Развиваемые в России направления устойчивого проектирования транспортных сооружений

Овчинников Илья Игоревич
доктор технических наук, доцент, заведующий кафедрой АО «Мостострой-11», Тюменский индустриальный университет; советник РААСН, bridgeart@mail.ru,

Мавзовин Владимир Святославович
кафедра высшей математики, Институт цифровых технологий и моделирования в строительстве (ИЦТМС), Национальный исследовательский Московский государственный строительный университет, mavzovin@mail.ru,

Овчинников Игорь Георгиевич
доктор технических наук, профессор, Тюменский индустриальный университет, bridgesar@mail.ru

Концепция устойчивого проектирования (Sustainable design) транспортных сооружений требует перехода от простого увеличения срока службы к комплексной экологической, экономической и информационной безопасности. Цель данного обзора — систематизировать передовые российские и мировые практики экологически рационального мостостроения. В работе анализируются девять ключевых направлений: от применения атмосферостойких сталей, алюминиевых сплавов и полимерных композитов до внедрения углеродно-негативных бетонов и трубобетонных конструкций. Отдельное внимание уделено интеграции возобновляемых источников энергии и бионическому подходу. Кроме того, обоснована необходимость формирования стратегии информационной защиты инфраструктурных объектов от деструктивного влияния вирусных фейков. Результаты работы могут быть использованы проектировщиками для выбора оптимальных решений, повышающих жизненный цикл сооружений и снижающих их углеродный след.

Ключевые слова: транспортное сооружение, идеальный мост, устойчивое проектирование, антикоррозионная защита, трубобетон, возобновляемая энергетика, бионический подход, информационная безопасность.

Introduction

Ensuring the durability of transport structures has traditionally been considered through the prism of fracture mechanics and construction economics. The idea of intentionally reducing the service life of products (planned obsolescence), applied in mechanical engineering to stimulate demand, is categorically inapplicable to bridge structures due to their colossal cost and social significance. Under modern conditions, a reasonable compromise is the concept of sustainable design, aimed at maximizing the life cycle while minimizing harmful environmental impact at all stages: from the production of materials to disposal [1–5].

Despite the growing interest in this concept, domestic practice lacks a systematized review of modern materials and technologies capable of ensuring the ecological and energy rationality of transport objects. The present article is intended to fill this gap. We examine in detail nine promising directions of sustainable design being implemented in Russia and worldwide, and also raise the little-studied problem of the information vulnerability of engineering structures in the face of the spread of fake news.

1. Possible Directions of Environmentally Rational Design of Bridge Structures

1.1. The Concept of an Ideal Bridge Structure

The application of the concept of an ideal bridge structure requires a correct assessment of durability [6]. Traditional damage parameters, such as stresses or deformations, are not always objective. For example, a reduction in stresses in a certain zone does not guarantee a decrease in the probability of its failure. Therefore, for the assessment of durability, it is advisable to apply the theory of damage accumulation in scalar or tensor variants.

1.2. Use of Weathering Steels

The use of weathering steels (for example, grade 14KhGNDTs) makes it possible to dispense with the application of protective paint coatings, which eliminates the negative impact of paints on the environment. The first practical implementation of this technology in Russia was carried out on railway infrastructure objects. In the period of 1989–1990, three superstructures with a span of 55 m were erected in three regions of the country. The structures were manufactured by the Voronezh plant from steel grade 14KhGNDTs (Rus ver. - 14ХГНДЦ)



Fig. 1. Elements of bridge superstructures made of weathering steel after 21 years of operation without the use of a paint coating. Source [7].

In the field of highway bridge construction, until recently, examples of the use of weathering steel grade 14KhGNDTs were absent. Its first application was realized during the construction of the new first-category highway M-11 "Neva": on the overpass located at station 2565+44.29, as well as on the bridge across the Shosha River at station 1260+38.

1.3. Use of Aluminum Alloys

The use of aluminum alloys in bridge structures makes it possible to completely dispense with the installation of anticorrosion protection. In the Nizhny Novgorod region, bridge structures made of these alloys were erected, including pedestrian and highway bridges, which have proven their high efficiency.



Fig. 2. Overpass at station 2565+44.29 on the first-category highway M-11 "Neva". Source [7]



Fig. 3. Bridge across the Shosha River at station 1260+38. Source [7]



Fig. 4. Pedestrian bridge made of aluminum alloys. Source [7].

