate). The tests were conducted by means of pulling out using the REM-100 machine at a speed of 5 mm/min. Statistical processing of the experimental results included the calculation of the average value of the destructive load for each group of the samples, as well as the variance, standard deviation, and coefficient of variation.

Research Results. The wooden samples with glued reinforcement bars showed a high strength of the wood–reinforcement joint which was close to the samples with a steel reinforcement with a difference of about 4% and was considerably beyond the strength of the samples with a composite reinforcement — up to 20%.

Discussion and Conclusion. The adhesive joint of wood with reinforcing elements made of reinforced concrete has a sufficiently high adhesive strength which was close to that of the samples with a steel reinforcement. Hence the use of UBSB as a material for reinforcing wooden elements and structures is an appropriate and efficient way of enhancing the performance of load-bearing structures made of wood. On top of that, such a solution would tackle the problem of the disposal of reinforced concrete, as well as to a degree reduce the cost of reinforced wooden structures (RWSs) "in action" due to the low cost of a reinforcing material.

Keywords*:* used band saws, wood reinforcement, adhesive strength, epoxy glue, wooden structures, waste disposal

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Оригинальное эмпирическое исследование

Адгезивная прочность клеевого соединения древесины с арматурой из отработанных полотен ленточных пил

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Аннотация

Введение. В связи с высокими объемами производства пиломатериалов в Российской Федерации возникает проблема по утилизации отработанных полотен ленточных пил (ОПЛП), срок службы которых составляет 20–500 часов. Одним из способов её решения является использование ОПЛП в качестве материала для армирования элементов из древесины. Такое решение способствует снижению стоимости «в деле» таких конструкций за счёт удешевления армирующего материала. Настоящая работа посвящена исследованию адгезионной прочности клеевого соединения ОПЛП с древесиной.

Материалы и методы. Исследования адгезивной прочности клеевого соединения «древесина–арматура» представляли собой сравнительный анализ результатов испытания образцов с включением ОПЛП, а также стержней стальной и композитной арматуры. Армирующие элементы были вклеены в заготовки из древесины сосны с применением клеевой композиции на основе эпоксидной смолы ЭД-20 (отвердитель — полиэтиленполиамин, наполнитель — кварцевый песок, пластификатор — дибутилфталат). Испытания выполнялись на выдергивание с помощью машины РЭМ-100 при скорости 5 мм/мин. Статистическая обработка результатов эксперимента включала расчет среднего значения разрушающей нагрузки для каждой группы образцов, а также дисперсии, стандартного отклонения и коэффициента вариации.

Результаты исследования. Деревянные образцы с вклеенными ОПЛП показали высокую прочность соединения «древесина–арматура», близкую к образцам со стальной арматурой с разницей значений около 4 % и значительно превышающую прочность образцов с композитной арматурой — до 20%.

Обсуждение и заключение. Клеевое соединение древесины с армирующими элементами из ОПЛП обладает достаточно высокой адгезионной прочностью, близкой к прочности образцов со стальной арматурой. Таким образом, использование ОПЛП в качестве материала для армирования деревянных элементов и конструкций является целесообразным и эффективным способом повышения эксплуатационных качеств несущих конструкций из древесины. Кроме того, такое решение позволит решить проблему по утилизации ОПЛП, а также несколько снизить стоимость армированных деревянных конструкций (АДК) «в деле» за счёт низкой стоимости армирующего материала.

Ключевые слова: отработанные ленточные пилы, армирование древесины, адгезивная прочность, эпоксидный клей, деревянные конструкции, утилизация отходов

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Introduction. The use of industrial waste for manufacturing reliable building structures is a trend in construction industry development regarding promoting environmental protection and environmental conservation [1]. In the Russian Federation, lumber production is accompanied by industrial waste accumulation, including used band saw blades with their service life limited to 20–500 hours with no recycling technologies in place [2]. The use of reinforced concrete as a material for reinforcing wood elements would tackle the problem of utilizing reinforced concrete, in addition, the cost of such structures "in action" would be lower due to a reduction in the cost of reinforcing material. It was noted in [3, 4] that reinforcement of wooden structures helps to increase their strength and rigidity, allows up to a 30% reduction in wood consumption and installation weight, the use of lower grades of wood, etc., which will enable a considerable reduction in the cost of building structures made of wood "in action" [5].

This study is dedicated to developing a method for reinforcing wooden structures (RWSs) using UBSB by examining the adhesive strength of the adhesive joint of such reinforcing elements with wood [6].

The scientific novelty of the work is a new method of reinforcing elements made of wood, the results of experimental studies of the adhesive strength of the wood–reinforcement joint using UBSB compared with reinforcing materials made of steel and composite reinforcement rods [7]. The aim of the work is to evaluate the adhesive strength of the wood–UBSB adhesive joint in comparison with the other types of reinforcement, such as steel and composite as well as to identify the degree of suitability of UBSB for manufacturing RWSs [8].

Materials and Methods. As part of the study, the adhesive strength of the wood–reinforcement joint was analyzed for three types of reinforcing materials:

– band saw blade with a cross-section of 1.2×25.6 mm and a variable tooth pitch of 10/14;

– steel reinforcement of a periodic profile with a nominal diameter of 8 mm;

– composite reinforcement of a periodic profile with a nominal diameter of 8 mm. Pulling tests were conducted on wooden blanks made of common pine wood with a cross-section of 50×50 mm [9].

Sample preparation. Three groups of samples (five models in each group) were produced with the following types of glued reinforcement elements (Fig. 1) [10]:

1. Bimetallic canvases (UBSB) with a cross section of 1.2×25.6 mm and a length of 200 mm (sample brand: BAP-1–BAP-5);

2. Steel reinforcement rods of periodic profile according to GOST 34028-2016 "Rolled Reinforcement for Reinforced Concrete Structures" with a diameter of 8 mm and a length of 200 mm (sample grade: BAD-01–BAD-05);

3. Rods of composite reinforcement according to GOST 31938-2022 "Composite Polymer Reinforcement for Reinforcing Concrete Structures" with a diameter of 8 mm and a length of 200 mm (sample grade: BAD-31–BAD-35).

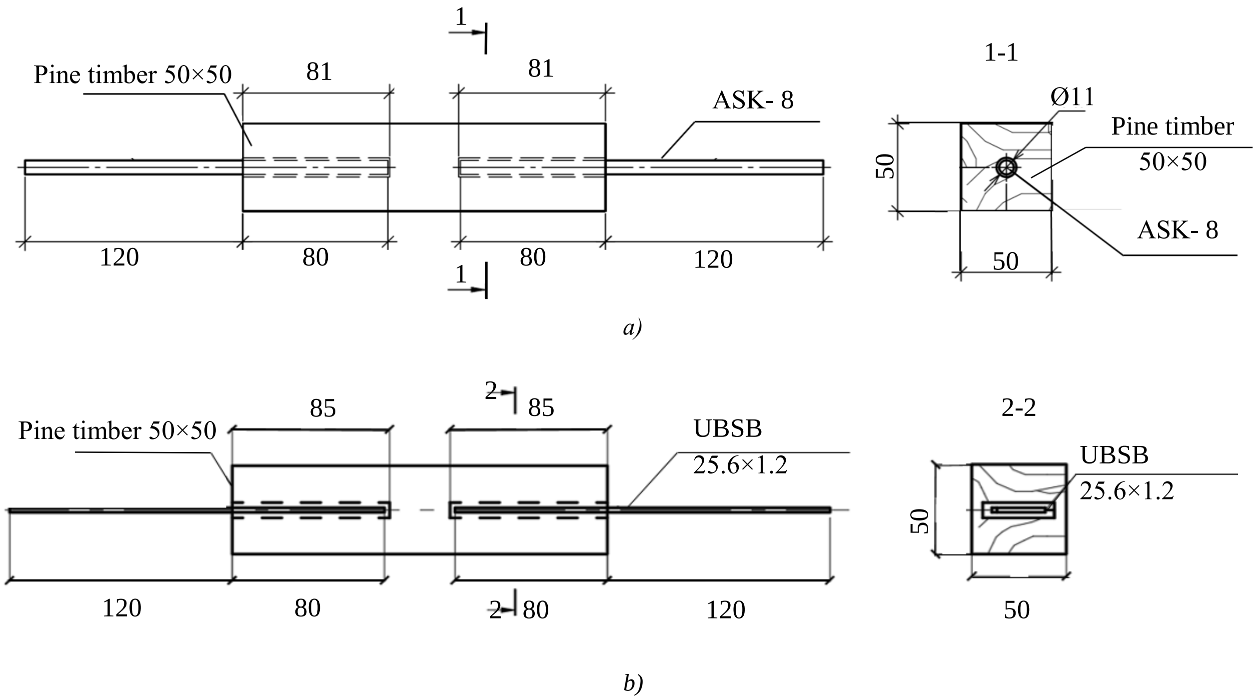


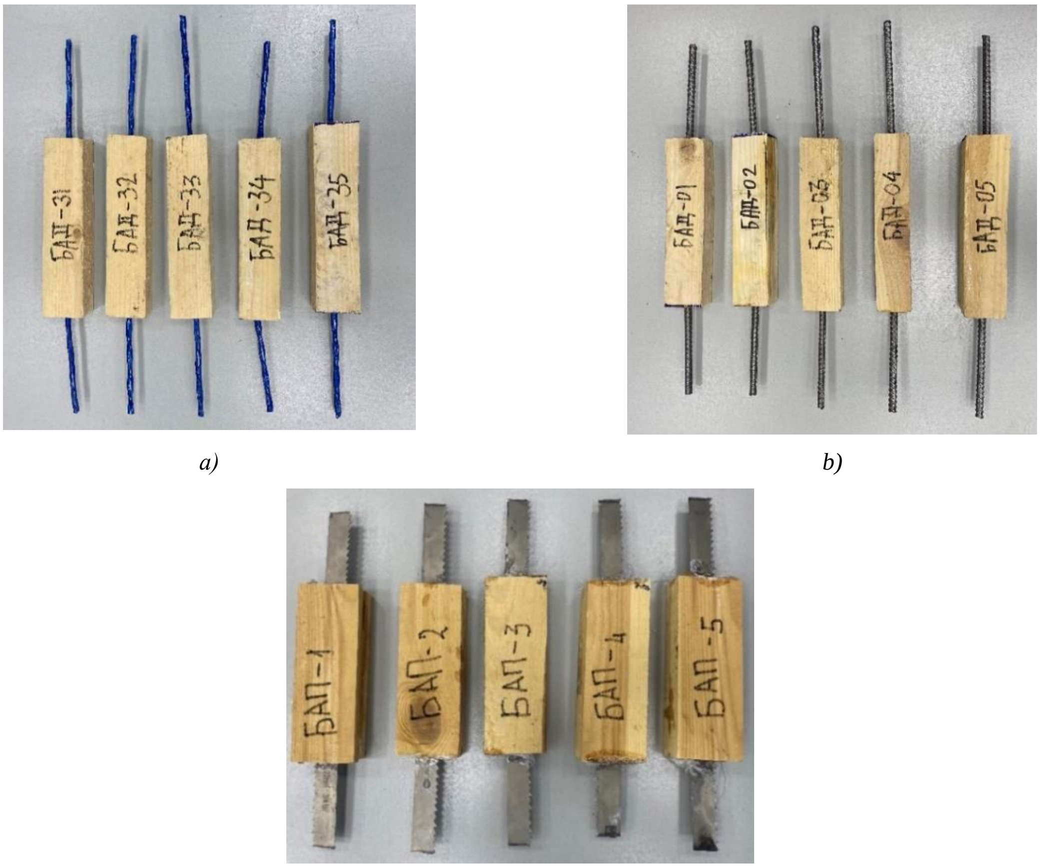
Fig. 1. Diagram of the samples with glued reinforcing elements:
a — composite, steel reinforcement; *b* — used band saw blades

The grooves in the wooden parts of the samples for gluing the struts were made of a rectangular shape with a depth of 3.7 mm and a width of 30.6 mm using a groove cutter with a diameter of 10 mm on a Makita 3612C milling cutter at 30,000 rpm [11]. For gluing the steel and composite reinforcement rods, blind holes with a diameter of 13 mm and a depth of 80 mm were arranged in wooden blanks [12].

UBSB canvases were subjected to mechanical treatment in order to remove the galvanic layer and roughen their surface for improving adhesion to the adhesive joint [13].

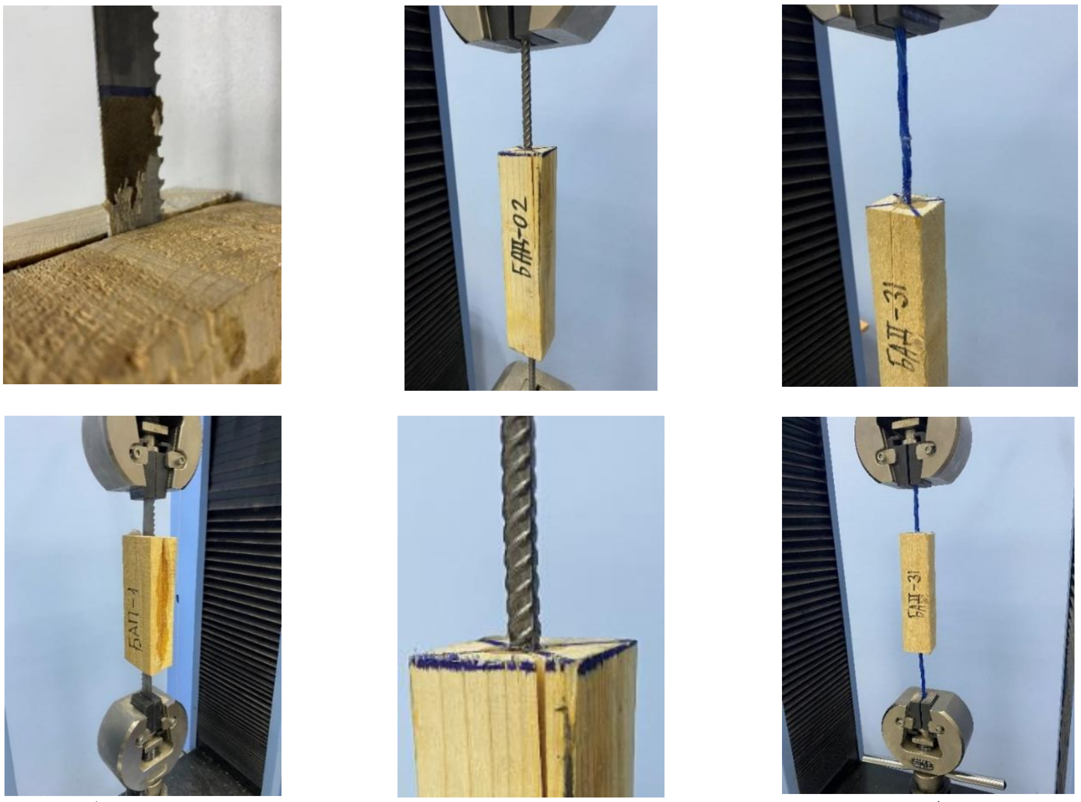
The adhesive composition had the following composition [14]: ED-20 epoxy resin (100 parts by weight), polyethylene polyamine (12 parts by weight), quartz sand (300 parts by weight) and dibutyl phthalate (20 parts by weight) [15]. The adhesive mass was kneaded in an Overhead stirrer PE-8300 blender at 300 rpm for 5 minutes [16]; applied to wooden blanks with a syringe (150 mm^3) or a spatula with a flow rate of 0.2 kg/m; curing was provided at 24°C for 12 hours (Fig. 2).

Testing methodology. Pulling tests were carried out on a REM-100 machine at a loading speed of 5 mm/min [17]. The destruction of the sample was an event where the reinforcing element was completely or partially pulled out of the wooden part of the sample (Fig. 3). The value of the destructive load was recorded automatically by means of the bursting equipment [18].



a) *b)* *c)*

Fig. 2. Finished samples with glued reinforcing elements:
a — composite reinforcement; *b* — steel reinforcement; *c* — used band saw blades



a) *b)* *c)*

Fig. 3. Scheme of the pulling tests on the REM-100 machine with the samples:
a — used band saw blades*;* *b* — steel reinforcement; *c* — composite reinforcement

Research Results. The main results of the experimental studies were the values of the destructive loads of the samples. The experimental results were processed by means of mathematical statistics elements [19]. The following statistical characteristics were calculated within each group of the samples: mean ($\bar{x}$), variance (ε), standard deviation (σ), coefficient of variation (*CV*) and minimum strength (*M*) shown in Table 1.

Table 1

Characteristics of statistical processing of the test data

Material	Loads, kN	$\bar{x}$, kN	ε, kN²	σ, kN	*CV*, %	*M*, kN
Band saw blades	11.0; 12.2; 10.8; 10.5; 11.4	11.18	0.4319	0.657	5.88	10.52
Composite reinforcement (d = 8 mm)	9.5; 8.7; 9.0; 8.2; 9.4	8.96	0.2830	0.532	5.94	8.43
Steel reinforcement (d = 8 mm)	12.3; 10.2; 10.8; 12.4; 12.5	11.64	1.1265	1.061	9.12	10.58

Fig. 4 shows a diagram of the values of destructive loads for the samples. The results are indicative of a high reliability of the data enabling one to quantify the mechanical characteristics of the tested samples [20].

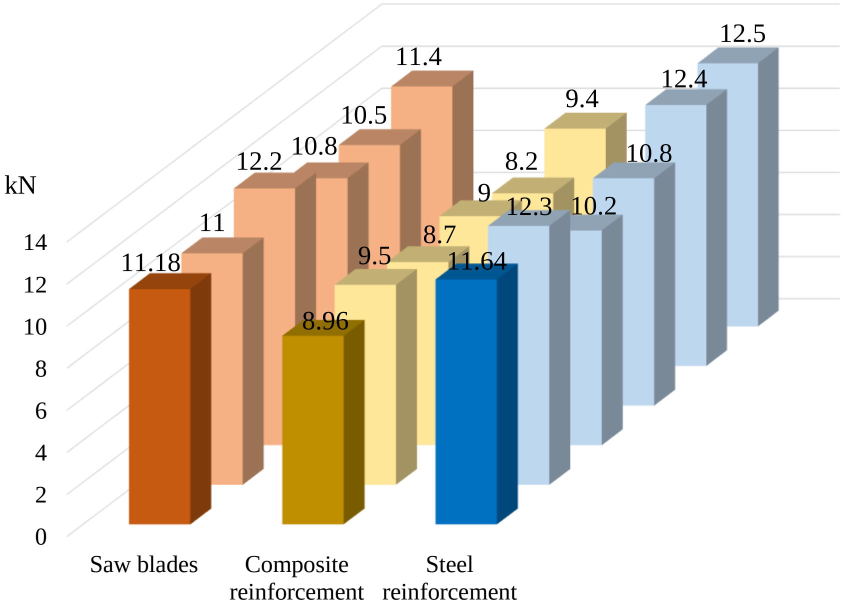


Fig. 4. Test results (the results of the average destructive load values are displayed in a brighter color)

UBSB joints with wood show a high adhesive strength (11.18 kN, *CV* = 5.88%) comparable to steel reinforcement (11.64 kN, *CV* = 9.12%) and superior to composite one (8.96 kN, *CV* = 5.94%) [21]. The stability of the joints is due to the mechanical treatment of the surface of the baldes, which increases adhesion to the adhesive [22]. The destruction occurred on the wood confirming the reliability of the adhesive joint [23].

Table 2

Comparative results of the average destructive load values

	Band saw blades	Composite reinforcement (d = 8 mm)	Steel reinforcement (d = 8 mm)
Average load $\bar{x}$, kN	11.18	8.960	11.640
Ratio of the values in proportions	1.00	0.801	1.041

Discussion and Conclusion. Wooden samples with glued-in used band saw blades showed a high strength of the wood–reinforcement joint, close to the samples with a steel reinforcement with a difference of about 4% and considerably beyond the strength of samples with a composite reinforcement – up to 20%.

In spite of the fact that the samples with a steel reinforcement showed the highest strength, its variability ($CV = 9.12\%$) calls for quality control of wood and adhesive joint [25]. In turn, the samples with a composite reinforcement are inferior in their strength to those with reinforced concrete due to the lower roughness of its surface [25].

The reliability of the data was ensured by a strict adherence to the rules and technology of testing and high-quality operation of the equipment being used. It is to be noted that in order to reliably adhere the surface of the wall to the adhesive layer, there was preliminary preparation, i.e., mechanical processing for removing the galvanic layer and at the same time to roughen it.

The use of solid waste for reinforcement of wooden elements of load-bearing structures allows for a reduction in the cost of solid waste disposal, as well in that of RWSs "in action". The suggested method of reinforcing wooden structures with the use of reinforced concrete has prospects to be implemented in producing light wood-based building structures.

All of the above is indicative of the fact that reinforced concrete structures are quite suitable for reinforcing load-bearing elements made of wood, but in order to completely evaluate the efficiency of such a solution, it is essential to investigate the stress-strain of wooden structures reinforced with UBSB.

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Original Empirical Research

Methods for Strengthening Reinforced Concrete Columns Using Carbon Fiber in China

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Abstract

Introduction. China's construction industry developed in three phases: the first peak occurred in the 1950s, and the second one in the 1980s and 1990s. Generally, buildings constructed during the construction boom were characterized by relatively low design and construction standards resulting in poor quality. Currently, buildings constructed during the first and second phases are entering a phase of "aging" due to some factors such as low construction standards and outdated construction methods. Both the buildings themselves and their structures are flawed. Over time, most buildings exhibit varying degrees of deterioration and serious damage requiring urgent inspection, repair, and reinforcement. To meet the needs of social development, proper repair, reinforcement, and reconstruction of existing buildings is essential. The aim of this study is to identify the possibilities of reinforcing defective building structures with modern composite materials manufactured in China.

Materials and Methods. The object of the research are methods of strengthening reinforced concrete pillars. The author suggests using a systematic approach that accounts for the adjacent functional areas, their mutual influence and an expert assessment of their significance.

Research Results. The analysis showed that the strengthening mechanism for reinforced concrete columns subjected to axial compression and strengthened with carbon fiber sheets is a combination of carbon fiber sheets and concrete influenced by a host of factors. The strengthening method is strictly regulated, and the lateral restraint provided by the carbon fiber sheets under loading is capable of improving the compressive strength, structural stability, and durability of the columns.

Discussion and Conclusion. The strengthening methods for existing buildings vary widely, each with its own unique advantages and limitations. For example, bonded steel is fast to construct but requires a high quality; section enlargement is cost-effective but reduces space; carbon fiber strengthening offers numerous advantages but has limitations in investigating nodes and calculating load-bearing capacity. Although extensive research has been conducted on strengthening reinforced concrete axial compressed columns, the effectiveness depends on a host of factors. The discussion demonstrates that the choice of a strengthening method should be tailored to actual conditions. Carbon fiber strengthening requires further research, while strengthening axial compressed columns requires technological optimization. Furthermore, existing standards and regulations should be revised to reflect new advances and best practices.

Keywords: building structures, carbon fiber strengthening method, strengthening of reinforced concrete structures

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Оригинальное эмпирическое исследование

Методы усиления железобетонных колонн с помощью углеродного волокна в Китае

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Аннотация

Введение. Строительная отрасль Китая в настоящее время стремительно развивается. Первый пик пришёлся на 1950-е годы, а второй — на 1980-е и 1990-е годы. В целом, здания, построенные в период строительного бума, характеризовались относительно низкими стандартами проектирования и строительства, что приводило к низкому качеству. В настоящее время здания, построенные в течение первого и второго этапов, вступают в фазу «старения» из-за таких факторов, как низкие стандарты строительства и устаревшие методы строительства. Как сами здания, так и их конструкции являются несовершенными. Со временем большинство зданий демонстрируют различную степень старения и серьёзные повреждения, требующие срочной диагностики, ремонта и укрепления. Для удовлетворения потребностей социального развития необходимо проводить надлежащий ремонт, укрепление и реконструкцию существующих зданий. Цель настоящего исследования: выявление возможностей усиления дефектных строительных конструкций современными композитными материалами, производимыми в Китае.

Материалы и методы. Объектом исследования являются методы усиления железобетонных столбов. Автор предлагает использовать системный подход, учитывающий прилегающие функциональные зоны, их взаимовлияние и экспертную оценку значимости.

Результаты исследования. Анализ показал, что механизм армирования железобетонных колонн, подвергающихся осевому сжатию и армируемых листами из углеродного волокна, представляет собой комбинацию листов из углеродного волокна и бетона, на которую влияют множество факторов. Метод армирования строго регламентирован, а боковое ограничение, обеспечиваемое листами из углеродного волокна при нагружении, может повысить прочность на сжатие, структурную устойчивость и долговечность колонн.

Обсуждение и заключение. Методы укрепления существующих зданий разнообразны, с уникальными преимуществами и ограничениями, например: метод приклеивания стали быстр в строительстве, но требует высокого качества; метод увеличения сечения экономичен, но сокращает пространство; метод укрепления углеродным волокном обладает множеством преимуществ, но имеет недостатки в исследовании узлов и расчете несущей способности, хотя исследование укрепления арматурно-бетонных осевых сжатых столбов достаточно глубокое и эффект зависит от многих факторов. Обсуждение показывает: выбор метода укрепления должен учитывать реальные условия; метод укрепления углеродным волокном требует дальнейших исследований, а укрепление осевых сжатых столбов — оптимизации технологии, при этом существующие стандарты и нормативы нужно пересмотреть с учетом новых достижений и практики.

Ключевые слова: строительные конструкции, метод усиления углеродной тканью, армирование железобетонных конструкций

Для цитирования: Чэ Сянюй. Методы усиления железобетонных колонн с помощью углеродного волокна в Китае. *Современные тенденции в строительстве, градостроительстве и планировке территорий*. 2025;4(4):69–77. https://doi.org/10.23947/2949-1835-2025-4-4-69-77

Introduction. Strengthening buildings entails reinforcing worn out and damaged structural materials and building structures in order to restore their functionality. Compared to the new construction, projects to repair and strengthen existing building structures offer the advantage of shorter construction time, lower investment costs, and higher payback. The building reinforcement and renovation sector in China is set to experience a considerable growth [1–2]. Thus research and practical use of the theory and technologies of building reinforcement and reconstruction are of a great theoretical and engineering value.

Materials and Methods. Of late China has made a major progress in both theoretical research and engineering development in renovation and reinforcement of existing buildings. There is a growing number of methods of reinforcing existing buildings and structures, particularly in the commonly used concrete structures. Lots of basic reinforcement methods have emerged. Let us take a look at some.

1. Bonding of steel elements. This method consists of attaching steel plates to the outer surface of concrete elements in order to increase their bending and shear strength, thereby their safety. It is commonly suitable for environments with a humidity of 20% and is used in order to reinforce bent elements exposed to conventional static forces [3]. Compared to large-scale construction, it is characterized by a short construction period, minimal amount of onsite work, and minimal impact on the physical appearance of existing building elements and the space above it. However, the method calls for high-quality construction, and the choice of adhesive material and the builders' professionalism are crucial to its efficiency. On top of that, if there are voids following bonding of the steel elements, they are extremely difficult to remove.

2. Increasing the cross-section. This method consists of increasing the cross-sectional area of concrete elements in order to enhance their load-bearing capacity and comply with the operational requirements. It is characterized by a relatively low construction cost and a wide range of applications, including reinforcement and modernization of various structural elements (beams, slabs, columns and walls) [4]. However, its major disadvantages are a long onsite construction time, significant environmental impact as well as reduction in usable area due to the increased cross-sectional area, which causes some limitations.

3. External steel reinforcement. This method consists of wrapping the surface of the concrete element with electro-welded steel profiles (available for both dry and wet methods) in order to increase the load-bearing capacity of the element. The method considerably increases the load-bearing capacity and rigidity of the element, is relatively easy to manufacture and calls for a short construction time making it commonly used to strengthen building elements [5]. However, external steel reinforcement also has a few disadvantages, such as high steel consumption, high cost and complexity of processing the joints of the elements.

4. Reinforcement by changing the design scheme. This method changes the transmission of forces in the structure by adding support points, beams (braces) or converting multi-span beams with simple supports into continuous ones. This considerably reduces the calculated bending moment, increases the load-bearing capacity of the structural element, and achieves the goal of reinforcing the original structure. Depending on the method of adding support points, the joint can be classified as a "wet" or a "dry" one. While using a wet joint, the contact surfaces between the beam and the support, as well as the concrete cast following pouring, at the support points call for roughening, scale removal and wetting. Micro-expanding concrete is commonly used for pouring. While using dry joints of steel clamps, cement mortar is poured between the steel clamp and the beam surface. After the steel clamp has been securely welded to the support, all of the gaps between the contacts are sealed and filled with a dry, durable solution. The method includes both additional reinforcement of the support and reinforcement used in combination. Additional reinforcement of the support strengthens the structure by adding load-bearing support elements. Despite the simple principle and the reliability of the transfer of effort, it is labour-intensive and might affect the aesthetics and functionality of a building, particularly spatial displacement. It is more suitable for strengthening structures with limited gaps and large spans. The complex reinforcement method can be divided into partial reinforcement, full reinforcement and foundation reinforcement. Strengthening is achieved by changing the transmission path of forces and increasing the load-bearing capacity and deformation capacity of the structure. The method also includes such methods as removal of girder (truss) walls, removal of girder columns, replacement of girder columns and modification of the load-bearing system [6]. It includes strengthening the structure, lifting with jacks and correcting the alignment of the superstructure, as well as removing rejected components. The method is characterized by a short construction time, low cost and minimal impact on production and daily life. It is suitable for strengthening tasks such as increasing usable area and ensuring structural safety in both new and existing buildings.

5. Prestressed fittings. Prestressed reinforcement can be divided into two types depending on the purpose of strengthening. One of them is prestressed reinforcement with screeds which is mostly used to strengthen beam-plate structures, frame structures, trusses and elements subject to significant non-central compression. Depending on the purpose of strenthening and the load requirements of the reinforced structure, the location of the ties can be divided into horizontal (or linear), reinforcing (or broken) and mixed. Another method is prestressed reinforcement which is mostly used for frame columns subject to axial compression and slight off-center compression. Double reinforcement reinforcement is suitable for reinforcing elements compressed axially and columns subject to small non-central compression, whereas single reinforcement is suitable for reinforcing columns subject to large non-central compression, with insufficient compressed reinforcement or low strength. The method makes use of prestressed steel rods (horizontal rods supporting transverse elements, retaining rods, and combined rods) in order to strengthen the load-bearing capacity of the structure. This method makes it possible to reduce the stress level in reinforced elements leading to a considerable increase in reinforcement efficiency and an increase in the overall load-bearing capacity of the structure. The method might also affect the appearance of reinforced elements. It is more suitable for reinforcing medium- and large-span structures, and is also effective for strengthening highly stressed and deformable concrete elements [7]. However, it should not be used in structures subject to increased shrinkage and creep of concrete, while corrosion of prestressed reinforcing rods should be paid a great deal of attention to.

6. Reinforcement method by gluing carbon fiber sheets. This method makes use of a special adhesive to glue carbon fiber sheets to the surface of the component, forming a composite material. This composite material interacts with the original structure or component, strengthening and improving its load-bearing capacity. This method has some advantages such as low weight, reduced thickness, availability of materials according to specifications, and resistance to alkalis, corrosion, and acids. The low weight and simplicity of the technological process enable it to be used in a limited space. On top of that, the reinforcement does not affect the normal use of the building making it simple, fast and widely applicable.

As early as in the late 19th century, the technology of gluing reinforcing carbon fiber fabric was widely used in developed countries such as the USA and Japan. Since it got introduced in China in the late 1990s, it has grabbed engineers' attention and has become a center for research and application of new materials for building reinforcement. A considerable number of previously constructed buildings currently fail to comply with the new operational requirements, have low design standards, low functionality and is in need of urgent strengthening. Gluing carbon fiber materials in order to reinforce concrete structures is the most convenient and effective reinforcement method that does not require the production to stop. It is particularly suitable in situations where the cross-sectional area of existing structural elements cannot be increased, space on the construction site is limited, and construction time is tight. On top of that, the method is suitable for reinforcing bridges, culverts and various other concrete structures. However, in the theoretical research and engineering application of the modern carbon fiber adhesive reinforcement method, there are still a number of issues to be solved. When it comes to the material properties, carbon fiber sheets used for reinforcement are typically less than 0.2 mm thick, but have a high tensile strength of over 3000–4000 MPa, which is about 10 times that of structural steel. They are thus particularly suitable for strengthening reinforced concrete elements subject to both bending and stretching. However, in order to reinforce a wide range of compressive elements, more research is needed on reinforcement mechanisms and methods of using carbon fiber sheets. Thus, in order to comply with the requirements for reinforcement and modernization of a large number of existing buildings, studies of the stress-strain state and methods of reinforcing compressive elements with carbon fiber sheets have a great theoretical and applied significance [8].