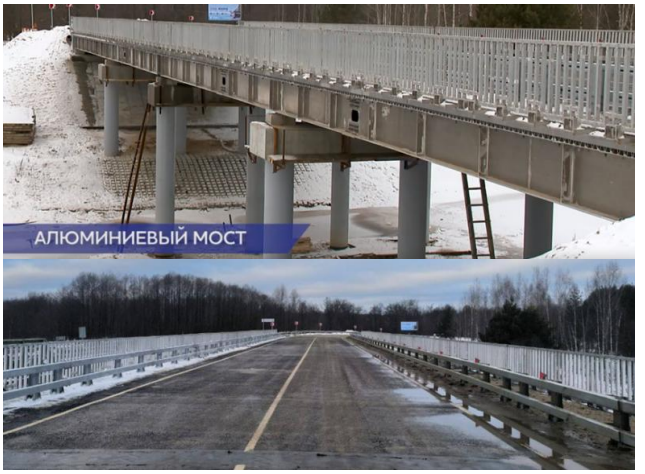


Fig. 5. Highway bridge made of aluminum alloys. Source [7].

1.4. The Pareto Principle in Anticorrosion Protection

The use of the Pareto principle in the design of anticorrosion protection systems presupposes taking into account that the direct cost of protective materials accounts for only about 20% of the total costs. The main share of expenses (approximately 80%) falls on surface preparation, the installation of auxiliary structures, and the performance of related operations necessary for the environmentally safe application of coatings.

In this regard, it is advisable to give preference to more expensive but high-resource protective systems. Their use makes it possible to reduce the frequency of repainting, increase the economic return over the life cycle, and reduce the negative impact on the environment [8]. Figure 6 shows the satisfactory condition of the Stelpant paint coating with a thickness of 220–263 μm, recorded on the elements of a bridge located in a coastal zone.

1.5. Implementation of Polymer Composite Materials

In recent years, fiberglass and carbon fiber materials have been finding increasingly wide application. They are mainly used in the superstructures of pedestrian bridges; however, attempts are being made to implement composite solutions for highway bridges as well. To date, about thirty pedestrian bridges with composite superstructures up to 38 m in length have been manufactured and built in Russia.



Fig. 6. Condition of the anticorrosion protection system of the bridge across the Matsesta River in the city of Sochi after 20 years of operation. Photo by the authors.



Fig. 7. Environmental measures during anticorrosion protection of bridge structures [8].

In general, five main directions of application of these materials can be identified. The first is related to the creation of bridge structures entirely or of individual elements thereof from polymer composite materials.



Fig. 8. Bridge superstructure made of polymer composite material. Source [7].

The second direction provides for the use of non-metallic composite reinforcement in the reinforcement of concrete structures.

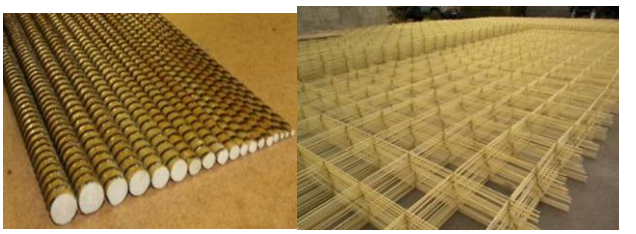


Fig. 9. Examples of bar-type polymer composite reinforcement. Source [7].

The third direction is related to the use of composite materials for the strengthening of existing metal and reinforced concrete bridge structures.

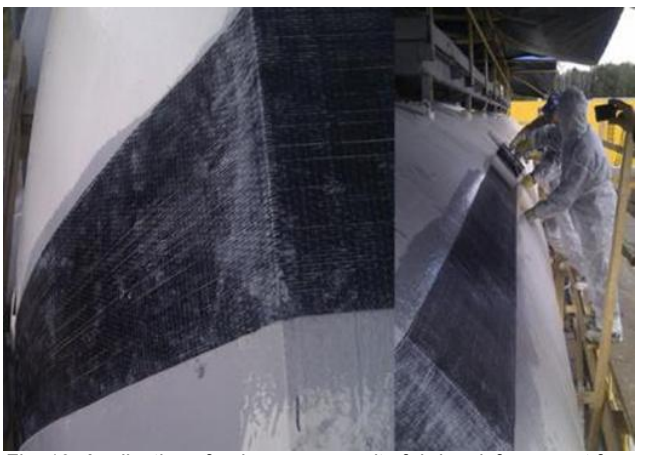


Fig. 10. Application of polymer composite fabric reinforcement for strengthening elements of bridge structures. Source [7].

At the same time, it should be noted that the current regulatory documents (in particular, clause 5.4 of SP 35.13330.2011) take a rather restrained approach to the issues of introducing polymer composite materials in bridge construction.