Due to the continuous development of carbon fiber reinforcement technologies in China, the "Technical Code for Reinforcing Concrete Structures with Carbon Fiber Sheets" CECS 146:2003 (the 2007 edition) has been officially published, and a corresponding set of drawings for reinforcing structures has been published. This code takes a full consideration of the latest research conducted by numerous domestic universities and research institutes over the recent years, integrating valuable practical experience gained by a range of organizations in using carbon fiber materials for structural reinforcement in design and construction. It also draws on extensive international literature in order to provide scientific and authoritative guidance on the theoretical research and engineering practice of carbon fiber reinforced concrete structures.

In general, the use of carbon fiber glued sheets for reinforcing concrete structures has led to numerous advances in both theoretical research and engineering applications. However, there are still lots of theoretical problems and technical difficulties to be addressed. For example, the mechanism of operation and specific methods of applying carbon fiber glued reinforcement at the joints of components have been insufficiently studied, and the system of analysis and calculation of load-bearing capacity is in need of improvement. In particular, in the field of reinforcement of compressed elements, although the current "Technical Code for Reinforced Concrete Structures with Carbon Fiber Sheets" CECS 146:2003 (the 2007 edition) clearly states that the use of carbon fiber sheets for reinforcing concrete columns might limit the deformation of concrete, thereby increasing compressive strength and reducing the axial coefficient with current research remaining insufficient and incomplete [10]. The regulations emphasize that the effect of reinforcement with carbon fiber sheets can be taken into account in the design only if there is reliable evidence [9]. Therefore, in order to further expand the scope of carbon fiber sheet reinforcement and increase the efficiency of its reinforcement, it is particularly essential to conduct more in-depth and systematic research on existing theoretical and technical issues.

Let us analyze the reinforcement mechanism and methods of constructing reinforced concrete columns operating on axial compression and reinforced with a carbon fiber sheet.

1. Theoretical analysis of elements operating on axial compression.

An element operating on axial compression perceives axial force along the axis of its center of gravity of the cross-section when the point of application of the external force acting on the element coincides with the center of gravity of the cross-section of the element, and the stress distribution over the cross-section of the element is uniform.

When an element operating on axial compression fails, the direction of force coincides with the axis of the element. As a rule, when a reinforced concrete column is subjected to axial compression, the clamps limit the lateral expansion and deformation of the concrete inside it, exerting lateral compression on the concrete core. The combined effect of various vertical axial pressures and a small initial eccentricity compresses the entire shaft of the column, causing compression and deformation of the steel rods, which results in the ultimate flow rate of the inner steel rods. Due to the protrusion of the steel reinforcement, there are cracks on the concrete surface of the column shaft that become more distinct as the load increases. After steel reinforcement has failed, the load-bearing capacity of the element is not sufficient, and cracks on the concrete surface eventually cause complete failure to occur.

2. Stress analysis during axial compression of elements reinforced with carbon fabric.

The characteristics of the elements under axial compression reinforced with carbon fabric differ significantly from those of non-reinforced elements.

After reinforcing the axial compressed element with carbon fabric, it becomes a structure subject to secondary stresses. Before the carbon fabric was applied, the axial compressed element had been under stress (primary stress), i.e., stresses and deformations in it. However, the newly glued carbon fabric is not stressed at this moment. It is only when a test load (secondary stress) is applied that the new part of the carbon fabric connected to the concrete starts being stressed. Therefore, the stress and deformation of the newly added carbon fiber part are always behind the accumulated stresses and deformations of the original component. When the load-bearing capacity of the original component has reached its limit, the newly added carbon fabric has not yet reached its limiting state of bearing capacity, and its tensile strength might continue playing its role.

The degree of unloading of the original component and the treatment of new and old joint surfaces are two important factors impacting the joint operation of the reinforced component.

In order to reduce the problem of the stresses and deformations of the newly added carbon fiber part, the component must be unloaded prior to reinforcement. When the reinforced component fails, the reinforced part can reduce accumulated stresses and deformations that lag behind the original component. At the initial stage of the load-bearing capacity, unloading has a greater impact on the reinforcement efficiency of the component. There are two specific unloading methods: direct unloading and indirect unloading. Direct unloading implies the complete or partial removal of the load from the component, while indirect unloading implies the application of a counteracting force to the existing structure in order to relieve accumulated stresses and deformations at the initial stage of the load.

3. Processing the interface between new and old reinforced components.

Processing of the interface and the quality of the bond between the carbon fiber sheet and the source component have a direct impact on the final reinforcement effect. Compressive and shear stresses between the new and old structures are transmitted across the boundary, so the interface must be smooth and even. In order to investigate the bond strength between the carbon fiber sheet and the original structure, the carbon fiber sheet is first glued to a concrete sample, and then a shear test is performed. This enables an analysis of the influence of the factors such as surface treatment, bonding material, and concrete strength on bond strength. Carbon fabric has an extremely high tensile strength. The transverse carbon fiber fabric in axially compressed elements not only coordinates the deformation with the clamps in axially compressed elements, but also works in conjunction with the longitudinal carbon fiber fabric acting as a hoop that increases the load-bearing capacity of axially compressed elements.

4. Stress mechanism in axially compressed elements reinforced with carbon fiber sheets.

When concrete in an axially compressed column is subjected to compressive forces in a few directions, its volume changes. This is due to a gradual change in stresses and deformations in the concrete resulting in small cracks. Applying lateral pressure to the concrete surface at this point might limit the rate of change of these small cracks thus causing an increase in the load-bearing capacity of the concrete. If the concrete surface is wrapped with a steel tube or other hoop-shaped shell, the expansion of the concrete volume is limited by the lateral force applied by the shell, thereby reducing or slowing down the rate of change of stresses and deformations in the concrete, which ultimately results in an increase in the axial compressive strength of the concrete and improves its ductility. This principle is commonly used in practical applications in engineering reinforcement, e.g., in pipe concrete. This type of material, which optimizes mechanical properties of concrete and increases its axial compressive strength by applying lateral forces to the concrete surface, is called space-limited concrete. If the prefabricated shell, which transmits lateral forces to the concrete surface, is made of carbon fabric, it is regarded as concrete with a limited space.

There has been some research into the methods of strengthening reinforced concrete columns operating on axial compression with carbon fabric. While using carbon fabric to reinforce concrete structures, there are three common reinforcement methods: wet bonding, continuous fiber winding, and prefabricated sheaths. The specific construction process using carbon fabric is the following:

1) preparation of the concrete column mounting surface to increase the contact area;

2) applying metal mesh in order to increase the strength of the concrete column;

3) pouring concrete into the gaps between the metal mesh to strengthen the structure;

4) wrapping with a plastic wrap in order to preserve moisture and prevent cracking;

5) cutting a carbon fiber sheet;

6) preparation and application of glue, sheet sticker (after the fastening is completed, it is necessary to wait till the adhesive joint has hardened);

7) inspection and additional reinforcement of all of the areas weakened with glue;

8) maintenance services.

Having studied multiple materials and relevant literature as well as having conducted numerous theoretical studies and engineering developments based on the characteristics of carbon fiber reinforcement, and in order to ensure effective reinforcement in combination with reinforcement methods for columns subjected to axial compression, carbon fiber sheets and static load tests, factors affecting the optimal construction method must be considered.

Researchers in China and abroad have achieved considerable results by means of the experimental research and analysis of factors affecting concrete reinforcement with carbon fiber sheets. The factors affecting the load-bearing capacity of reinforced concrete columns subjected to axial compression and carbon fiber reinforcement can be summarized as follows:

– Smoothness of the surface to be bonded.

While using carbon fabric for bonding and reinforcing concrete structures, the surface of the concrete component must be preliminarily polished. Mechanical methods or manual polishing can be used in order to remove loose and damaged areas of the concrete surface, as well as the dirt from the aggregate and mortar making the surface of the concrete component relatively smooth and even. This contributes to the carbon fabric adhering tighly to the surface of the concrete component, thereby improving the adhesion of the surface to be bonded.

– Selecting and cutting carbon fabric.

While choosing a carbon fabric, it is necessary to confirm the strength of the materials used by the manufacturer prior to the testing to ensure that they are in compliance with the specification and specify the strength class. The choice of strength class (1 or 2) must be taken into account while designing the concrete component to be tested.

Cutting carbon fiber fabric. Firstly, the formed carbon fiber fabric must be cut to a specified size according to the design requirements. Uneven or oblique cutting against the fibers is strictly prohibited in order to prevent the fibers from falling off. Secondly, after cutting, the bonding direction should correspond to the direction of the carbon fiber fibers. Thirdly, the cut carbon fiber tape must be dry, clean and unpolluted to avoid the sticking of sand, wax, oil, etc .

– Choosing the glue.

While choosing an adhesive, it should be taken into account whether the microstructure of bonding and the bond strength are in compliance with the requirements. There are lots of types of interface agents on the market with different compositions and binding properties. The selection must be carried out in compliance with the requirements of the carbon fiber fabric operating instructions.

– The method of gluing carbon fiber fabric.

According to the research and analysis of carbon fiber fabric at home and abroad, different bonding schemes have varying degrees of an increase in the load-bearing capacity of concrete components. This can be controlled by means of adjusting the size of the spacing, width of the location and shape of the circumference of the carbon fiber fabric ring. There are presently four types of bonding methods used:

– single-layer annular concrete column;
– double-layer annular concrete column;
– vertical and horizontal wrapping;
– full wrapping.

Research Results. A comprehensive and in-depth analysis and study of the reinforcement mechanism and methods of constructing reinforced concrete columns subjected to axial compression using carbon fiber sheets has been performed. From both a microscopic and macroscopic perspective, the reinforcement mechanism shows that due to their high strength and elasticity carbon fiber sheets are tightly bound to concrete. When exposed to columns undergoing axial compression, these stresses are impacted by complex and diverse factors. The concrete strength, degree of reinforcement, as well as the number and quality of carbon fiber sheet layers have a considerable effect on reinforcement.

When it comes to the construction methods, each stage from the preparation of the structure to the direct bonding is strictly regulated. Safety and precautions are of primary importance during construction. Employees must utilize personal protective equipment in order to prevent injury from flying fibers of carbon fiber sheets. On top of that, the construction conditions must be in compliance with the requirements, including appropriate temperature and humidity, in order to ensure reliable adhesion of carbon fiber sheets to concrete. According to the in-depth analysis of the stress mechanism, carbon fiber fabric glued to a concrete column undergoing axial compression will generate lateral constraints. Due to the ring effect created by the carbon fiber fabric, this passive restraint system can effectively limit the lateral deformation of concrete, thereby improving the compressive strength of the reinforced concrete column and the overall stability and durability of the structure.

Discussion and Conclusion. In the field of construction, strengthening existing buildings is essential to ensuring their structural safety and functionality. There are currently lots of strengthening methods with their own characteristics.

The method of reinforcement using steel plate bonding allows for quick work and shorter construction time, but puts a great deal of pressure on the quality of work: from choosing the materials to the bonding technology, each stage must be in compliance with the standards, otherwise it will affect strengthening and building safety. The method of reinforcement by increasing the cross-section has a low cost, but it takes up space inside the building, changes the internal layout and affects the functionality of the building. The carbon fiber reinforcement method is commonly used — the materials have high strength, lightness and corrosion resistance, and are capable of increasing load-bearing capacity and earthquake resistance without adding significant weight. However, it has limitations in the analysis of nodes and the calculation of load-bearing capacity calling for further research to be conducted. The effectiveness of strengthening centrally compressed reinforced concrete pillars depends on lots of factors, such as material properties, quality of work, etc.

In actual practice, while choosing a reinforcement method, it is necessary to conduct a comprehensive assessment of the condition of a building and flexibly adjust the approach. The carbon fiber reinforcement method calls for an in-depth study and improvement of the theoretical foundations of design; strengthening centrally compressed pillars calls for development of new materials and technologies, as well as increased quality control. On top of that, outdated standards and regulations are in need of a timely reviewe in order to ensure the scientific justification of reinforcement.

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BUILDING CONSTRUCTIONS, BUILDINGS AND ENGINEERING STRUCTURES

СТРОИТЕЛЬНЫЕ КОНСТРУКЦИИ, ЗДАНИЯ И СООРУЖЕНИЯ

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Original Empirical Research

Prospects for the Use of LEGO Blocks for the Construction of Warehouse and Storage Facilities of the Agro-Industrial Complex

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Abstract

Introduction. The major task in designing warehouse and storage facilities whose building structures experience horizontal operational loads is not only ensuring strength, load-bearing capacity and permissible vertical deformations (residue), but also stability and operability under the action of horizontal operational loads caused by lateral pressure from the weight of liquids or bulk materials. Traditional constructions of such structures made of monolithic reinforced concrete or metal are characterized by high material consumption, labor intensity and duration of construction (assembly). The article explores the prospects for constructing warehouse and storage facilities from prefabricated blocks of various structures.

Materials and Methods. Applied structures and technologies for constructing warehouse and storage facilities have been analyzed, their main disadvantages and issues arising at the stages of construction and operation have been identified. New structures of LEGO blocks and technology for the assembly of prefabricated buildings and structures using the method of vertical reinforcement of masonry for perceiving horizontal operational loads are set forth. Mathematical modeling and calculation of the parameters of the stress-strain state (hereinafter referred to as SSS) of warehouse structures made of LEGO blocks under the action of permanent and temporary operational loads from the weight of liquids or bulk materials has been conducted.

Research Results. New designs of LEGO blocks have been developed, a technology of constructing prefabricated warehouse and capacitive objects from them has been set forth, the regional parameters of vertical reinforcement of masonry from LEGO blocks have been identified depending on the height of the structure and the level of filling containers with liquid and bulk materials.

Discussion and Conclusion. The results are recommended for use in the design and construction of warehouse and storage facilities for agricultural and other purposes. The introduction of such structures implies an increase in the pace of construction, enhanced quality control of construction and a scientific justification for monitoring a technical condition during operation of a facility.

Keywords: storage facilities, warehouses, prefabricated structures, LEGO blocks, mathematical modeling

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Оригинальное эмпирическое исследование

Перспективы применения ЛЕГО-блоков для возведения складских и емкостных сооружений агропромышленного комплекса

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Аннотация

Введение. Основной задачей при проектировании складских и емкостных сооружений, строительные конструкции которых воспринимают горизонтальные эксплуатационные нагрузки, является не только обеспечение проч-

ности, несущей способности и допустимых вертикальных деформаций (осадок), но и устойчивость и работоспособность при действии горизонтальных эксплуатационных нагрузок, вызванных боковым давлением от веса жидкостей или сыпучих материалов. Традиционные конструкции таких сооружений из монолитного железобетона или металла отличаются высокой материалоемкостью, трудоемкостью и продолжительностью возведения (монтажа). В статье рассмотрены перспективы строительства емкостных и складских сооружений из сборных быстровозводимых блоков различных конструкций.
Материалы и методы. Выполнен анализ применяемых конструкций и технологий возведения емкостных и складских сооружений, выявлены их основные недостатки и проблемы, возникающие на стадиях строительства и эксплуатации. Предложены новые конструкции ЛЕГО-блоков и технология монтажа быстровозводимых зданий и сооружений с использованием метода вертикального армирования кладки для восприятия горизонтальных эксплуатационных нагрузок. Выполнено математическое моделирование и расчет параметров напряженно-деформированного состояния (далее – НДС) конструкций складских сооружений из ЛЕГО-блоков, возникающего при действии постоянных и временных эксплуатационных нагрузок от веса жидкостей или сыпучих материалов.
Результаты исследования. Разработаны новые конструкции ЛЕГО-блоков, предложена технология сооружения из них быстровозводимых складских и емкостных объектов, определены рациональные параметры вертикального армирования кладки из ЛЕГО-блоков в зависимости от высоты сооружения и уровня заполнения емкостей жидкими и сыпучими материалами.
Обсуждение и заключения. Полученные результаты рекомендуется использовать при проектировании и строительстве емкостных и складских сооружений сельскохозяйственного и иного назначения. Внедрение таких конструкций предполагает увеличение темпов строительства, улучшение контроля качества возведения и научное обоснование мониторинга технического состояния в процессе эксплуатации объекта.

Ключевые слова*:* емкостные сооружения, склады, быстровозводимые конструкции, ЛЕГО-блоки, математическое моделирование

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Introduction. The design and construction of warehouse and storage facilities has a number of features that are determined primarily by their purpose and the technological processes provided for at such facilities. In this article, we will consider agricultural facilities designed for long-term storage of bulk (grain, seeds, granular fertilizers, compound feed, etc.) and liquid (water, molasses, mineral fertilizers of the CAS type (carbamide-ammonia mixture)) materials.

For long-term storage of bulk materials in agriculture, one-story frame-type warehouses are commonly used whose structures and engineering systems are designed to store a certain type of products, e.g., grain, vegetable and potato, corn storages, etc. The design of the load-bearing structures of such warehouses depends on a product storage method and thereby the distribution of operational loads. While storing products (grains, seeds, vegetables) in bulk, considerable horizontal loads can be transferred to the warehouse walls depending on the filling height, specific gravity of products, as well as adhesion and friction between particles, similar to sand, crushed stone and other dispersed soils (materials).

Another common type of storage of agricultural products are bunker (storage) and silo (tower) tanks. In manufacturing or installing them, both monolithic reinforced concrete or reinforced concrete blocks and steel structures are used: metal sheets, thin-sheet wavy steel sections, etc.

There has been well-known scientific research conducted in the field of design and construction of warehouse and storage facilities, including agricultural ones reported in dissertations by Goldenberg L.I. [1], Sazanbaev S.K. [2], Streltsov I.V. [3], Karsunkin V.V. [4], Rashchepkin S.V. [5], Feidengold V.B. [6], Markovich A.S. [7], etc. In them the operation of structures of warehouse and storage facilities under various types of loads that occur both during construction and during operation of facilities, including loading and unloading processes was investigated accounting for technological features, climatic factors, etc. The methods of theoretical and structural mechanics were employed. Based on the research, rational designs of warehouses, silos, bunkers, elevators and other agricultural facilities have been developed, as well as rules and recommendations for the safe operation of such facilities accounting for the special features of the technological processes occurring in them and the requirements for ensuring climatic parameters (temperature, humidity, air mobility).

Such facilities are facing increased technical, economic and operational requirements, including ensuring high efficiency and reliability throughout the whole life cycle of a facility. The development of new constructive and technological solutions in designing, constructing, operating and dismantling of warehouse and storage facilities for the agro-industrial complex is thus an urgent scientific and practical task.

The aim of this article is to analyze the advantages and disadvantages of the existing warehouse and storage facilities used in the agro-industrial complex as well as to develop new design and technological solutions based on using prefabricated LEGO blocks to ensure high construction efficiency and long-term safety of such facilities.

Materials and Methods. The major research methods employed in preparing the study include:

– analysis of the results of modern scientific studies and of domestic and foreign experience in designing, constructing and operating warehouse and storage facilities;

– identification of the advantages and disadvantages of the structures being used, assessment of modern requirements for such facilities and outlining promising areas for improving them, including exploring the possibility of making use of prefabricated LEGO blocks for constructing load-bearing structures of warehouses and reservoirs;

– design work on developing and substantiating the parameters of universal LEGO blocks to allow reinforced masonry bearing structures of warehouses and reservoirs to be designed;

– design of mathematical models of warehouse structures built from LEGO blocks and study of their VAT parameters resulting from combinations of constant and operational loads from the lateral pressure of stored bulk and liquid materials while varying the height of the structure, of the filling (liquid level), physical and mechanical properties of bulk and density of liquid materials;

– development of the recommendations for designing load-bearing walls of warehouses and tanks (height, thickness, reinforcement, etc.) depending on the properties and height of the filling of stored products.

According to an analysis of the currently used structures of agricultural warehouses, single-storey frame buildings with one, two or more (less frequently) spans consisting of columnar foundations, columns, beams or floor trusses, crossbars, girders, inclined connections, etc., have become common. Such buildings typically include external enclosing structures made of sandwich panels, corrugated board, and other lightweight elements that are not load-bearing ones and are not capable of withstanding a horizontal operational load from the lateral pressure of bulk material or products. In this case, additional load-bearing vertical walls (monolithic or prefabricated ones) have to be erected inside such warehouses that separate different materials or grades of stored products and absorbing lateral pressure (Fig. 1*a*). Construction of a metal frame and of monolithic reinforced concrete walls up to a certain height for filling bulk materials (products) (Fig. 1*b*) can be combined. This increases material consumption, labor intensity and cost of constructing warehouse and storage facilities. With a small filling height at the edges of the building, wall panels can also perceive a lateral load transmitting an operational load through load-bearing metal columns with buttresses and additional connections (Fig. 1*c*).

Similar design solutions are employed in foreign practice of building and operating warehouses of the agro-industrial complex. Fig. 2 shows typical buildings constructed by Accu-Steel, USA [8] and intended for storage of bulk agricultural products. Load-bearing walls perceiving horizontal pressure from bulk material are designed from low wall panels (Fig. 2*a*), masonry from reinforced concrete blocks (Fig. 2*b*) or LEGO blocks in combination with buttresses allowing an increase in a lateral load.

Solutions for warehouse and storage facilities with vertical monolithic reinforced concrete walls can provide both load-bearing capacity and stability under lateral loads and are also employed in the agro-industrial complex in the form of silo-type and warehouse-type storages (with a floor storage) [9]. However, they also possess a few disadvantages due to some structural, technological and operational factors. The major issues during construction of monolithic reinforced concrete storage facilities include: poor or unstable concrete quality (distinct "layering" or "rubble", a lot of unfilled cavities and obviously unvibrated layers) resulting in crumpling of wall concrete in horizontal sections and thereby a reduced service life and rapidly occurring emergencies. On top of that, construction of such facilities calls for a very high quality that can be provided by few construction organizations with extensive experience in the field. Reinforced concrete structures are more labor-intensive and 20-30% more costly, e.g., granaries with round metal silos of a large diameter that have begun to substitute them [10].

a) *b)*

c)

Fig. 1. Examples of domestic metal–framed structures of warehouses for storing agricultural products: *a* – with prefabricated inner walls accepting horizontal operational load; *b* – with external load-bearing reinforced concrete walls at the filling height; *c* – with wall panels, rod buttresses and additional connections

a) *b)*

c)

Fig. 2. Examples of typical buildings for the agro-industrial complex of Accu–Steel, USA: *a* – vaulted form made of metal frame and fabric covering with low side panels (Advantage series); *b* – with a gable roof made of metal frame, external and internal walls made of reinforced concrete blocks to accommodate an operational horizontal load (Crossover series); *c* – a parabolic-shaped frame made of metal trusses and low load-bearing walls made of reinforced concrete LEGO blocks with the same buttresses (Integrity series) [8]

Metal containers (silos, bunkers, tanks, etc.) are also commonlyused in the agro-industrial complex for storing both bulk and liquid products. Along with the unquestionable advantages of such structures (compactness due to a vertical location, durability, quick installation, easy operation during loading and unloading), they possess a few disadvantages, particularly:

– high thermal conductivity of metal that might have a negative effect on the storage of products such as grain;

– danger of corrosion wear of metal and need for constant corrosion protection during operation;

– condensation of moisture on the inner walls that might cause spoilage of grain, its self-heating and loss of its consumer, feed and seed properties;

– high sensitivity of vertical tanks to uneven laying of the base. Based on our experience, a few cases of rolls and over-design deformations of metal tanks used for storing liquid foodstuffs are known causing their further operation to become impossible without costly measures taken in order to level the rolls and strengthen the foundations [11]. Constant geotechnical monitoring [12] is also needed accounting for the mutual influence of both the reservoirs themselves on each other and the surrounding buildings [13];

– stress-strain state of the metal shell of the tanks that constantly changes due to loading and unloading, and the absolutely flexible "metal bottom – ground base" system for typical tanks with ring foundations built only under the walls [14].

Based on the analysis of the advantages and disadvantages of the existing structures of warehouse and storage facilities for the agro-industrial complex, the following conclusions can be made:

– most frame buildings used for this are considerably limited in their height due to an inability to perceive considerable horizontal operating loads caused by lateral pressure of bulk products or materials (grain, potatoes, fertilizers, etc.);

- the task of developing effective design solutions to ensure high construction rates and reliable operation with considerable lateral pressure on the load-bearing walls is a relevant one;

– a promising direction for improving structures of buildings in the agro-industrial complex is the use of prefabricated concrete LEGO blocks;

– the major issues with introducing such structures is the insufficient load-bearing capacity while working on horizontal operating loads, as most of these blocks are laid "on the dry" and do not have masonry reinforcement.

We are attempting to develop and scientifically substantiate the parameters of reinforced masonry made of concrete LEGO blocks to allow for the construction and operation of high storage facilities with a high degree of loading (to a high filling height) while maintaining stability and reliability throughout the whole life cycle of a facility.

Research Results. Concrete LEGO blocks are being manufactured by a variety of companies both in Russia and abroad. There is a well-known positive experience in designing and constructing buildings made of LEGO blocks (Fig. 3*a*) and LEGO bricks (Fig. 3*b*) in Siberia [15].

The size of a regular block: length – 500 mm; height – 220 mm; width – 250 mm. The special geometry of the shaped blocks ensures convenient installation and reliable connection.

Depending on the type of a building, three different technologies of construction from LEGO blocks are recommended [15]:

– laying with no mortar;

– mortar-free installation with reinforcement;

– laying on mortar.

As the major disadvantages of such blocks, in [15] an impossibility of erecting tall buildings and structures, insufficient testing of the use of such blocks in construction practice, as well as the lack of a regulatory framework are outlined.

The IS GROUP Engineering and Construction production group produces foundation LEGO blocks of the FBS series (Fig. 4) [16].

Manufacturers point the following out as the major advantages of such blocks [16]:

– fast construction – a structure with an area of about 50 m^2 can be erected in as little as an hour;

– no need for bonding mortar or reinforcement – the tongue-and-groove joint system is not only convenient, but also allows one to save on the purchase of mortar and fittings;

– multiplicity – LEGO blocks are easy to assemble and easy to disassemble. They can be used multiple times and applied on a range of objects and for different purposes;

– reliable adhesion – the building blocks are characterized by a high level of adhesion accuracy to secure structural strength throughout their entire service life and to enable them to withstand a wide range of loads and impacts;

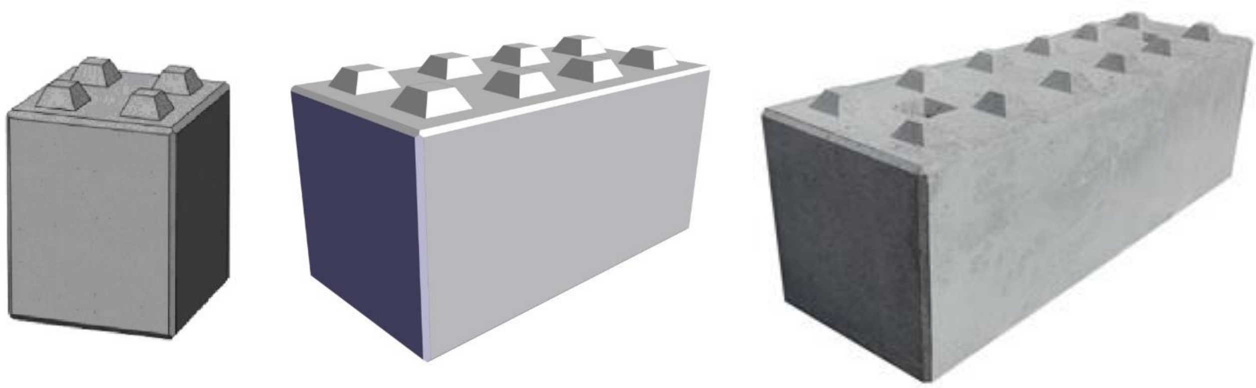
– independence from a season – LEGO blocks can be built regardless of the time of year and weather conditions. The product itself and its assembly technologies are "weather-resistant". One does not have to wait for favourable weather or special temperatures to install it, which means neither downtime no money losses are involved;

– LEGO blocks are ideal for construction of prefabricated temporary buildings and low-load structures. This is a cutting-edge highly aesthetic European technology that delivers high-quality results at affordable costs. The required number of blocks is purchased once and reused following a demolition.

a) *b)*

c)

Fig. 3. Prefabricated structures used in Siberia:
a — LEGO blocks, *b* — LEGO bricks; *c* — an example of masonry made of polystyrene concrete blocks with no mortar [15]



a) *b)* *c)*

Fig. 4. IS GROUP foundation LEGO blocks [16]: *a* – FBS 6-6-6; *b* – FBS 12-6-6; *c* – FBS 24-6-6 [16]

In the Rostov region, concrete LEGO blocks of different sizes are produced:

– Ferroconetoninvest LLC (Rostov-on-Don) — 21 standard sizes of FBS foundation blocks [17];

– Mineral Trading House LLC (Tselina town) — 10 standard sizes of universal concrete LEGO blocks [18].

In 2025 TD Mineral LLC developed Technical specifications 23.61.12-001-86245892-2025 "Lego-Type Concrete Blocks" according to which blocks are manufactured of heavy concrete according to GOST 26633-2015 "Heavy and Fine-Grained Concretes" with the following characteristics:

– concrete compressive strength class — at least B20;

– water resistant — W4;

– frost resistance — F1 100 according to the 1st basic method.

The technical specifications indicate the following areas of application for these blocks:

– zoning of premises (construction of compartments and niches for a separate storage, e.g., of agricultural products within a facility);

– durable, non-removable formwork for monolithic construction;

– construction of walls and basements, internal partitions;

– construction of retaining walls;

– construction of storage and utility rooms.

In 2024-2025, in the territory of JSC Tselinskagrokhimservice (Tselina town, Rostov region), a one-storey warehouse building for storing agricultural products (basement-free, pentagonal according to the plan, with the total dimensions of 96.5×48.5 m) was erected from LEGO blocks of TD Mineral LCC with the following characteristics:

– the maximum height of the building is 14.0 m;

– the level of responsibility is normal (II);

– the degree of durability — II (at least 50 years);

– the degree of fire resistance — II;

– the building area is 4347 m^2.

Employees and graduate students of the Department of Engineering Geology, Bases and Foundations at the Don State Technical University, commissioned by JSC Tselinskagrokhimservice, were tasked with an inspection of the technical condition of a building (at the stage of incomplete construction) and scientific and technical support for its construction. The major goal of the Contractor was to identity whether walls from LEGO blocks could be loaded with horizontal operational loads from bulk and liquid materials. The general view (individual facades) and structural elements of the warehouse building are in Fig. 5.

Here is what the survey concluded. The structural scheme is a frame one: load-bearing combined columns (the lower part is reinforced concrete, the upper one is metal); metal girders and roof trusses. The spatial rigidity of the building is ensured by the joint work of columns of LEGO blocks with monolithic cores, a monolithic reinforced concrete belt at a height of 6.0 m around the entire perimeter of the building and metal roof trusses. Due to the complexity of the building configuration, a large number of elements with different rigidity, and the heterogeneity of the soil base, the finite element method was employed, which had been properly tested in solving similar problems in a three-dimensional formulation [19, 20]. In order to assess the VAT of structures from the effects of combinations of permanent and temporary loads, a three-dimensional finite element model of the building was developed. In order to design the initial geometric model of the building, constructive solutions were adopted with the dimensions of the elements identified during the measurement. The general view of the 3D model of the warehouse building is shown in Fig. 6.