The fourth direction consists in the use of composites in elements subjected to relatively small loads, such as railing fences, drainage troughs, and noise barriers. Railing fences made of polymer composites have a number of important advantages: corrosion and biological resistance, color stability, high strength at a relatively low weight (5 times lighter than steel), as well as dielectric properties.

However, polymer composites also have disadvantages related to the need to ensure their fire safety [9], as well as a high sensitivity to installation inaccuracies (Fig. 11).



Fig. 11. Deviation of the railing fence axis from the design position [10].

The fifth direction is the manufacture of structures from recycled polymers. The use of polymer waste as secondary raw material will make it possible to solve problems related to ecology and disposal [11].



Fig. 12. Pedestrian plastic bridge made of recycled polymer materials withstands a truck [11].

1.6. Application of Modern Concrete Modifications

Approximately 90% of load-bearing structures are erected using concrete. The advantages of concrete include the possibility of using local materials, a wide range of mechanical properties, and low labor costs. Recently, high performance concretes have appeared [12], with the use of which bridges and overpasses on the Moscow Ring Road, the "Floating Bridge" in Moscow, and others have been erected.



Fig. 13. Monolithic post-tensioned superstructure of the "Floating Bridge" in Zary

adye Park [13].

Of particular note are the developments of carbon-negative materials (for example, enzymatic structural material — ESM), in which an enzyme (carbonic anhydrase) catalyzes reactions with atmospheric CO_2. According to preliminary laboratory data, the creation of 1 m³ of ESM can absorb more than 6 kg of CO_2 (unlike ordinary concrete, which emits about 330 kg). However, this material requires additional field testing in various climatic conditions before mass implementation.

1.7. Concrete-Filled Steel Tube Structures

One of the promising directions is the application of concrete-filled steel tube structures in the construction of small bridges. Of greatest interest are elements working in bending, which can be effectively used as beams of superstructures and load-bearing elements of arch structures [14, 15].



Fig. 14. Installation of arched concrete-filled steel tube elements of a soil-filled bridge in the Ulyanovsk region [14, 15].

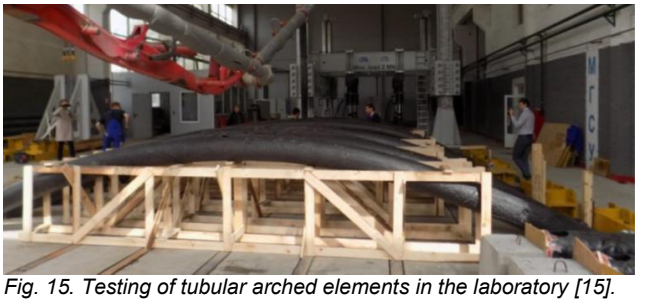


Fig. 15. Testing of tubular arched elements in the laboratory [15].

Concrete-filled steel tube elements acquire particular efficiency when used with second-hand pipes as the outer shell of the structure, which solves the problem of disposal of pipeline system waste.



Fig. 16. Concrete-filled steel tube superstructure using second-hand pipes and possible variants of pipe cross-section filling.

1.8. Integration of Renewable Energy Sources into Bridge Structures

It includes the installation of wind generators, solar panels, hydrogenerators on supports, as well as the use of piezoelectric elements as part of the bridge deck.

At present, the majority of energy consumed by humans is generated from natural gas, oil, and nuclear energy. However, all these sources are non-renewable and may be depleted in the future. In this regard, the question arises of possible ways to meet energy needs in the future. One of the solutions is the use of continuously occurring natural processes, as well as plant raw materials and organic waste. The energy obtained in this way belongs to the category of renewable energy. Wind energy installations, solar power plants, and hydroelectric power plants using the energy of water flows are used as its sources.

It should be noted that the operating principle of hydroelectric power plants is based on the conversion of the potential and kinetic energy of falling water into electrical energy. This method has a number of advantages compared to other technologies for the use of renewable resources, since the efficiency of hydroelectric installations, as a rule, exceeds the corresponding indicators of solar and wind power plants.



Fig. 17. Submersible turbine of a free-flow small hydroelectric power station [19].

Bridge structures possess the potential for energy generation. Wind energy installations, solar power plants, and hydroelectric power plants are used as its sources.

Use of hydrogenerators. Hydrogenerators are placed underwater near bridge supports. Small free-flow hydroelectric power stations do not require frequent maintenance and have a high efficiency (more than 90%).

Use of wind generators. Wind generators are proposed to be installed under viaducts, since air flows between the supports develop higher speeds. Patents for wind generators with a vertical axis of rotation mounted on the pylons of bridge structures are also described.



Fig. 18. Arrangement of wind generators on a viaduct [17].

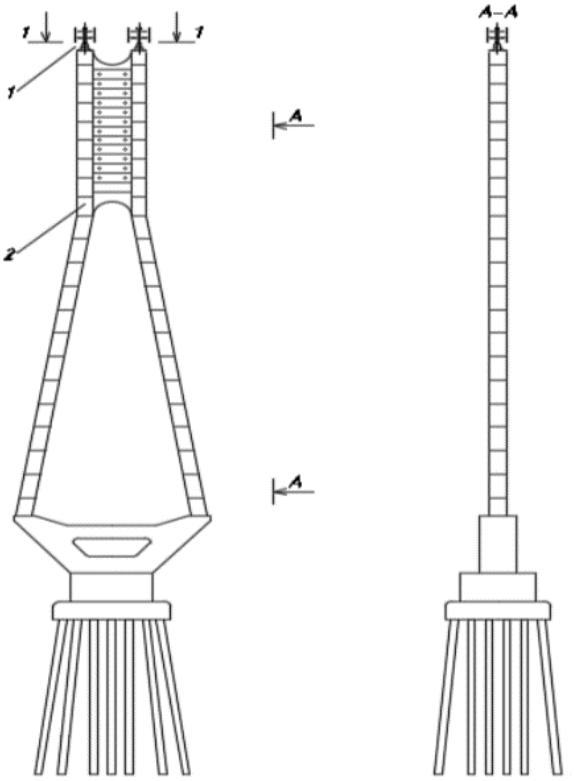


Fig. 19. General view of a bridge structure pylon with an installed wind generator: 1 – wind generator; 2 – A-shaped pylon [18].

Use of solar panels. At present, solar panels are widely used for generating electricity, including on bridge structures.



Fig. 20. Solar panels on the Levi's Stadium bridge.

Use of piezoelectric and triboelectric generators. A promising innovative direction in the field of renewable energy sources is piezoelectric generators, functioning on the basis of the piezoelectric effect. The essence of this phenomenon consists in the emergence of electric charges on the surface of a material upon its mechanical deformation. Due to their small working area, piezogenerators are finding increasing application in road surfaces, since they do not create restrictions for the movement of vehicles and pedestrians. The possibility of their integration directly into the structure of the roadway ensures both safety and efficiency of use, implementing the principle: the volume of generated energy corresponds to the magnitude of the mechanical impact.

As an example, one can cite the experience of Japan, where at the Marunouchi Station of the metropolitan subway a piezoelectric floor has been installed, converting the energy of passengers' steps into electrical energy sufficient to power the turnstiles. At the same time, a significant disadvantage of this technology is the low power of individual piezoelectric elements, which requires their use in large quantities. This circumstance significantly increases the cost of the system and reduces its economic efficiency in mass implementation.

The application of triboelectric generators, converting the energy of bridge deck vibrations into electricity, is also described (Fig. 21).

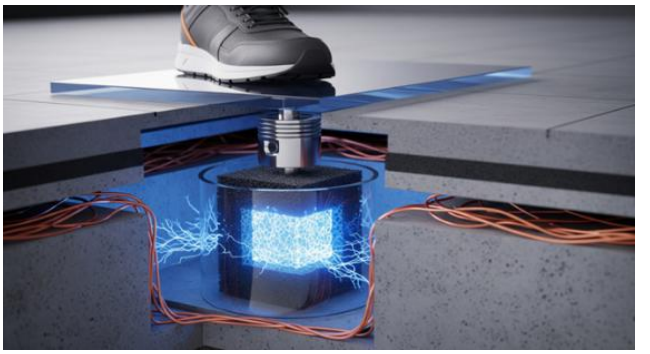


Fig. 21. Schematic of the operation of a triboelectric nanogenerator.

1.9. Bionic Approach

The use of this approach is based on borrowing the principles and forms of living nature to solve engineering problems in bridge construction.

Bionics in bridge construction is applied at the macro level (borrowing external forms) and at the micro level (using the adaptive and self-regulating properties of living organisms).

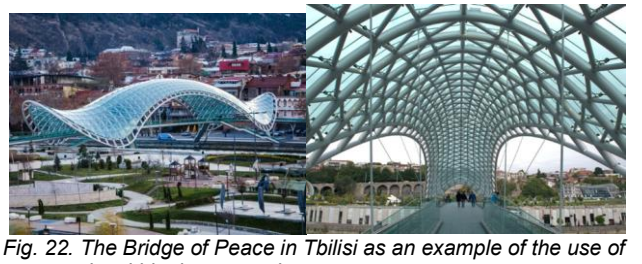


Fig. 22. The Bridge of Peace in Tbilisi as an example of the use of a macro-level bionic approach



Fig. 23. The Helix Bridge pedestrian bridge in Singapore as an example of a micro-level bionic approach [20].