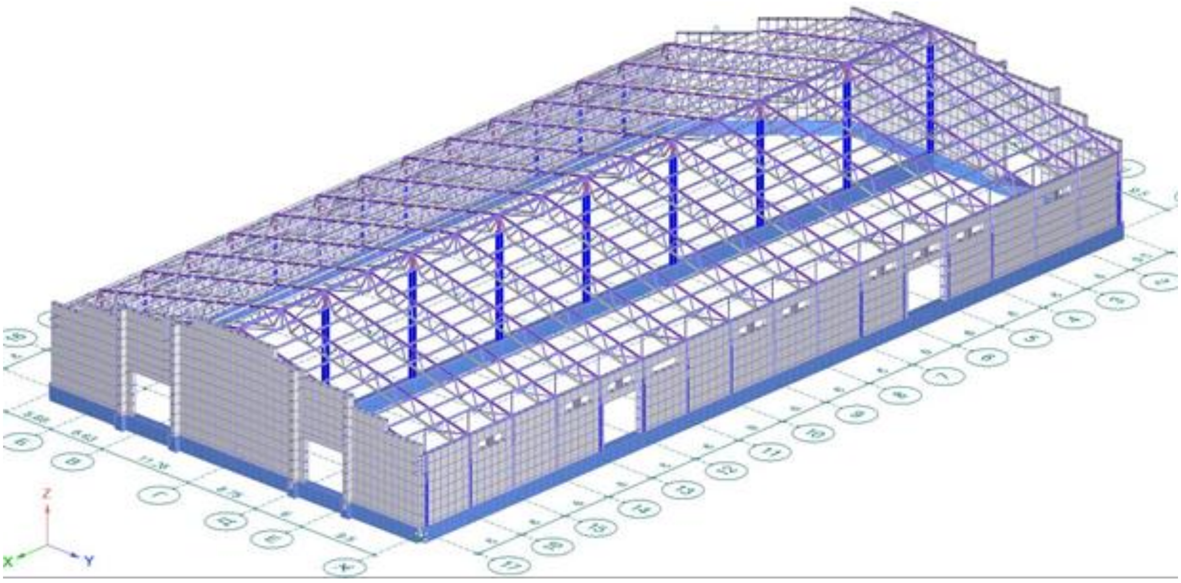
The model accounts for all of the supporting elements: columns, walls, metal frame trusses with the precise purpose of the rod sections according to the survey. At the 1st stage of modeling, the geometric variability of the scheme was identified with the existing truss design solution. 4 options for reinforcing structures with additional core elements were thus explored, and the 1st reinforcement option was recommended, i.e., installing additional strut rods between the lower girdle of the trusses and the metal column, as well as of additional connections between the trusses in order to increase the overall rigidity of the frame. At the same time, those were only constant loads, snow and wind that were specified.

a)

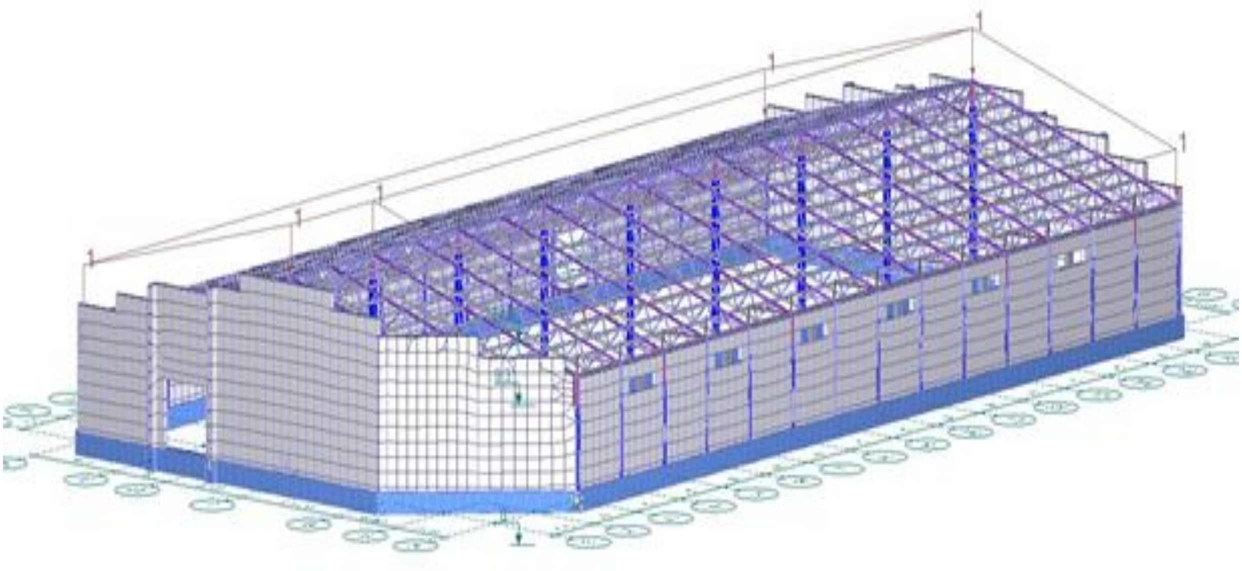
b)

c)

Fig. 5. Examined building of an agricultural warehouse under construction with exterior walls made of LEGO blocks (Tselina town, February 2025): *a* — facade in axes A–W; *b* — facade in axes 17–1; *c* — frame elements



a)



b)

Fig. 6. General view of the 3D model of the building: *a* — view from the facades A–G and 17–1;
b — view from the facades G–A and 1–17

At the 2nd stage of the simulation, the operability and stability of the structure against horizontal operating loads were tested that resulted in the loss of stability of structures of non-reinforced walls made of LEGO blocks being established even with minimal loading of bulk material (with grain). Due to no chance of using non-reinforced walls made of concrete LEGO blocks for perceiving calculated operational loads, scientific and technical cooperation with Tselinskagrokhim-service JSC was commissioned by the employees of the DSTU Department of Engineering Geology, Basements and Foundations, which included:

– examining positive and negative experiences of construction and operation of buildings and structures made of LEGO blocks;

– analyzing the advantages and disadvantages of the well-known LEGO blocks, as well as buildings and structures built from them;

– developing constructive solutions to improve LEGO blocks in order to reinforce the masonry of these blocks;

– analyzing the operational loads acting on load-bearing walls from the storage of various materials and products: liquid fertilizer and grain;

– developing a computer model of a wall made of LEGO blocks in the Lira 10 PC and assessing the stress-strain state under various loads and wall heights;

– developing the recommendations for designing load-bearing reinforced walls made of LEGO blocks.

The major aim of the study is scientific substantiation and development of technical solutions to allow the use of concrete LEGO blocks in load-bearing structures that accept horizontal operational loads. Due to a possibility of storing liquid and bulk materials with different densities of ρ, t/m^3 inside the premises (containers) made of LEGO blocks, the calculation and selection of reinforcement of masonry made of LEGO blocks was performed for walls up to 15 m high at operating loads up to 13 m high for 2 different options:

– depending on the weight of the fertilizer-32 (ρ = 1.32 t/m^3);

– from the weight of the grain (ρ = 0,8 t/m^3) accounting for the dynamic loads from the loader.

As a result of the analysis of domestic [15–18, 23] and overseas [21, 22, 24–26] experiences in designing and constructing buildings and structures made of LEGO blocks, including those designed using 3D printing [24], it was found that the major disadvantage of masonry made of such blocks is its low resistance to horizontal (shear and tipping) loads that might occur during the operation of buildings and structures for storing bulk and liquid materials.

In this case, there are tensile stresses in the masonry causing excessive deformations and even complete destruction of such structures, which has been confirmed by some negative experiences of operating them.

Reinforcement of individual blocks would increase the strength of each block rather than the strength of their connection to each other. The main direction of improving the masonry of concrete LEGO blocks is thus its reinforcement with vertical reinforcing rods connecting a few concrete blocks in height. This solution serves to significantly increase the strength of the masonry and creates favorable conditions for perceiving horizontal operational loads from the weight of bulk or liquid materials.

In order to enable reinforcement of masonry in LEGO blocks, solid vertical holes are to be provided during their manufacture that can be formed by placing them in the form of removable rods or pipes of a specified diameter. While designing LEGO blocks that enable their vertical reinforcement, an essential engineering task is to select the rational placement of holes in the block. While solving the problem at hand, the following factors were accounted for:

– geometric parameters of the blocks and the distance in a row between the axes of adjacent spike-groove joints (250 mm);

– a protective layer of concrete to the operating reinforcement as specified in Table 2 of GOST 13015-2015 "Concrete and Reinforced Concrete Products for Construction", from 15 to 35 mm, depending on the operating conditions of the building structures;

– stress distribution in the masonry under horizontal operational loads.

As the maximum tensile stresses in the masonry from horizontal operational loads will be in the upper blocks from the side of the load (from inside the building or structure), the reinforcement and thereby the vertical holes in the blocks under it must be shifted towards the side of the load.

Given all of the above, the suggested design of the improved LEGO block provides for vertical holes with a diameter of 50 mm located at a distance of 250 mm from each other. The distance from the axis of the holes to the inner side of the block is 125 mm, so the protective layer of concrete will be 100 mm ± 15 mm. An example of the design of such an improved LEGO block for the standard size 500×1500×600 mm is in Fig. 7.

Vertical holes for reinforcing masonry in blocks of other standard sizes are formed in a similar way to the above drawing.

For the developed LEGO blocks, the VAT of wall structures was calculated and the required reinforcement was selected. Two impacts are perceived by the wall structures: net weight and lateral pressure from the useful load. The useful load is represented by the hydrostatic pressure of the liquid fertilizer KAS-32 or the pressure of the bulk medium, i.e., grain (wheat). The walls are made of masonry concrete LEGO blocks on a cement-sand mortar. The thickness of the blocks is 500 mm. The concrete class accepted for calculation is B25.

Table 1 shows the physical and mechanical characteristics of the grain used for load modeling and calculation. As the load from wheat is the most disadvantageous one, it was decided to calculate the impact of this type of bulk medium.

The lateral pressure on the wall from the bulk medium is given by the formula:

$$P = \gamma \cdot h \cdot \mathrm{tg}^2(45\,° - \varphi/2),$$

where γ is the specific gravity of wheat, kN/m^3; h is the height of the filling, m; φ is the angle of internal friction, degrees.

The results of calculating the pressure on the wall from the weight of the grain depending on the height of the filling are summarized in Table 2.

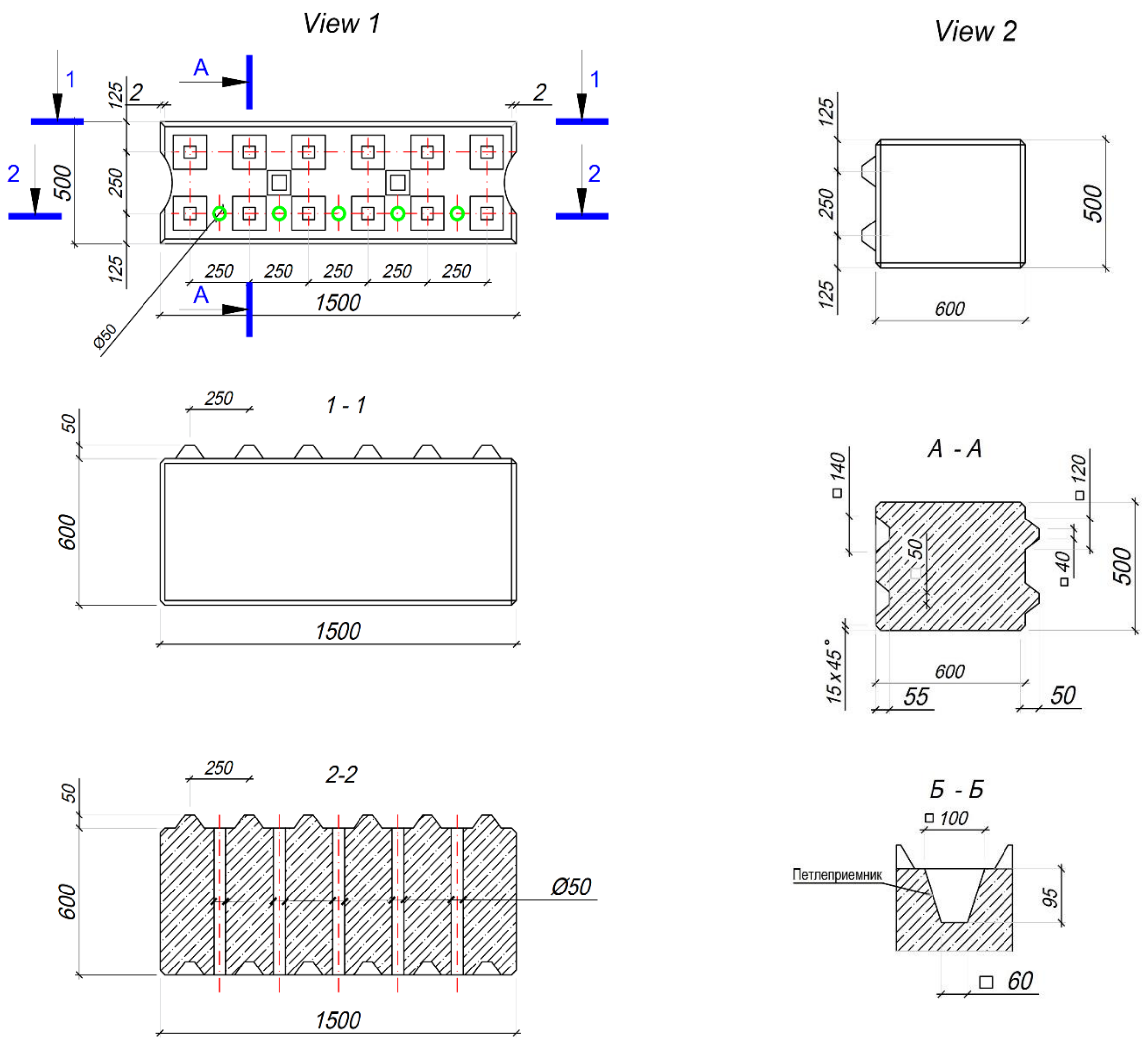


Fig. 7. Design of an improved LEGO block for the formation of reinforced masonry

Table 1

Physical and mechanical characteristics of the grain

Grain material	Average grain diameter *d*, mm	External friction angle ψ, °	Internal friction angle φ, °	Humidity, %	Density ρ, kg/m^3
Wheat	3.8	22.1	17.5	14.4	808
Sunflower	5.0	26.6	16.7	14.7	450
Corn	7.1	22.4	18.4	16.6	783
Millet	2.2	20.2	15.1	15.0	770

Table 2

Calculated pressure on the wall depending on the weight of the grain

Filling height, m	3	4	5	6	7	8	9	10	11	12	13	14	15
Maximum pressure at the lower face, kPa	13	17	22	26	30	34	39	43	47	52	56	60	65

The formula for calculating the pressure from liquid fertilizer CAS-32 is as follows:

$$P = \gamma \cdot h,$$

where γ is the specific gravity of liquid fertilizer CAS-32, kN/m^3; *h* is the height of the hydrostatic column, m.

The results of calculating the pressure on the wall from the liquid fertilizer CAS-32 depending on the height of the hydrostatic column are summarized in Table 3.

Table 3

Pressure on the wall from CAS-32

Height of the hydrostatic column, m	3	4	5	6	7	8	9	10	11	12	13	14	15
Maximum pressure at the lower face, kPa	39.6	52.8	66.0	79.2	92.4	105.6	118.8	132.0	145.2	158.4	171.6	184.8	198.0

The reinforcement pitch in the block is 250 mm with a connection to the outer face is 100 mm.

The loads on the walls from the hydrostatic pressure of the fertilizer CAS-32 with a column height of 3 to 7 m for walls with a height of 3 to 15 m were calculated. The summary of the maximum wall movements under operational loads in comparison with the maximum permissible movements, mm (according to Table L2 SP 20.13330.2016 "Loads and Impacts") is shown in Table 4.

According to Table 4, the height of the hydrostatic column of liquid (CAS-32) should not be over 6 m. With a higher fluid height, structural deformations are above those allowed for any wall height (7–15 m). In Table 4 and 5, the values of horizontal displacements that are unacceptable according to SP 20.13330.2016 are highlighted in red.

Table 4

Summary of horizontal movements of wall structures under the liquid fertilizer CAS-32

		Maximum horizontal movement, mm at the wall structure height, m:												
		3	4	5	6	7	8	9	10	11	12	13	14	15
Height of the hydrostatic column CAS-32, m	3	0.37	0.52	0.67	0.83	0.98	1.13	1.29	1.44	1.59	1.75	1.9	2.05	2.21
	4		1.55	2.04	2.52	3.01	3.49	3.98	4.47	4.95	5.44	5.92	6.41	6.89
	5			4.74	5.93	7.12	8.3	9.49	10.7	11.9	13.1	14.3	15.4	16.6
	6				11.8	14.3	16.7	19.2	21.7	24.1	26.6	29.1	31.5	34
	7					**25.6**	**30.1**	**34.7**	**39.3**	**43.9**	**48.4**	**52**	**57.4**	**62.2**
Maximum permissible horizontal movement, mm (SP 20.13330.2016)		10	13.3	16.7	20	23.3	26.7	30	33.3	36.7	40	43.3	46.7	50

The loads on the walls from the lateral pressure of the grain mound with a height of 3 to 9 m for walls with a height of 3 to 15 m were calculated. The summary of the maximum wall movements due to operational loads in comparison with the maximum permissible movements, mm (according to Table L2 SP 20.13330.2016) is shown in Table 5.

Table 5

Summary of horizontal movements of wall structures under the action of the grain

		Maximum horizontal movement, mm at the wall structure height, m:												
		3	4	5	6	7	8	9	10	11	12	13	14	15
Grain filling height, m	3	0.15	0.21	0.27	0.33	0.39	0.45	0.51	0.59	0.63	0.69	0.75	0.81	0.87
	4		0.6	0.79	0.97	1.16	1.35	1.54	1.73	1.91	2.1	2.29	2.48	2.66
	5			1.9	2.4	2.9	3.3	3.8	4.3	4.8	5.2	5.7	6.2	6.7
	6				4.7	5.6	6.6	7.6	8.5	9.5	10.5	11.5	12.4	13.4
	7					9.96	11.7	13.5	15.3	17.1	18.9	20.7	22.4	24.2
	8						19.3	22.3	25.3	28.3	31.3	34.4	37.4	40.4
	9							**35.4**	**40.4**	**45.3**	**50.2**	**55.2**	**60.1**	**65**
Maximum permissible horizontal movement, mm (according to SP20.13330.2016)		10	13.3	16.7	20	23.3	26.7	30	33.3	36.7	40	43.3	46.7	50

According to Table 5, the height of the grain filling should not be over 8 m. With a higher height of the grain filling, structural deformations exceed those allowed for any wall height (9–15 m).

As a result of modeling all the possible combinations of wall height and load height from liquid fertilizer CAS-32 and grain filling, the recommended masonry reinforcement parameters are calculated as shown in Table 6 and 7, respectively. The tables show both the values of the total reinforcement area per 1 square meter of the wall structure and the specific diameters of the reinforcement rods calculated based on the reinforcement pitch of 250 mm (i.e., 4 rods per 1 square meter).

Table 6

Summary of the required reinforcement at the stretched face of the wall structures under the liquid fertilizer CAS-32, cm^2 per 1 p. m. (at a pitch of 250 mm)

		Required reinforcement area, cm^2, and reinforcement diameter, mm at the wall structure height, m:												
		3	4	5	6	7	8	9	10	11	12	13	14	15
Height of the hydrostatic column CAS-32, m	3	2.60 Ø10	2.39 Ø10	2.14 Ø10	1.96 Ø8	1.78 Ø8	1.59 Ø8	1.41 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8
	4		7.49 Ø16	7.57 Ø16	7.29 Ø16	7.02 Ø16	6.78 Ø16	6.87 Ø16	6.63 Ø16	6.21 Ø16	6.09 Ø14	5.91 Ø14	5.73 Ø14	5.57 Ø14
	5			17.1 Ø25	16.7 Ø25	17.0 Ø25	16.6 Ø25	16.9 Ø25	16.5 Ø25	16.1 Ø25	16.5 Ø25	16.1 Ø25	15.7 Ø25	15.3 Ø25
	6				35.1 Ø36	33.9 Ø36	35.0 Ø36	34.3 Ø36	33.7 Ø36	34.8 Ø36	34.2 Ø36	33.5 Ø36	34.6 Ø36	34.0 Ø36
	7					**62.0**	**60.9**	**62.9**	**61.8**	**60.7**	**62.5**	**61.2**	**59.9**	**61.4**
Maximum permissible horizontal movement, mm (according to SP20.13330.2016)		10	13.3	16.7	20	23.3	26.7	30	33.3	36.7	40	43.3	46.7	50

Note: based on the minimum percentage of reinforcement, it is recommended that rods with a diameter of at least 14 mm are used.

Table 7

Summary of the required reinforcement at the stretched face of the wall structures from the action of grain, cm^2 per 1 p. m. (at a pitch of 250 mm)

		Required reinforcement area, cm^2, and reinforcement diameter, mm at the wall structure height, m:												
		3	4	5	6	7	8	9	10	11	12	13	14	15
Grain filling height, m	3	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8
	4		2.21 Ø10	1.94 Ø8	1.76 Ø8	1.57 Ø8	1.4 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8
	5			5.53 Ø14	5.32 Ø14	5.11 Ø14	4.92 Ø14	4.74 Ø14	4.56 Ø14	4.38 Ø12	4.21 Ø12	4.04 Ø12	3.89 Ø12	3.70 Ø12
	6				10.6 Ø20	10.6 Ø20	10.4 Ø20	10.1 Ø18	10.3 Ø20	9.94 Ø18	9.65 Ø18	9.83 Ø18	9.55 Ø18	9.06 Ø18
	7					18.8 Ø25	18.3 Ø25	18.7 Ø25	18.3 Ø25	17.8 Ø25	18.3 Ø25	17.8 Ø25	17.4 Ø25	17.9 Ø25
	8						32.1 Ø32	31.5 Ø32	30.9 Ø32	30.3 Ø32	31.2 Ø32	30.7 Ø32	30.0 Ø32	31.0 Ø32
	9							**52.3**	**51.0**	**52.3**	**50.8**	**52.1**	**51.4**	**50.7**
Maximum permissible horizontal movement, mm (according to SP20.13330.2016)		10	13.3	16.7	20	23.3	26.7	30	33.3	36.7	40	43.3	46.7	50

Note: based on the minimum percentage of reinforcement, it is recommended that rods with a diameter of at least 14 mm are used.

The following possible connections are recommended for reinforcing bars in the masonry of LEGO blocks (according to SP 63:13330.2018 "Concrete and Reinforced Concrete Structures"): threaded coupling; crimped coupling; lap-welded according to GOST 14098-2014 "Joints of Welded Fittings and Embedded Products of Reinforced Concrete Structures" (type C23). The length of the reinforcement joint must be accepted in compliance with SP 63.13330.2018 and the recommendations of the coupling manufacturer.

Conclusion. Based on the analysis of spatial planning and architectural solutions of warehouse and storage buildings and structures of the agroindustrial complex, single-storey frame-type warehouses, bunker (storage) and silo (tower) tanks have been found to be primarily used in both domestic and overseas practice. The major feature of the operation of such facilities is the time-varying horizontal operating loads from the weight of liquids or bulk materials. The analysis of the advantages and disadvantages of the existing agricultural storage facilities has revealed the relevance of developing new highly effective, prefabricated, reliable and safe throughout the life cycle of constructive and technological solutions for such facilities. Using the example of an agricultural warehouse building under construction in Tselina town of the Rostov region, its technical condition, measurement work were examined, the engineering and geological conditions were investigated, and a mathematical 3D model was developed using which the VAT of structures for operating loads was studied. As a result of the simulation, it was found that the masonry of non-reinforced LEGO blocks does not provide structural strength even with a minimum loading height of bulk or liquid material.

The major direction of improving the masonry of LEGO concrete blocks is its reinforcement with vertical reinforcing rods connecting a few concrete blocks in height. The solution serves to significantly increase the strength of the masonry and creates favorable conditions for perceiving horizontal operational loads from the weight of bulk or liquid materials. The authors have thus improved the design of concrete LEGO blocks produced by TD Mineral LLC according to TU 23.61.12-001-86245892-2025 "Concrete Blocks of the Lego Type". The suggested design of the improved LEGO block provides for vertical holes with a diameter of 50 mm located at a distance of 250 mm from each other. The distance from the axis of the holes to the inner side of the block is 125 mm, so the protective layer of concrete will be 100 mm ± 15 mm. The blocks in the masonry must be oriented with the reinforced side in the direction of the horizontal operating load from the side of the bulk or liquid material. Mathematical models have been employed in order to select rational reinforcement parameters for LEGO block masonry for various combinations of warehouse height and height of bulk material (grain) or dense liquid (fertilizer CAS-32).

The results presented in the article can be routinely used in design and construction of warehouse and storage facilities of the agro-industrial complex, while the major advantages of implementing the suggested structural solutions of reinforced masonry from LEGO blocks are high construction rates, adaptability, possibility of increasing horizontal loads from bulk or liquid materials on external load-bearing walls, a more rational use of the internal volume of the premises, etc.

The new design solution enables one to reinforce LEGO blocks and build warehouses up to 10–15 m high while filling with grain up to 8 m or filling with fertilizer KAS-32 up to a height of 6 m. This greatly expands the scope and technical and economic indicators of such facilities. The recommended schemes for reinforcing masonry made of LEGO blocks with rational combinations of the specified maximum wall height and the height of loading warehouses with products will optimize storage costs while maintaining the operational reliability of a facility throughout its life cycle.

As a follow-up, it is planned to develop curved LEGO blocks for forming round objects (silos, bunkers) as well as a system for monitoring the stress-strain state of such structures throughout their entire operation period.

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AYu Prokopov: formation of the basic concept, aims of the study, modeling and calculations, analysis of the research results, revision of the manuscript, correction of the conclusions.

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Original Empirical Research

Correlations between the Strength and Electrical Resistance of Concrete. Part 1. A Brief Overview

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Abstract

Introduction. The existing methods of non-destructive testing of concrete strength entail access to the concrete surface, which is not always possible to accomplish in concrete work technology. E.g., while continuously forming a structure in a sliding formwork, it is required that the strength of the concrete is identified during the molding process with no direct access to the layers of the hardening concrete mix being laid. The well-known method of identifying concrete strength by means of measuring its electrical resistance is neither commonly used nor standardized, and tends to yield contradictory results. The aim of the study of the first part of the article is to investigate the previously identified correlations between the concrete strength and its electrical resistance, to identify the advantages and disadvantages of measurement methods in order to find how feasible such an approach is for identifying a method for sinking concrete.

Materials and Methods. The classical method of literature review is employed with grouping of certain features into separate comparative tables followed by generalization assisting understanding an extent to which the research topic has been studied. Those were only the most important and informative, largely foreign, sources that were selected from the reviewed sources.

Research Results. The analysis of the review data enabled us to identify the methods of measuring electrical resistance (surface, volumetric, internal, direct ones), types of the investigated concrete, sample sizes, test dates, concrete strength ranges, types of dependencies and correlation coefficients. Among the factors affecting the measurement result were the following: water-cement ratio, type of binder and aggregates, type of additives, temperature of concrete, its porosity, etc. To explain the essence of the methods for identifying concrete electrical resistance, a brief overview is provided.

Discussion and Conclusion. The major difficulty of the indirect methods of identifying the strength lies in designing calibration dependencies with the results affected by a wide range of factors. There are also some difficulties with fastening of ohmic contacts to the formwork or concrete. All of these will be accounted for in follow-up studies to identify the relationship between the concrete strength and electrical resistance and to improve the measurement accuracy. The advantages of the method of strength control, such as maintaining the integrity of the structure, efficiency and low measurement complexity enable it to be employed in automated concrete technologies.

Keywords: non-destructive testing methods, concrete strength, concrete electrical resistance, concrete technology, correlation

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Оригинальное эмпирическое исследование

Корреляции между прочностью и электрическим сопротивлением бетона. Часть 1. Краткий обзор

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Аннотация

Введение. Существующие методы неразрушающего контроля прочности бетона предполагают доступ к поверхности бетона, что не всегда возможно в технологии бетонных работ. Например, при непрерывном формовании конструкции в скользящей опалубке требуется определять прочность бетона в процессе формования без непосредственного доступа к уложенным слоям твердеющей бетонной смеси. Известный метод определения прочности бетона посредством измерения его электросопротивления редко используется, не стандартизирован и часто приводит к противоречивым результатам. Целью исследования первой части статьи является изучение обнаруженных ранее корреляций между прочностью бетона и его электросопротивлением, выявление преимуществ и недостатков методов измерений, чтобы выяснить целесообразность такого подхода для способа опускающегося бетона.

Материалы и методы. Применен классический метод обзора литературы с группированием определенных признаков в отдельные сравнительные таблицы с последующим обобщением, что облегчает понимание разработанности темы статьи. Из рассмотренных источников были выбраны только самые важные и информативные, в основном, иностранные.

Результаты исследования. Анализ данных обзора позволил установить: способы измерения электросопротивления (поверхностный, объёмный, внутренний, прямой), типы исследованных бетонов, размеры выборок, сроки испытаний, диапазоны прочности бетона, типы зависимостей и коэффициенты корреляции. Среди факторов, влияющих на результат, измерений отмечены: водоцементное отношение, тип вяжущего и заполнителей, вид добавок, температура бетона, его пористость и др. Для пояснения сути методов определения электросопротивления бетона приведена краткая информация.

Обсуждение и заключение. Основной сложностью в косвенных методах определения прочности является построение градуировочных зависимостей, на результаты могут оказывать влияние различные факторы. Трудности связаны также с креплением омических контактов на опалубку или бетон. Все эти особенности будут учтены в дальнейших исследованиях для определения связи между прочностью и электросопротивлением бетона и повышения точности измерений. Преимущества рассмотренного способа контроля прочности, такие как сохранение целостности конструкции, оперативность и малая трудоёмкость измерений, обуславливают его применение в автоматизированных бетонных технологиях.

Ключевые слова: неразрушающие методы испытаний, прочность бетона, электрическое сопротивление бетона, технология бетона, корреляция

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Introduction. In the patented technology of sinking concrete developed at South Ural State University [1] and in other automated concrete technologies, there is a task of controlling concrete strength directly in the mold (formwork), which allows no access to a concrete surface for traditional methods of non-destructive testing. The possibility of assessing the strength of concrete by its electrical resistance was accepted as a hypothesis with monitoring sensors easily placed on the formwork and requiring no stopping of production and access to the structure.

Concrete strength tests must be conducted in compliance with the requirements of GOST 28570 "Concretes. Methods for Identifying Strength Based on Samples Taken from Structures", GOST 22690 "Concretes. Identifying Strength with Mechanical Methods of Non-Destructive Testing", GOST 17624 "Concrete. Method for Identifying Ultrasonic Strength", GOST 18105 "Concrete. Rules for Strength Control and Evaluation", GOST 10180 "Concretes. Methods for Identifying

Strength Using Control Samples". There are three groups of concrete strength control methods: destructive, non-destructive direct and non-destructive indirect ones. The first group of methods enables one to obtain the most reliable data on concrete strength, as the deep layers of the structure are tested, but they are labour-intensive during testing and call for local damage in structures to be fixed. At the same time, non-destructive methods retain the structure integrity, are relatively not costly, but call for calibration dependencies to be designed for each concrete type and composition. At the same time, a broad range of factors has a major effect on the measurement accuracy, such as defects and fittings in the measuring area, concrete surface condition, temperature, humidity, etc. [2].

Materials and Methods. Non-destructive testing is an essential part of the technology of production and application of ready-mixed concrete and precast reinforced concrete. Modern standards establish the mandatory use of non-destructive methods in order to identify concrete strength based on pre-established calibration dependencies [3]. The complexity of non-destructive testing lies directly of measuring a parameter with a device (striker rebound, impact pulse, ultrasound velocity, fingerprint diameter, etc.) after an appropriate number of measurements has been performed.

However, the above standards fail to standardize the method of electrical resistance strength control. According to the literature on the topic [3–13], electrical resistance is largely closely related to concrete strength, but calls for proper calibration and accounting for the parameters of the mix, and for certain types of concrete there might be no or a negative correlation.

The literature review explored the following research aspects: concrete type, sample size, method of measuring electrical resistance, concrete strength range, correlation coefficient type, influencing factor type and influence outcome.

Research Results. Measurements of electrical resistance have different correlations with concrete compressive strength. The studies [4] identified a logarithmic dependence, and at the same time, the authors of [8] using the Venner probe confirm a strong nonlinear logarithmic dependence ($R^2 > 0{,}99$). In [10] it is concluded that the methods of internal electrical resistance reliably predict the strength of mixes with different properties of binder and filler. This study also serves as evidence of a strong positive correlation (R^2 values from 0,823 to 0,999). On the contrary, the authors of [12] failed to identify a considerable correlation in electrically conductive concretes, and [7] notes a negative correlation while replacing a large aggregate with steel slag (which appears to make sense).

Some studies also show that the parameters of the concrete mix, such as the ratio of water and cement or water and binder, the cement type and the use of additives (zeolite or pozzolan) impact both electrical resistivity and strength [9]. Different methods of measuring resistance also have an effect on the correlation strength [10]. These results show that provided proper calibration is performed and the influencing factors are accounted for, measurements of electrical resistivity can serve as a practical non-destructive method for evaluating concrete strength of building materials [8]. The key characteristics of the studies are shown in Table 1.

Table 1

Key characteristics of the studies included

Researchers, source	Concrete type	Sample size	Research duration
Araújo and Meira, 2022 [4]	Six different mixes	No mention found	No mention found
Deda, 2020 [10]	24 mixes with a different content of fillers, water-binder ratio, additives	24 mixes	Up to 28 days
Dehghanpour and Yılmaz, 2019 [12]	Electrically conductive concrete with carbon fiber and black carbon	8 mixes and control series	28 days
Hnin et al., 2016 [13]	Different water-binder ratio, ash-cement paste content	No mention found	No mention found
Medeiros-Junior et al., 2014 [9]	12 mixes with four types of Brazilian cement	12 mixes	The same
Medeiros-Junior et al., 2019 [6]	Mixes with two cement types and different pozzolan content	No mention found	The same
Nzar et al., 2022 [7]	Normal strength concrete with steel slag waste as a coarse aggregate	338 data points	1–180 days
Scasserra et al., 2023 [8]	Precast reinforced concrete	No mention found	Up to 28 days
Silva et al., 2016 [5]	No mention found	The same	Up to 28 days
Yurt et al., 2023 [11]	Alkali-activated concrete composites	4 mixes	28 days
Stackelberg et al., 2010 [3]	Cement-concrete composites	8 mixes	No mention found

An analysis of the studies included revealed the following.