2. Information Sustainability and Protection of the Reputation of Engineering Structures

Sustainable design traditionally focuses on the physical durability and environmental friendliness of materials. However, in the era of digitalization, an equally important aspect is the information sustainability of an object. Innovative infrastructure projects require enormous investments and public recognition. Viral myths and fake news can instantly destroy the reputation of even a technically flawless structure, which leads to an increase in maintenance costs and a decline in trust in engineering innovations as a whole.

Illustrative in this regard is the analysis of recent information attacks on historical engineering objects. In 2024, mass reports appeared online about Paris's readiness to carry out the dismantling of the Eiffel Tower due to "structural deterioration." These reports led to the appearance of numerous emotional comments about the "end of an era" having arrived.



Fig. 24. View of the Eiffel Tower.

The original source of this fake was humorous information in a satirical online magazine. However, a couple of weeks later, the tower was closed for an entirely different reason (due to a strike by public sector workers). For safety reasons, the tower was closed for several days, and photographs of the closed ticket offices served as "evidence" for supporters of the demolition rumors.

The Eiffel Tower is a monument of engineering art that undergoes regular inspection using modern non-destructive testing methods every 7 years. The situation with the tower demonstrates that modern engineering objects depend on their public perception. Large infrastructure objects must possess a strategy of information protection. The spread of rumors about the unsafety of an object leads to a decrease in its value. Therefore, information security should be considered as a new direction of construction expertise, and the engineering community needs to participate more actively in public education.

Conclusion

Sustainable design of transport structures represents a complex task that goes beyond the simple selection of materials. Modern engineering practice must integrate the use of weathering steels, composites, energy-saving concretes, and renewable energy sources. At the same time, the implementation of innovations requires not only the resolution of technical and regulatory tasks but also the formation of a culture of information sustainability capable of protecting the results of engineering labor from the destructive influence of media fakes.

Directions in Sustainable Design of Transport Structures Developed in Russia

Ovchinnikov Il.I., Mavzovin V.S., Ovchinnikov I.G.
Tyumen Industrial University, RAASN, National Research Moscow State University of Civil Engineering, Institute of Digital Technologies and Modeling in Construction (IDTMC)

JEL classification: L61, L74, R53

The concept of sustainable design of transport structures requires a transition from simply increasing the service life to comprehensive ecological, economic, and information security. The purpose of this review is to systematize advanced Russian and global practices of environmentally rational bridge construction. The paper analyzes nine key directions: from the use of weathering steels, aluminum alloys, and polymer composites to the implementation of carbon-negative concretes and concrete-filled steel tube structures. Special attention is given to the integration of renewable energy sources and the bionic approach. In addition, the necessity of forming a strategy for information protection of infrastructure objects from the destructive influence of viral fakes is substantiated. The results of the work can be used by designers to select optimal solutions that increase the life cycle of structures and reduce their carbon footprint.

Keywords: transport structure, ideal bridge, sustainable design, anticorrosion protection, concrete-filled steel tube, renewable energy, bionic approach, information security.

References

1. Ovchinnikov I. G., Ovchinnikov I. I. Sustainable bridge design in Russia // International Scientific and Practical Conference "Railway Transport and Technologies". AIP Conf. Proc. 2624, 030021-1–030021-8. DOI: 10.1063/5.0133764.
2. Korotkov M. A., Ovchinnikov I. G. The impact of environmentally rational design on the transport construction industry // Transport. Transport Structures. Ecology. – 2022. – No. 2. – P. 64–71. DOI: 10.15593/24111678/2022.02.08.
3. Venkateswaran B. Sustainable Practices in Bridge Construction // Journal of Sustainable Construction Materials and Technologies. – 2021. – Vol. 6, No. 1. – P. 24–28. DOI: 10.29187/jscmt.2021.56.
4. Penadés-Plà V., García-Segura T., Martí J. V., Yepes V. A Review of Multi-Criteria Decision-Making Methods Applied to the Sustainable Bridge Design // Sustainability. – 2016. – Vol. 8, 1295. DOI: 10.3390/su8121295.
5. Navarro I. J., Penadés-Plà V., Martínez-Muñoz D., Rempling R., Yepes V. Life cycle sustainability assessment for multi-criteria decision making in bridge design: a review // Journal of Civil Engineering and Management. – 2020. – Vol. 26, No. 7. – P. 690–704. DOI: 10.3846/jcem.2020.13599.