Concrete types: in 6 studies a few mixes with different compositions were used; in 4 studies, specialized concretes (e.g., electrically conductive, precast, alkali-resistant) were used; in one study, no information on the concrete type was found.

Sample size: mentioned in 6 studies and is not indicated in 5 studies. The reported sample size ranged from 4 to 24 mixes, and one study included 338 data points.

Study duration: there are mentions of study duration in 6 studies; there are no mentions in 5 studies. Of these, 3 studies took up to 28 days to complete, two studies took exactly 28 days to complete, and one study lasted from 1 to 180 days.

The analyzed studies to identify the correlation type between the electrical resistance and concrete strength, the research results are summarized in Table 2.

Table 2

Correlations between the electrical resistance and strength

Researchers, source	Method of electrical resistance studies	Strength range	Correlation coefficient	Results
Araújo and Meira, 2022 [4]	Surface electrical resistance	No mention found	No mention found	The logarithmic ratio
Deda, 2020 [10]	Volumetric, surface and internal	The same	The same	Electrical resistance is reliable for strength prediction
Dehghanpour and Yılmaz, 2019 [12]	Dual Probe Sensor, Venner Method and ASTM C1760-12	The same	Not relevant	No correlations to mention
Hnin et al., 2016 [13]	Four Venner probes	The same	No mention found	A good correlation
Medeiros-Junior et al., 2014 [9]	Surface electrical resistance	The same	R^2 = 0.823–0.999	A strong positive correlation
Medeiros-Junior et al., 2019 [6]	No mention found	The same	No mention found	The inverse proportionality of the water-cement ratio (w/c)
Nzar et al., 2022 [7]	The same	10–55 MPa	The same	Negative correlation with steel slag
Scasserra et al., 2023 [8]	Venner's method (four-probe)	No mention found	$R^2 > 0.99$	Strong nonlinear logarithmic correlation
Silva et al., 2016 [5]	No mention found	The same	No mention found	A close bond
Yurt et al., 2023 [11]	Direct measurement (megaohmmeter)	The same	The same	Strong bond, decrease in the strength as the proportion of zeolite in the composition rises
Stackelberg et al., 2010 [3]	No mention found	2–72 MPa (according to the graphs)	The same	A linear or close to linear correlation

Let us provide a brief explanation of the essence of the major methods employed. The two-probe method (a sensor) is used to measure the resistivity of samples with a regular geometric shape and a constant cross-section. In this case, ohmic contacts are made on the end faces of a sample, e.g., in the form of a rectangular plate, i.e., contacts between a metal and a semiconductor or two dissimilar semiconductors with linear and symmetrical volt-ampere characteristics. An electric current is passed through these contacts along the sample. Two contacts in the form of metal probe needles are installed on a sample surface along the current lines, which have a small contact area with the surface and allow the potential difference to be measured. If the sample is homogeneous, its resistivity is measured in Ohm · cm.

The four-probe method for measuring the resistivity of semiconductors (the Wenner method) is the most common one. In addition to high metrological parameters, the advantage of the method is that its application does not call for designing ohmic contacts to the sample, it is possible to measure the resistivity of bulk samples of a wide range of shapes and sizes, as well as the resistivity of layers of semiconductor structures. As far as the sample shape is concerned, it can be used provided that there is a flat surface with the linear dimensions beyond those of the probe system. Four probes placed at an equal distance are applied to the sample in a line. Two external probes supply current to the sample, and two internal probes measure the resulting potential drop. All the probes are mounted on the same sample surface making the method suitable for on-site measurements of bulk concrete resistivity.

The method according to the ASTM C1760-12 standard is designed to identify the volumetric electrical conductivity of saturated samples of hardened concrete. The aim of the method is provide a quick evaluation of concrete resistance to chloride ion penetration by means of diffusion. The measurement procedure is as follows:

1) a cylindrical sample with a diameter of 10 cm and a length of 20 cm is placed between two cells filled with a sodium chloride solution;

2) A potential of 60 volts is applied between the cells;

3) the total amount of current in a minute between two cells is measured;

4) based on the measured current, applied voltage, and sample size, the volumetric concrete electrical conductivity is calculated.

The measurement results were influenced by a number of factors, including the water-cement materials ratio, the type and quantity of additional cement materials, polymer additives, etc.[1]

The analysis of the correlations of electrical resistance and strength revealed the following. References to methods of identifying electrical resistance were found in all of the studies:

– surface methods were mentioned in 3 studies;

– Venner's methods were mentioned in 3 studies;

– the other methods (internal, volumetric according to ASTM C1760-12, direct) were mentioned in individual studies;

– no mention of a specific method was found for 4 studies.

Correlation coefficients: correlation coefficients were mentioned in 3 studies:

– a strong correlation was reported in two studies ($R^2 > 0.99$ or $R^2 = 0.823–0.999$);

– in one study, it was concluded that there was no considerable correlation (corresponding to $r < 0.6–0.7$ in technical sciences).

The importance of the mutual bonds: all of the studies provided some information on the significance of a relationship between electrical resistance and concrete strength:

– logarithmic dependencies were reported in 2 studies;

– strong ratios with no type specification were reported in 2 studies;

– a negative correlation with concrete additives was found in 2 studies (steel slag, zeolite);

– individual studies reported: a linear or close to linear correlation, inconsiderable correlation, good correlation, inverse dependence on the water-dry matter ratio, as well as a correlation from the internal electrical resistance reliable for predicting the strength.

Concrete strength range: the concrete strength range was mentioned in only 2 studies (10–55 and 2–72 MPa).

The influencing factors were directly indicated in most of the studies included (Table 3).

The analysis of the influencing factors showed the following.

Types of the factors: The types of factors are indicated in all of the studies included. The most common factors were the water-binder ratio and temperature mentioned in 2 studies. Each of the other 14 factors was mentioned in only one study.

The effect on electrical resistance was indicated in 8 studies: various factors were report to influence electrical resistance in 4 studies; in each of the 11 studies, a significant effect was reported: increased conductivity, decreased electrical resistance, or that it depends on time and water-cement ratio (w/c).

The effect on the strength was mentioned in 7 studies: the experiments revealed a considerable or enhanced strength; each study reported that strength depends on the cement type, water-cement ratio, porosity, additives, and decreases when zeolite is added. No mention of the effect on the resistance in 2 studies and the effect on the strength in 4 studies was found.

[1] Note:the ASTM C1760-12 method was abolished in January 2021

Different methods of measuring the electrical resistivity were used in the studies, including surface, volumetric and internal ones. Although a direct comparison of accuracy and reliability in all of the studies is limited due to a wide range of approaches being employed, a few key conclusions can be made.

Table 3

Description of the influencing factors

Researchers, source	Factor type	Impact on the electrical resistance	Impact on the strength
Araújo and Meira, 2022 [4]	No mention found	No mention found	No mention found
Deda, 2020 [10]	A binder type, a filler nature	Considerable impact	Considerable impact
Dehghanpour and Yılmaz, 2019 [12]	Carbon fiber, black nanocarbon	Increased conductivity	Enhanced strength
Hnin et al., 2016 [13]	Water/binder ratio, fly ash content	Influenced by the factors	Influenced by the factors
Medeiros-Junior et al., 2014 [9]	Cement type, water/binder ratio	Increases with time, decreases as the w/c ratio rises	Depends on the cement type
Medeiros-Junior et al., 2019 [6]	Pozzolan content in the water/cement ratio (w/c)	Higher with a larger amount of pozzolan, lower with a higher w/c ratio	Lower with a higher w/c
Nzar et al., 2022 [7]	Steel slag content	Reduced	Increased
Scasserra et al., 2023 [8]	Temperature, shape, sample size	Influenced by the factors	No mention found
Silva et al., 2016 [5]	Temperature	Influenced by the temperature	The same
Yurt et al., 2023 [11]	Zeolite replacement, activation temperature	Influenced by the factors	Decreases as the zeolite content rises
Stackelberg et al., 2010 [3]	Porosity of the cement stone and cement-concrete compositions	Proportional to the increase in the gel porosity	Proportional to the increase in the strength

Surface and internal measurements: in [10] the methods of internal electrical resistance proved to be especially reliable for predicting compressive strength. This is indicative of likely differences in accuracy between surface and internal measurement methods.

Comparison of a few methods: in [12], three different methods were compared (two-probe, Venner method and ASTM C1760-12). Although none of them was able to identify a significant relationship with the strength of conductive concretes, the linear relationships between the resistivity values measured by means of these methods proved to be appropriate indicating the consistency of the results obtained using a range of measurement methods.

Using Venner probes: in [8, 12, 13] the Venner probe method was used indicating its wide application range in this kind of studies. The authors of [8] reported a very strong correlation ($R^2 > 0.99$) while using this method indicating its potential reliability.

Special equipment: The researchers [11] made use of a megaohmmeter to directly measure resistance, which might be an advantage for some concrete types (e.g., for alkali-activated composites).

Discussion and Conclusion. The studies identified a few potential practical applications of measuring electrical resistivity to evaluate concrete strength.

Non-destructive testing: In [8] the importance of using electrical resistance as a non-destructive method for evaluating concrete strength in producing precast reinforced concrete structures is emphasized.

Concrete strength evaluation at an early age: the researchers [5] demonstrated the possibility of predicting strength at the age of 28 days by measuring resistivity at an early age.

Quality control: The strong correlations identified in most of the studies suggest that resistivity measurement can be employed as a fast and efficient method of continuous quality control in concrete production [3, 4, 8–10].

Specialized concretes: Studies of conductive concretes [12] and alkali-activated composites [11] show that resistivity measurements can have unique applications in specialized types of concrete, although the dependencies might differ from those for conventional concretes.

The authors of [8] noted the need for calibration and use of correction factors emphasizing the importance of developing standardized procedures for diverse types of concrete and applications to ensure reliable strength evaluation.

As indicated in an article looking back on lots of years of research [3], the correlations between the strength of cement-concrete compositions and their electrical conductivity are either linear or close to linear ones. In the ongoing study we have attempted to reveal the physical essence of the linear correlations of "strength-electrical resistance". At the same time, it is shown that linear correlations depend on the type and amount of a hardening retarder additive, cement brand and concrete class. The increase in electrical resistance is due to that in the gel component of the porosity formed during hardening, as well as a change in its own electrical conductive properties [3].

Therefore, having considered the advantages and disadvantages of the existing concrete strength control methods, what was clear was that a non-destructive strength control method by means of electrical resistance (indirect method) is applicable for the sinking concrete method. In order to identify further research directions and a method of measuring electrical resistance, the results of the recent research were analyzed with comparative tables designed according to a number of criteria where research methods, sample features, sample sizes, type and degree of correlation, and influencing factors were identified. The analysis was a foundation for further research on a relationship between electrical resistance and concrete strength that the authors are going to report in the second part.

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СТРОИТЕЛЬНЫЕ МАТЕРИАЛЫ И ИЗДЕЛИЯ

BUILDING MATERIALS AND PRODUCTS

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Original Empirical Research

Assessment of the Compressive Strength of Concrete in a Structure in Cases of Doubt as to its Compliance with the Established Requirements

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Abstract

Introduction. When assessing the strength of concrete based on standard tests, there may be doubts about its compliance. The procedure for assessing the strength of concrete in such cases is carried out in accordance with GOST R 57360-2016 (Russian Federation) and STB EN 13791-2012 (Republic of Belarus). Fundamentally different approaches to assessing concrete strength are contained in EN 13791-2019 (introduced in 2020), many provisions of which differ significantly from the previous version and are new to specialists who monitor concrete strength during the construction stage and during the inspection of reinforced concrete structures.

Materials and Methods. The object of the study is a section of a concrete or reinforced concrete structure where the concrete strength is assessed when there is doubt about its compliance with established requirements. In such cases, the following concrete tests are conducted: preliminary indirect testing; indirect testing followed by the selection and testing of concrete specimens by the direct method from areas with the lowest concrete strength; testing of concrete specimens by the direct method.

Research Results. Information is provided on the selection of test areas and sites, their number, methods of core sampling and assessment of compressive strength of concrete based on the results of core testing, combined tests, including the indirect method and core testing. An analysis of concrete strength evaluation methods is performed in cases of doubt as to the compliance of concrete with the established requirements.

Discussion and Conclusion. The paper presents the fundamental differences in the methods for assessing the strength of concrete in structures in cases of doubt as to the compliance of concrete with the established requirements provided in in the European standard and the national standards of Russia and the Republic of Belarus. The disadvantages of the methodology set forth in EN 13791-2019 are outlined.

Keywords: concrete, compressive strength, structures, doubts, assessment methods, indirect tests, core tests

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Оригинальное эмпирическое исследование

Оценивание прочности на сжатие бетона в конструкции в случаях сомнений в его соответствии установленным требованиям

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Аннотация

Введение. При оценке прочности бетона на основе стандартных испытаний могут возникать сомнения относительно его соответствия. Процедура оценивания прочности бетона в таких случаях производится в соответствии

с ГОСТ Р 57360-2016 (РФ) и СТБ EN 13791-2012 (РБ). Принципиально другие подходы к оценке прочности бетона содержатся в EN 13791-2019 (введен в 2020 г.), многие положения которого имеют значительные отличия от предыдущей версии и являются новыми для специалистов, осуществляющих контроль прочности бетона на этапе возведения и при проведении обследования железобетонных конструкций.
Материалы и методы. Объектом исследований является участок бетонной или железобетонной конструкции, в которой оценивают прочность бетона при сомнениях в соответствии бетона установленным требованиям. В таких случаях проводят следующие испытания бетона: предварительное косвенное испытание; косвенное испытание с последующим отбором и испытанием образцов бетона прямым методом из мест с наименьшей прочностью бетона; испытание образцов бетона прямым методом.
Результаты исследования. Приведены сведения о выборе области и мест испытаний, их количестве, методах отбора кернов и оценивания прочности на сжатие бетона по результатам испытаний кернов, комбинированных испытаний, включающих косвенный метод и испытания кернов. Выполнен анализ методик оценивания прочности бетона в случаях сомнений относительно соответствия бетона установленным требованиям.
Обсуждение и заключение. Приведены принципиальные отличия методик оценки прочности бетона в конструкциях в случаях сомнений относительно соответствия бетона установленным требованиям, приведенных в европейском стандарте и национальных стандартов России и Республики Беларусь. Отмечены недостатки предлагаемой в EN 13791-2019 методики.

Ключевые слова: бетон, прочность на сжатие, конструкции, сомнения, методы оценивания, косвенные испытания, испытания кернов

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Introduction. There might be doubts as to whether the required compressive strength of concrete in structures under construction has been achieved due to some uncertainties concerning the quality of the concrete mix supplied to the construction site, violations occurring routinely or following an extraordinary occassion on the construction site. The term "doubt" includes, but is not limited to:

– insufficient compressive strength of concrete samples selected for production control;

– insufficient compressive strength of concrete samples selected for identical testing;

– routine violations.

The procedure for assessing the strength of concrete in cases of doubt as to the compliance of concrete identified based on the standard tests is set out in the standards of Russia and the Republic of Belarus GOST R 57360-2016 "Precast Reinforced Concrete Structures. Identification of Concrete Compressive Strength" and STB EN 13791-2012 "Assessment of the Actual (In-Situ) Compressive Strength of Structures and Precast Concrete Elements" that are identical to the European standard EN 13791-2007 "On-Site Assessment of Concrete Compressive Strength in Structures and Precast Elements". In 2020 a new version of the above standard, EN 13791-2019, came into effect that contains the fundamentally different approaches to assessing the strength of concrete in structures or structural elements. Lots of provisions of the standard are new to specialists monitoring the strength of hardened concrete during construction and inspection of reinforced concrete structures and are in need of a detailed analysis and assessment.

Materials and Methods. The standard EN 13791-2019 considers two options for assessing concrete compressive strength in a structure (Latin — *in-situ*):

– assessment of the characteristic value of the compressive strength of concrete in a structure and/or the strength of concrete in a specific place of a structure;

– assessment of the compressive strength class of concrete supplied and laid in a structure when there are some doubts as to the compressive strength of concrete based on the results of standard tests or poor-quality concrete work.

In the latter the compressive strength of concrete in situ is assessed in order to:

1) evaluate the test area, for which it is confirmed that the supplied concrete is in compliance with the stated compressive strength, but the test results of the samples selected on site show non-compliance, e.g., when:

– the compressive strength of the supplied concrete is established that causes doubts and suspicions;

– the air content in the concrete mix exceeds the maximum allowable;

– water is added to the concrete mix on the construction site according to the consumer’s instructions of with no control tests.

2) control of the compressive strength of concrete when the manufacturer has declared non-compliance;

3) control of the compressive strength of concrete in case of violation of the technology of work related to the laying, compaction or strength gain of concrete.

According to EN 13791-2019, the object of research is a test area or a test site where the characteristic compressive strength of concrete is identified that is used directly in order to assess the compliance of reinforced concrete or concrete structures with the current technical regulations (hereinafter referred to as CTR). Therefore, the standard EN 13791-2019 provides no procedure for reducing the strength of concrete identified according to the standard samples, to the strength of concrete in a structure using a coefficient of 0.85 and establishing a concrete compressive strength class in an existing structure (Table 1 of EN 13791-2007).

This article explores the methods for assessing the strength of concrete that are employed in case of doubts or controversies regarding the quality of concrete delivered to the construction site and laid in a structure.

Manufacturer can express doubts as to the quality of concrete. In this case, they are obliged to provide the consumer with a complete set of information that allows them to identify the scope of violations and possible risks. Based on the inspection of a structure, the site where the concrete causing doubts has been laid is localized. The concrete manufacturer is obliged not only to account for the causes of non-compliance, but also to assess the characteristic compressive strength of the concrete at the time of its delivery and provide the information used to analyze the concrete strength. If the compressive strength of concrete is underestimated, an in-situ assessment of the compressive strength class and an assessment of structural safety might be required.

If the examination reveals the need to test the concrete in a structure in order to resolve the controversies regarding the compliance of the concrete delivered to the construction site and laid in the structure, the following options are possible:

– preliminary testing;

– indirect testing followed by sampling and testing of cores from sites with the lowest concrete strength;

– core testing.

A block diagram of the concrete compressive strength class is shown in Fig. 1.

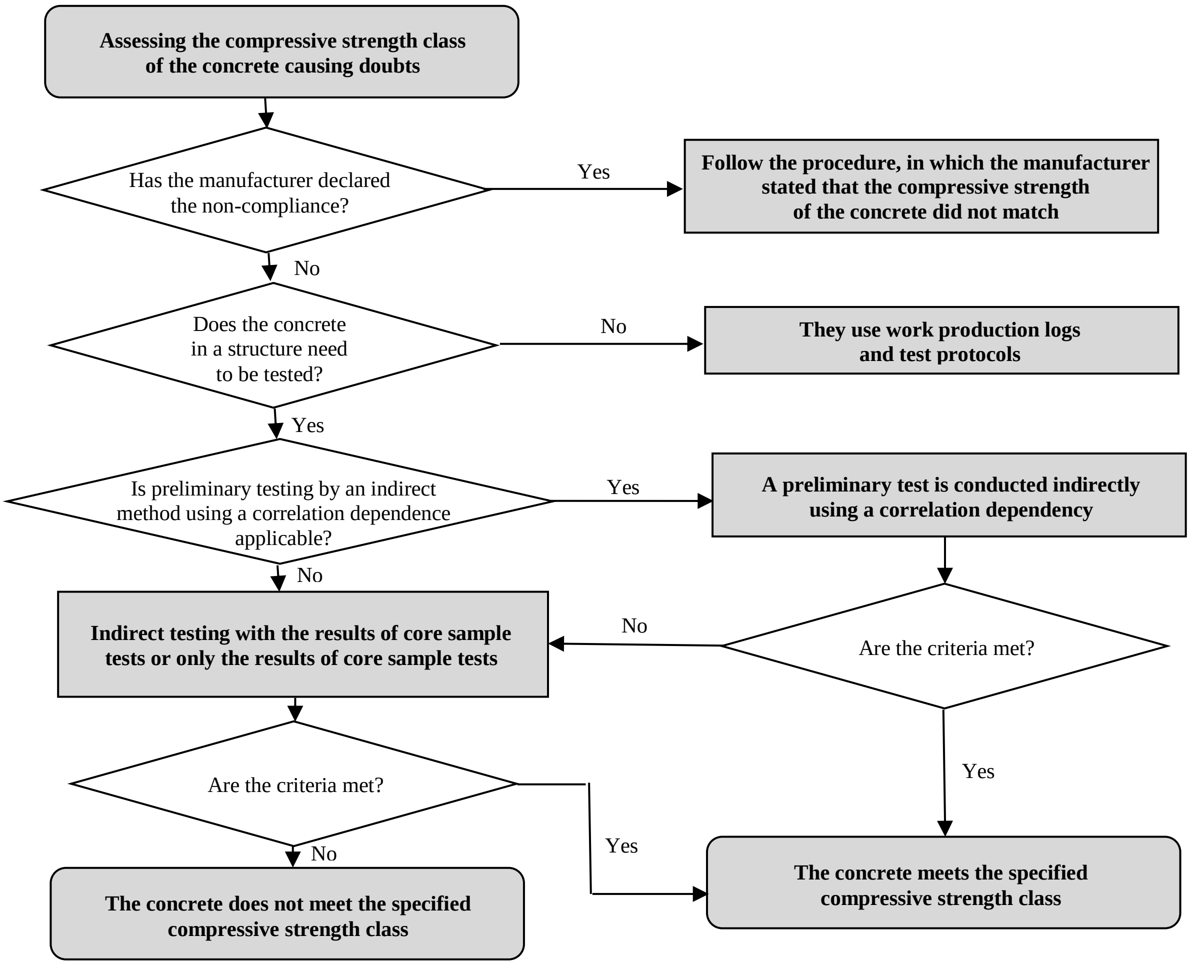

Fig. 1. Block diagram of concrete compressive strength class assessment in case of doubt with references to relevant points of EN 13791-2019

In case of a positive test result, the concrete supplied to a structure is deemed in compliance with the specified compressive strength class, any adjustments to the concrete supplied to the construction site are deemed insignificant, and the quality level of work during laying, compaction and hardening of concrete is deemed appropriate.

If the test results fail to prove that the concrete is in compliance with the specified compressive strength class, it might be necessary to verify that the structure is in compliance with the established requirements, taking into account the resulting compressive strength of the concrete. Regardless of the causes for the non-compliance (incorrect choice of the components, a poor quality of the concrete works, defects in the concrete), the load-bearing capacity and serviceability of a structure must be ensured.

Research Results. Preliminary tests involve the use of an indirect method with an established correlation between the result of the indirect testing and the compressive strength of concrete. In EN 13791-2019, two methods of indirect concrete strength testing are considered: the elastic rebound method (EN 12504-2-2001 "Testing Concrete in Structures. Part 2. Non-destructive testing. Identification of the Rebound Criterion") and the UPV ultrasonic pulse propagation velocity method (EN 12504-4-2004 "Concrete Testing in Structures. Part 4. Identification of the Velocity of Propagation of an Ultrasonic Pulse"). It is to be noted that the standard EN 13791-2019 provides no indirect test method based on the breaking of anchors from concrete according to EN 12504-3-2005. In domestic practice, the method of non-destructive testing of concrete strength is recommended as a reference method [1–3]. Discarding this test method in the new version of the standard must be due to the uncertainties caused by the differences in the strength of concrete in the surface layers of the structure and its main volume, as well as the test conditions (type of an aggregate, presence of a reinforcement, humidity, etc.). For the same reason, EN 13791-2019 requires that, after the core selected from the structure has been cut, it should not contain:

– any concrete within 30 mm to any surface;

– any concrete within 50 mm or 20% of the upper surface of the concrete layer, depending on whichever is greater, in the areas with a layer thickness of no more than 1.5 m;

– any concrete within 300 mm of the upper surface of the layer where the layer thickness is 1.5 m or more.

The test result according to EN 12504-2-2001 is the rebound value, which is the median value of at least nine reliable results on the test site. While identifying the velocity of propagation of an ultrasonic pulse UPV according to EN 12504-4-2004, the test result is a single value of the velocity of propagation of the ultrasonic pulse or the value of the average velocity of propagation of the ultrasonic pulse, if more than one measurement was carried out on the test site.

The value of the rebound and the velocity of propagation of the ultrasonic pulse are not direct measurements of the compressive strength of concrete, but while using the correlation, they can be used in order to assess the compressive strength of concrete in a structure.

Tests for identifying the elastic rebound of a hammer enable measurements of the surface hardness of concrete, but not its evaluation over the entire section of the structure. The method is not recommended in the following cases:

– the depth of carbonization of concrete is more than 5 mm;

– the formwork with controlled dehumidification or surface concrete hardeners were used;

– the concrete has been damaged in fire;

– the concrete surfaces have been damaged as a result of a chemical exposure or defrozen.

Tests for identifying the velocity of propagation of an ultrasonic pulse make it possible to assess the quality of concrete over the entire section of a structure, but the test results are considerably influenced by the concrete moisture as well as some other factors.

Preliminary testing can be used in order to assess the uniformity of the concrete composition in the test area, to identify areas with a lower compressive strength as well as to assess whether the specified compressive strength class of the concrete has been achieved if there is a reliable correlation between the strength of concrete and the result of the indirect testing. EN 13791-2019 contains the following, "if the results of indirect testing indicate that the required criteria have not been complied with, this does not prove that the concrete is not in compliance with the specified compressive strength class." In this case, additional studies based on core testing or combined tests involving one of the indirect methods and core testing should be performed. Prior to the combined tests, the concrete must be divided into areas containing a volume of concrete not exceeding 180 m^3. The test area is then divided into sections with a concrete volume of approximately 30 m^3. Depending on the number of areas, the number of sites where indirect testing will be performed, as well as core sampling is set (Table 1).

Table 1

Minimum number of test locations in the test area for the indirect method

Number of sites containing approximately 30 m^3 of concrete in the test area^a	Minimum number of indirect test locations
1^b	9
from 2 to 4	12
from 5 to 6	20

^{a} If the volume covers a large area, the number of indirect tests should be increased in order to reflect the variability of the results within the test area.
^{b} Provided that it is considered as a single volume

According to Table 1, even with a very small volume of concrete having been laid, the minimum number of indirect test sites is nine. In the areas involving large volumes of concrete (about 30 m^3), indirect testing sites should be distributed evenly over the area of the site. Indirect testing serves as the foundation for identifying the sites where core sampling will be conducted. The principle of core sampling and the assessment criteria are shown in Table 2.

Table 2

Core sampling sites and assessment criteria

Number of volumes is approximately 30m^3, in the test area	Minimum number of the core sampling sites	Average value of the core test results in the locations closest to the median rebound value or the average UPV value for the test area ^{b}	Minimum value of the test results$^{b,\,c}$
1^d	A core for each of the two lowest values of the indirect test for the test area	—	≥ 0,85 ($f_{ck,spec}$ – M)
from 2 to 4	A core at the lowest indirect test value for the test area and a core at each of the 2 test sites closest to the median rebound value or the average UPV value for the test area	≥ 0,85 ($f_{ck,spec}$ + 1)	≥ 0,85 ($f_{ck,spec}$ – M)
from 5 to 6		≥ 0,85 ($f_{ck,spec}$ + 2)	≥ 0,85 ($f_{ck,spec}$ – M)

^{b} The core strength can be expressed as $f_{c,1:1core}$ or $f_{c,2:1core}$ depending on the chosen $f_{ck,spec}$.
^{c} For concretes of the compressive strength class C20/25 or higher M = 4 MPa. For concretes C16/20, C12/15 and C8/10 M is 3, 2 and 1 MPa respectively.
^{d} Provided that it is considered as a single volume.

According to Table 2, in order to assess its compliance with the established compressive strength class for a small volume of concrete, it is sufficient to conduct indirect concrete testing in nine locations and test two cores.

The $f_{ck,spec}$ values from Table 1 refer to the strength of concrete identified on cylindrical ($f_{ck,cyl}$) or cubic ($f_{ck,cube}$) samples corresponding to this compressive strength class. If it is necessary to conduct concrete strength studies based on the core tests, as in the case of combined tests, each area is to be divided into sections containing no more than 30 m^3 of concrete. The minimum number of test sites depends on the number of sites the test area is divided into (Table 3).

Cores with a length-to-diameter ratio of 2:1 or 1:1 and a diameter of ≥ 75 mm are used for testing. If it is not possible to select them, it is allowed to assume a core diameter of at least 50 mm. While identifying the compressive strength of concrete in a structure, the core test result is converted to an equivalent value for a core with a length-to-diameter ratio of 2:1 using the core length coefficient (CLF).

Table 3

Assessment criteria based on the core testing results

Number of sites comprising approximately 30m^3 of concrete in the test area	Minimum number of the test areas for each site	Average value of the core test results for the test area^b	Lowest test result^{b,c}
1^d	3	—	$\geq 0{,}85\ (f_{ck,spec} - M)$
from 2 to 4	2	$\geq 0{,}85(f_{ck,spec} + 1)$	$\geq 0{,}85\ (f_{ck,spec} - M)$
from 5 to 6	2	$\geq 0{,}85(f_{ck,spec} + 2)$	$\geq 0{,}85\ (f_{ck,spec} - M)$

^{b} The core strength can be expressed as $f_{c,1:1core}$ or $f_{c,2:1core}$ depending on the chosen $f_{ck,spec}$.
^{c} For concretes of the compressive strength class C20/25 or higher M = 4 MPa. For concretes C16/20, C12/15 and C8/10 M is 3, 2 and 1 MPa respectively.
^{d} Provided that it is considered as a single volume.

For heavy concrete, the core test results with a length-to-diameter ratio of 1:1 to an equivalent value for a core with a length-to-diameter ratio of 2:1 are converted by taking the CLF value of 0.82, which is lower than the CLF value set in EN 13790-2007 and equals 0.85. It is to be noted that in the specified standard, the diameter of the cores is recommended to be at least 100 mm. In order to obtain the test result, core sampling is carried out at each test site (three cores with a diameter of 50 mm or one core with a diameter of ≥ 75 mm). The concrete compliance assessment criteria are shown in Table 3. If both criteria are met, it can be argued that for the test area concrete is in compliance with the established compressive strength class.

Multipliers equal to 0.85 in the evaluation criteria (see Tables 2, 3) express the ratio of the characteristic strength of concrete identified in situ, to the strength of concrete obtained based on tests of the standard samples. The observed difference in concrete strength is due to the differences in the laying of the concrete mix, maintenance, shrinkage, and exothermy of the hardening concrete [1–5]. Therefore even under ideal conditions of concreting and concrete maintenance its strength identified in situ is unlikely to be over 70–85% of the strength obtained on the standard samples [6–10]. It is for this reason that the Eurocode 2 (EN 1992-1-1-2004) establishes the requirements for modifying a particular coefficient for concrete if its strength is obtained based on tests in the completed structure.

Discussion and Conclusion.

The methodology for assessing the strength of concrete in structures in cases of doubt as to the compliance of concrete with the established requirements provided in the standard EN 13791-2019 is fundamentally different from the previous version of the standard, as well as the national standards of Russia and the Republic of Belarus - GOST R 57360-2016 and STB EN 13791-12. The major differences are:

– in the introduction of a different methodology for identifying the compressive strength of concrete in a structure and changing the criteria for assessing it in case of doubt as to the quality of concrete;

– identifying the number of test sites depending on the methods used to assess the compressive strength of concrete;

– refusing to establish the current compressive strength class of concrete in the structure taking into account the coefficient of 0.85 that expresses the ratio of the strength of concrete in the structure to that of concrete of the standard samples (see Table 1 in EN 13791-2007). According to the standard EN 13791-2019, the characteristic strength of concrete in a structure (on site or in the test area) is evaluated;

– a change in the conversion coefficient of the values obtained on cores with a height-to-diameter ratio h/d = 2 to those with a height-to-diameter ratio h/d = 1, from 0.85 to 0.82;

– reducing the diameter of the main core samples from ≥ 100 mm to ≥ 75 mm;

– exclusion of the indirect method based on the breaking of anchors while assessing the compressive strength of concrete structures.

It is to be noted that the statistical analysis methods set forth in the standard EN 13791-2019 for assessing concrete strength values from small-volume empirical data samples are not without some disadvantages of the previous version. This mostly applies to the establishment of a specific distribution law for a random variable (normal or lognormal), as well as the availability of the results of identifying concrete strength.

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